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Cue- versus response-locked processes in backward inhibition: Evidence from ERPs

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Abstract

A task set may need to be inhibited to facilitate the switch to another task. This event-related potential (ERP) study determined (1) whether backward inhibition (BI) is exerted preferentially in high interference environments, and (2) whether ERPs locked to critical time points reflect BI during cue preparation and/or response stages. High interference (HI) and low interference (LI) were created by manipulating task difficulty. A reaction time (RT) BI effect (i.e., BI > control trials) was shown only during HI tasks. Cue-locked ERPs on LI tasks suggest increased attentional resources were allocated during the reactivation of a recently inhibited task. For HI tasks, BI versus control trial differences were reflected in a response-locked ERP negativity only after response selection (indexed by the response-locked lateralized readiness potential), indicating that BI is a lateral inhibition mechanism exerted during response preparation.

Descriptors: Task switching, Backward inhibition, Event-related brain potentials, Lateralized readiness potentials (LRP)

The ability to switch efficiently between two or more tasks is thought to require executive control because the control settings appropriate on one trial are no longer relevant when a new task is required. As such, inhibitory mechanisms that suppress the now inappropriate task may be required to facilitate switches between two or more tasks.

Cumulative evidence suggests that inhibition of a just-performed task set does occur in task switching (Allport, Styles, & Hsieh, 1994; Allport & Wylie, 2000; Arbuthnott & Frank, 2000; Arbuthnott & Woodward, 2002; Dreher & Berman, 2002; Dreisbach, Haider, & Kluve, 2002; Gade & Koch, 2005; Gilbert & Shallice, 2002; Hubner, Dreisbach, Haider, & Kluve, 2003; Koch, Gade, & Philipp, 2004; Mayr, 2001, 2002; Mayr & Keele, 2000; Schuch & Koch, 2003). Although there is evidence that this control mechanism is a form of lateral inhibition, whereby the activation of one task causes the suppression of competing tasks, we hypothesized that inhibition is not exerted uniformly on all competing tasks but is applied to a greater extent on tasks with a higher interference potential.

In this study, we varied task difficulty in order to manipulate task interference and the need for inhibitory control. We complemented the collection of behavioral data with event-related brain potentials (ERPs) because we hoped that their high time resolution would inform us about the timing of control processes involved in task switching.

Task Switching

Although the task switching paradigm has been implemented in several forms, the essential feature of the procedure is a contrast between trials where the participant must switch to a different task versus trials where the participant is able to repeat a task. The reaction time (RT) difference that typically results from slower performance on switch trials and faster performance on repeat trials has been termed the switch cost (Rogers & Monsell, 1995). A large part of this switch cost has been attributed to the need to reconfigure the internal control settings required to perform a given task, also known in the cognitive literature as the "task set". Evidence in favor of this reconfiguration process comes from the substantial reduction of the switch cost given by advanced preparation (Rogers & Monsell, 1995; Meiran, 1996). However, the persistence of a residual switch cost even after long preparation intervals suggests the existence of other factors. A source of switch cost variance that has received considerable interest has been the effects of previous trials on current task performance, with particular emphasis on the potential interference from previous tasks.

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Meiran (1996) introduced the cued task switching paradigm, in which a target is preceded by the presentation of a task cue. In this paradigm, the cue–target interval (CTI) can be used by participants to prepare for the upcoming task, whereas in the interval between the response and the presentation of the following cue (RCI), the just-performed task set can be deactivated to avoid interference with performance of the upcoming task. Results showed that increasing the response–cue interval while keeping the response–target interval constant led to a reduction of the switch cost, suggesting the presence of lingering interference from the previous task set. This lingering interference highlights an important property of task sets: their tendency to remain active after their instantiation. When rapidly shifting from one task to another, mechanisms of inhibitory control may be required to counteract this persistent activation.

The strongest evidence in favor of the existence of inhibitory processes in task switching comes from the alternating task effect first demonstrated by Mayr and Keele (2000). The critical contrast in their design was performance between a task set that had been active two trials earlier (i.e., an A–B–*A* sequence of task sets) and a task set that occurred less recently (i.e., a C–B–*A* sequence of task sets). RT was slower when a task had been performed two trials earlier relative to RT on a task performed less recently. This *backward inhibition* (*BI*) *effect* was attributed to the need to inhibit a just-performed task set in order to facilitate a switch to a new task (i.e., task A is inhibited when switching from task A to task B). When the inhibited task set (i.e., task A) is reactivated shortly after, as in the run sequence A–B–*A*, it has to overcome this suppressed state, leading to a behavioral cost. This inhibitory control appears to act at the level of the task set rather than on individual stimulus–response (S–R) associations (i.e., the activation of the letter task itself rather than the association between, for example, the vowel "A" in the compound target "2A", and a "left" button response) because it is not modulated by stimulus repetition or response repetition between lag-2 (i.e., the task performed two trials back) and the current task (Hubner et al., 2003; Mayr & Keele, 2000; Schuch & Koch, 2003). Although it appears to act at a higher level of the task set, backward inhibition should not be mistaken with a higher order "voluntary" mechanism. In fact, it appears to be a low level mechanism, recruited at all switch transitions regardless of the time allowed to prepare for a new task (Mayr & Keele, 2000, Experiments 1a, 1b; Schuch & Koch, 2003) or whether participants have full knowledge of the task sequence (Koch, Philipp & Gade, 2006; Mayr & Keele, 2000, Experiment 5).

There appears to be consensus in the literature that backward inhibition is a form of lateral inhibition whereby selection of a new task set is accompanied by suppression of competing task sets (Hubner et al., 2003; Mayr & Keele, 2000; Schuch & Koch, 2003). However, it is not clear whether this lateral inhibition is applied uniformly to all competing task sets or whether it is a form of reactive inhibition (Houghton & Tipper, 1994) whereby increased control is exerted preferentially on tasks that can cause increased interference. Some evidence exists that BI is a form of reactive inhibition, but this evidence comes from studies that modulated BI effects by changing the interference afforded by the previous task through target distractors (Hubner et al., 2003; Mayr & Keele, 2000, Experiment 2). Although plausible, it remains unproven that dominant tasks with a high potential for interference may be inhibited to a larger extent than nondominant low interference tasks. An important goal of the current study was to address this question.

Another issue that is currently debated in the BI literature is whether inhibitory control is exerted during task preparation or whether it is tied to response processes. Hubner et al. (2003) found that backward inhibition was present only when participants knew in advance which task was going to be performed next, suggesting that backward inhibition is closely tied to task preparation. Likewise, Dreisbach et al. (2002) suggested that BI is associated with the ability to effectively prepare a task set and does not depend on target- or response-related processes. On the other hand, using a go-no go task switching paradigm, Schuch and Koch (2003) provided evidence that BI is associated with response selection by showing that BI is observed only when responses are selected regardless of whether or not task preparation was required (see also Koch et al., 2004). We sought to take advantage of the high temporal resolution of event-related brain potentials (ERP) to shed light on this debate. ERPs are derived from an electroencephalogram (EEG) recorded from electrodes located over the scalp. EEG activity time-locked to the presentation of particular events such as cue presentation or the execution of a response is then averaged so that random fluctuations of the spontaneous EEG cancel each other out and ERPs associated with the processing of a given event become visible. ERPs typically consist of a sequence of positive- and negative-voltage deflections that differ in their latencies, amplitudes, and scalp topography.

We reasoned that ERP differences between BI and control trials observed in the cue–target interval would support the idea that BI is associated with preparatory processes whereas BI effects (i.e., BI vs. control trials) observed just prior to the execution of the response would support the idea that BI is associated with response-related processes.

ERPs and Task Switching

Accumulating studies have demonstrated that task switching is associated with a number of different ERP waveform patterns. Cue-locked activity has been reflected in a sustained negative wave (i.e., CNV-like activity) lasting until target presentation, observed in both switch and repeat trials at frontal (Lorist et al., 2000; Phillips, Poulsen, & Segalowitz, 2000; Poulsen et al., 2005; Swainson et al., 2003) or posterior sites (Goffaux, Phillips, Sinai, & Pushkar, 2006; Karayanidis, Coltheart, Michie, & Murphy, 2003; Kray, Eppinger, & Mecklinger, 2005; Lorist et al., 2000; Phillips et al., 2000; Poulsen et al., 2001; Swainson et al., 2003), which is sometimes preceded by a posterior positive wave (i.e., P3b-like activity). The switch contrast has been shown to significantly modulate these two components (i.e., CNV and P3b). For example, studies in our laboratory have shown increased sustained negativity to repeat relative to switch trials and a significant relationship between sustained cue-locked negativity at parietal sites and faster performance on the upcoming trial (Goffaux et al., 2006; Phillips et al., 2000) and the posterior positive wave has been shown to be enhanced on switch trials and has been interpreted as reflecting processes involved in updating the task set during task preparation (Kieffaber & Hetrick, 2005; Kray et al., 2005; West, 2004). However, others have suggested that this modulation may reflect a "switch-related" component superimposed on P3b and CNV activity (Karayanidis et al., 2003, although cf. Tieges et al., 2006). Despite some equivocation in the findings, it is still the case that the high temporal resolution of ERPs can be exploited to shed light on relevant questions concerning task switching.

To our knowledge, no ERP studies have yet looked at backward inhibition. If present, cue-locked BI differences (i.e., task preparation) were expected to be reflected by increased P3b activity on BI runs reflecting more effortful context updating due to task set inhibition. Further, we expected increased cue-locked posterior negativity for control trials relative to BI trials, reflecting better task preparation.

Although behavioral studies have implicated response processes in BI (Mayr & Keele, 2000; Schuch & Koch, 2003), it is not clear whether BI is exerted before, during, or after response selection. To answer this question, we also examined the response-locked lateralized readiness potential (LRP-r). The LRP-r is a slow negative wave measured by subtracting activity recorded over the ipsilateral motor cortex from activity recorded over the contralateral motor cortex, relative to the response hand (Coles, 1989). Because motor response preparation and execution is associated with increased activation in contralateral relative to ipsilateral motor cortex, the onset of the LRP-r (i.e., the beginning of the hemispheric difference) is thought to reflect the completion of the response-selection phase and the beginning of response preparation (Coles, 1989; de Jong, Wierda, Mulder, & Mulder, 1988). Its measurement in this study will provide an important reference point with which to interpret other response-locked effects. If response-locked BI effects are present before LRP-r onset, it would suggest that BI is tied to response selection. Alternatively, if BI effects are found after LRP-r onset, it would suggest that BI is associated with response preparation and is exerted *after* response selection.

Present Study

The first goal of this study was to test whether BI is affected by task difficulty. There is evidence that task difficulty may affect inhibitory requirements in task switching. Allport et al. (1994) showed that switching from a more dominant task (i.e., word reading) to a less dominant task (i.e., color naming) yielded a smaller switch cost than switching from a nondominant task to a dominant one. This suggests that, in order to perform the less dominant task, the more dominant task requires more inhibition to avoid interference. Consequently, when the dominant task must be performed again shortly thereafter, it must overcome inhibition, leading to higher switch costs.

We manipulated task set difficulty by presenting tasks with response requirements based on semantic and episodic memory. Episodic memory is responsible for the encoding, storage, and retrieval of temporally and spatially defined events and the temporal and spatial relationships among them (Tulving, 1983). By contrast, semantic memory is described as the memory of information necessary for language, including not only lexical information (word meaning and concepts) but also facts and general world knowledge (Tulving, 1983). Despite compelling evidence supporting the idea that episodic and semantic memory are distinct memory systems (Squire, 1987), some have proposed that the two systems may be at different levels of a continuum, with the distinction being that episodic associations tend to be novel whereas semantic associations tend to be overlearned (Mayr & Kliegl, 2000). In the context of this study, tasks that require semantic judgments are presumed to be more dominant, because they are overlearned, relative to tasks that require episodic judgments. Semantic tasks require additional inhibitory control because they have an increased tendency to linger in working memory, increasing the potential for subsequent task interference (see Mayr & Kliegl, 2000, for similar design and rationale). We therefore reasoned that when switching from a dominant task (i.e., semantic) to a nondominant one (i.e., episodic), inhibitory demands would be greater relative to the opposite set transition (i.e., from nondominant to dominant). We hypothesized that, in situations with high potential for interference (i.e., semantic–episodic–semantic runs; SES runs), backward inhibition would be larger than in low interference environments (i.e., episodic–semantic–episodic runs; ESE runs).

The second aim of this study was to investigate the timing of control processes associated with backward inhibition through the analysis of ERPs. We focused our analyses on two critical time points (cue presentation and response execution) to determine whether BI effects are associated with task preparation and/or response processes. As we already proposed, if BI is associated with preparatory processes, we would expect BI effects (i.e., differences between BI and control waveforms) to occur before target presentation (i.e., in the cue–target interval; CTI). Alternatively, BI effects in response-locked waveforms (i.e., in the activity preceding the response) would suggest that BI is associated with response processes (i.e., response selection or response preparation and execution). Finally, response-locked BI effects that precede the onset of the LRP-r would indicate that BI is associated with response selection, whereas response-locked BI effects after the onset of LRP-r would suggest that BI is associated with preparation of the selected responses for execution. Finally, we expected ERP BI effects to be larger in high interference environments (semantic or SES BI runs) relative to low interference environments (episodic BI or ESE runs), mirroring the expected behavioral results.

To test these hypotheses, we tested participants using a cued task switching design. Participants had to switch between four tasks: two easier, semantic judgment tasks (i.e., S_1 and S_2), and two harder, episodic judgment tasks (i.e., E_1 and E_2). Backward inhibition runs (e.g., E_1–S_1–E_1, S_1–E_1–S_1) were contrasted with control runs (e.g., E_2–S_1–E_1, S_2–E_1–S_1) to calculate backward inhibition.

Method

Participants

A group of 17 young participants (mean age 24.1 years, *SD*: 3.6) were recruited. All participants were screened through a health and language screening questionnaire administered over the phone. Inclusion criteria for all participants included proficiency in English, self-reported good health, and no prior history of heart disease, alcohol abuse, heavy tobacco usage, neurological disease, or any other medical illness or chronic use of medication that might influence cognitive functioning. Reflecting the demanding nature of the experiment, 1 participant was not able to perform satisfactorily in the first phase of the study (Learning to Criterion Phase) and was excluded from further testing. Also, 1 participant was excluded from data analysis due to noisy ERP recordings. Therefore, data analysis was performed on 15 participants (2 men and 13 women).

Materials

The target stimuli consisted of 16 concrete nouns (LION, TREE, HORSE, BEAR, FRUIT, BABY, FLOWER, LEAF, TABLE, SHIP, TRUCK, SOFA, BALL, BOOK, COIN, and RING). The cue words (SIZE, EXISTENCE, POSITION, and COLOR) represented the four relevant dimensions under which the 16 target words could be categorized. Each target and cue was presented in white uppercase 24 point Times New Roman font on a black computer screen background. Targets were distinguished from cues by a distinctive rectangle surrounding the word (see Figure 1).

Each target word could be classified in terms of two semantic dimensions: whether it was living or nonliving and whether it was large or small (relative to a human toddler), evoked by the task cues "existence"[1] and "size" respectively, creating four cells of four nouns each (e.g., small/living: Fruit, Baby, Flower, Leaf; large/living: Lion, Tree, Horse, Bear; small/nonliving: Ball, Book, Coin, Ring; large/nonliving: Table, Ship, Truck, Sofa). The 16 nouns were selected in order to balance the four cells on the basis of word length, familiarity, concreteness, and imageability according to the MRC Psycholinguistic Database on the University of Western Australia's Web site (http://www.psy.uwa.edu.au/MRCDataBase/uwa_mrc.htm).

In addition to the semantic classifications, the 16 nouns were also associated with two arbitrary episodic memory dimensions paired during a training phase: font color (i.e., words were presented in red or yellow font for the "color" task) and screen location (i.e., words were presented at the top or bottom of the screen for the "position" task). The four possible episodic combinations were completely orthogonal with the four possible semantic combinations, resulting in each word being represented by a unique combination across participants.

Procedure

The experiment consisted of one 5-h session[2]. The first part of the session was a learning-to-criterion phase that lasted approximately 2 h and was immediately followed by the experimental phase, which lasted approximately 3 h. Frequent pauses were allowed to avoid participants' fatigue. This study received ethics approval by the Jewish General Hospital Department of Clinical Neurosciences and Concordia University.

The goal of the learning-to-criterion procedure was to establish the associations between the target words and their arbitrary episodic dimensions (see Mayr & Kliegl, 2000, for a similar procedure). It consisted of a learning phase and a test phase. During the learning phase, each noun appeared on the computer screen in a random order for 5 s in their episodic context. For example, for the color training phase, each noun was presented centrally either in yellow or red font. In the test phase, each noun was presented in random order, centrally, and in white font. The participant was asked to recall the appropriate word–color pairing and respond by pressing the appropriate key (e.g., right for red, left for yellow). The learning–test cycle was repeated until the participant responded correctly four times in a row to each of the 16 word–color associations up to a maximum of nine cycles. The same procedure was repeated for the word–screen position pairings. In this learning phase, the target word appeared at either the top or the bottom part of the screen in white font. In the test phase, each word was presented in the center of the screen in white font and participants had to recall its initial screen position pairing and respond with the appropriate key press (e.g., right for top, left for bottom). The task learning order (i.e., color and position) was counterbalanced across participants. If a participant did not learn all the associations after nine cycles, the experimenter decided whether to terminate training or to continue. If the criterion was not reached because of an isolated error, testing was continued, but if the participant persistently made the same error for more than one trial, training was terminated and the participant was excluded.

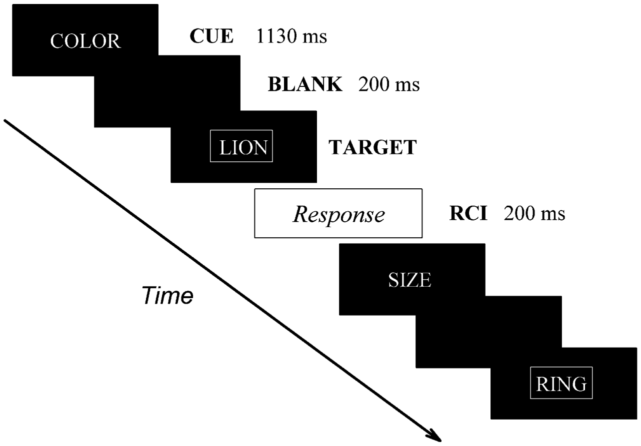

Figure 1. Time course of stimulus presentation. The values beside the frames represent the duration of the event. Each trial started with the presentation of a cue followed by a blank screen, followed by the presentation of a target that remained on the screen until the participant responded. Examples of two judgment tasks are depicted here. Note that participants had to switch between the four tasks (size, existence, color, and position) in the same block of trials.

Following the episodic association training, participants underwent two practice blocks of 96 trials each to become familiar with the semantic tasks' key assignment (e.g., size task: right button for small, left button for large; existence task: right for living, left for nonliving). The order of presentation of the two semantic tasks was counterbalanced across participants. A practice block of 32 trials involving all four tasks intermixed finished the training phase.

Experimental Design

Participants were asked to switch between the four classification tasks, two of which were overlearned and thus easier to perform (i.e., two semantic memory tasks, S1 and S2) and two of which were more novel and difficult (i.e., two episodic memory tasks, E1 and E2). This design allows the contrast between trial triplets where task difficulty is manipulated at significant points of a run of three trials (see Figure 2). For each run of three trials, the current task (n) and the task performed two trials back ($n-2$) were of the same type (i.e., either semantic or episodic) whereas the middle task ($n-1$) was different. This design created high interference environments, where the dominant task was performed on n and $n-2$ trials and the nondominant task was performed on the $n-1$ trial (i.e., S_1–E_1–S_1 vs. S_2–E_1–S_1), and low interference environments, where the nondominant task was performed on n and $n-2$ trials and the dominant task was performed on the $n-1$ trial (i.e., E_1–S_1–E_1 vs. E_2–S_1–E_1).

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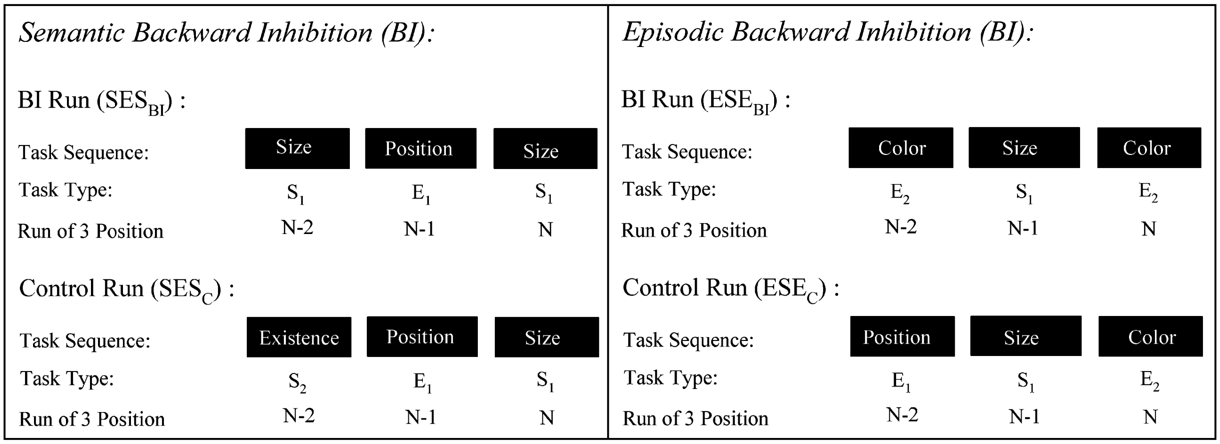
[1] Although cue word "existence" may not immediately come to mind as a prompt for a living/nonliving judgment task, we wanted to avoid using a cue word such as "living," "alive," or "animate" so as not to bias toward the living response versus the nonliving response. Participants reviewed the category task cues with the examiner prior to the practice session and then performed a large number of practice trials to consolidate the task sets.

[2] Despite the lengthy testing session, there was no evidence that fatigue modulated BI effects in this study. We compared BI RT on the first two blocks versus the last two blocks and found no significant differences in either the semantic, $F(1,14) = 0.13$, MSE = 5399.8, $p = .73$, or episodic contrasts, $F(1,14) = 3.55$, MSE = 4575.6, $p = .08$.



Semantic Backward Inhibition (BI):

BI Run (SES_{BI}) :

Task Sequence:	Size	Position	Size
Task Type:	S_1	E_1	S_1
Run of 3 Position	N-2	N-1	N

Control Run (SES_{C}) :

Task Sequence:	Existence	Position	Size
Task Type:	S_2	E_1	S_1
Run of 3 Position	N-2	N-1	N

Episodic Backward Inhibition (BI):

BI Run (ESE_{BI}) :

Task Sequence:	Color	Size	Color
Task Type:	E_2	S_1	E_2
Run of 3 Position	N-2	N-1	N

Control Run (ESE_{C}) :

Task Sequence:	Position	Size	Color
Task Type:	E_1	S_1	E_2
Run of 3 Position	N-2	N-1	N

Figure 2. Examples of semantic and episodic backward inhibition (BI) runs. Semantic BI and control runs were characterized by semantic tasks at n and $n-2$ positions and an episodic task at position $n-1$. Episodic BI and control runs were characterized by episodic tasks at n and $n-2$ positions and a semantic task at position $n-1$. BI runs were characterized by a lag-2 task repetition (i.e., Tasks $n-2$ and n are identical) whereas control trials were characterized by a lag-2 task nonrepetition (i.e., Tasks $n-2$ and n are different).

Finally, we excluded within dominance backward inhibition runs (e.g., S1–S2–*S1* vs. S1–E2–*S1*) from analysis because difference in current task (underlined) may be due to backward inhibition effects or to interference effects from the previous (i.e., $n-1$) task (see Table 1 for a list of all possible runs and their associated frequencies).

Experimental Phase

Participants were tested for six blocks of 256 trials each. The first six trials of each block were considered warm-up trials and were excluded from analysis. The approximate duration of each block was 10–15 min and long pauses between blocks were allowed to control for fatigue. On each trial, the task cue appeared centrally in white font on black background and remained on the screen for 1130 ms. The cue was then replaced by a blank screen for 200 ms, followed by presentation of the target (see Figure 1). Participants were instructed to respond as fast as they could but to keep errors to a minimum and to minimize muscle and eye movement. The following trial began 200 ms after the response with the appearance of the next cue word. Participants held a standard mouse with both hands and responded by pressing either the left or right button with their thumbs. In case of response error, feedback was signaled by a 400-Hz, 100-ms tone immediately following the response and the following trial began after an 800-ms delay.

Table 1. *Percentage of All Relevant Trial Runs in the Experimental Design*[a]

Semantic		Episodic	
Run type	Frequency (%)	Run type	Frequency (%)
Backward inhibition		Backward inhibition	
SES_{BI}	9.0	ESE_{BI}	9.0
SSS_{BI}	8.2	EEE_{BI}	8.2
Control		Control	
SES_{C}	9.4	ESE_{C}	10.2
EES_{C}	3.1	SSE_{C}	3.1
ESS_{C}	4.3	SEE_{C}	3.9
Repeat trials	8.0	Repeat trials	8.0

[a] The sum of these percentages does not add up to 100 due to other nonrelevant trial runs not reported here (e.g., a switch trial after a repeat trial).

Within each block, target words were selected pseudorandomly with the following constraints: first, no more than four response repetitions (e.g., left button responses) were allowed; second, each block had the same number of tasks (i.e., 64 trials for each of the four tasks); third, each block had the same number of left and right button responses (128 each); fourth, no run of three repeated tasks was allowed; and fifth, the same target word was not allowed to be repeated for the following two trials.

Each participant received a unique key assignment combination (e.g., left button for living, large, top, and yellow). Likewise, stimulus–response mappings were counterbalanced across participants (e.g., the target "book" would have a unique response mapping for each participant).

Electrophysiological Recording

A nylon EEG cap containing tin electrodes (Electro-Cap International) was used for EEG recording. The EEG was recorded from six midline sites (FPz, Fz, FCz, Cz, CPz, Pz) and 24 left/right lateral sites (prefrontal: FP1/2; frontal: F3/4, F7/8; frontocentral: FC3/4; frontotemporal: FT7/8; central: C3/4; centroparietal: CP3/4; temporal: T3/4/5/6; temporoparietal: TP7/8; parietal: P3/4; occipital: O1/2). A forehead location was used as ground. All sites were referenced to the left ear and re-referenced off-line to linked ears. Electrooculogram (EOG) activity was recorded from electrodes placed at the outer canthi of both eyes (horizontal EOG) and above and below the left eye (vertical EOG). EOG artifacts were corrected off-line for all participants using the spatial filter procedure as implemented by the Neuroscan software (Edit 4.3; Neuroscan, 2003, p. 246). EEG was sampled continuously with stimulus- and response-locked EEG epochs. EEG data were amplified using Neuroscan Synamps in a DC-30-Hz bandwith and sampled at 100 Hz.

Behavioral Data Analysis

Behavioral data were obtained simultaneously with ERP data. Participants' RTs were measured as the time taken to respond to the target stimulus after it appeared on the screen. Data for switch trials only are reported in this study. RTs were analyzed for correct trials only; the two trials that followed an incorrect response were also excluded from analysis as these are pertinent to our hypotheses. RTs exceeding three standard deviations from the mean and trials with RT less than 200 ms were excluded from analysis.

A within-subject ANOVA with task type (semantic vs. episodic) and backward inhibition (BI vs. control) as factors was run. Planned comparisons were conducted to analyze semantic (SES_{BI} vs. SES_C) and episodic (ESE_{BI} vs. ESE_C) backward inhibition contrasts. Main effects of variables are reported first but described only if they did not interact with other variables. Statistical significance is assumed at the $\alpha = .05$ level.

ERP Data Analysis

ERPs were recorded time-locked to the cue and the response (key press) onsets and were analyzed separately. Cue-locked epochs spanned − 100 to 1250 ms and employed a baseline 100-ms interval before cue presentation. Response-locked epochs and LRP-r waveforms were computed from 800 ms prior to the response to 200 ms after the response. The baseline for these averages was the 200-ms interval between 800 and 600 ms before the response. ERPs were also computed for target-locked waveforms, but no significant results were found. These data are therefore not reported, but the interested reader can contact us for specific statistical details.

Given that the focus of this study was the backward inhibition contrasts, statistical analyses were based on the difference waveforms derived by subtracting the ERP waveform for control trials from BI trials (i.e., BI – control) for each BI type (semantic and episodic). Following Karayanidis et al. (2003), point-by-point *t* tests were conducted on each contrast to identify areas of significant deviation. Type 1 error was controlled at $\alpha = .05$ using the Guthrie and Buchwald (1991) procedure, with autocorrelation estimated at .9. This method controls for consecutive time points correlated with each other. Because this is the first ERP study on backward inhibition, we did not have specific a priori hypotheses as to exactly where significant effects would be and therefore chose to use the conservative approach of analyzing the entire cue- and response-locked intervals with appropriate statistical corrections. For cue-locked data, the sampling interval was set from 0 to 1250 ms (i.e., 125 data points). For response-locked epochs, the sampling interval was set from 800 ms preceding the response to 200 ms after the key press (i.e., 100 data points). Therefore, the data were required to meet a conservative level of statistical significance of at least 12 consecutive data points (i.e., 120 ms) above threshold (i.e., $t[14] = \pm 2.14$) in the cue-locked epochs, and at least 11 consecutive data points (i.e., 110 ms) in the response-locked epoch (see Karayanidis et al., 2003, for a similar method used in a recent task switching experiment). Only midline sites are reported for point-by-point analysis and graphical presentation because effects were most prominent there[3].

LRP-r waveforms were computed by subtracting the activity recorded over the ipsilateral from the contralateral motor cortex relative to the responding hand (i.e., subtracting C4 from C3 for right-hand responses and C3 from C4 for left-hand responses, and then averaging both subtraction waveforms). LRP-r onset was calculated as the time when LRP-r amplitude exceeded 15% of its peak value on a consistent basis to avoid false onsets. LRP-r peak amplitude (in microvolts) and latency (in milliseconds) were detected as the point of most negative displacement in the − 100 to 50 ms period relative to the response (see Mordkoff & Gianaros, 2000).

Results

Behavioral Data

There was no significant RT difference between the two episodic tasks (color and position; $t[14] = -1.27$, $SEM = 49.2$, $p = .23$). For the two semantic tasks, the existence task was significantly slower than the size task, $t(14) = -2.19$, $SEM = 30.6$, $p = .046$); however, the task factor did not interact with the backward inhibition factor, $F(1,14) = 0.9$, $MSE = 3623.1$, $p = .354$, indicating that the magnitude of the BI effect was the same despite differences in baseline RT performance. Therefore, the two episodic tasks and the two semantic tasks were collapsed for all subsequent analyses.

Although not a central issue in this article, we analyzed switch cost RT data for both semantic and episodic tasks (Table 2). There was a significant switch cost, $F(1,14) = 27.0$, $MSE = 8701.3$, $p < .001$, and although switch cost for semantic tasks was about 40% larger than the switch cost for episodic tasks, the interaction between task type and switch factors was not significant, $F(1,14) = 3.1$, $MSE = 2011.2$, $p = .1$. Error rate data (Table 2) showed significantly more errors on episodic relative to semantic conditions, $F(1,14) = 9.8$, $MSE = 9.3$, $p = .007$, but no significant switch main effect or switch by task interaction, $ps > .12$.

Backward inhibition RTand accuracy data are summarized in Table 3. There was a significant RT main effect of task type, $F(1,14) = 6.6$, $MSE = 15176.1$, $p = .022$, with performance on episodic tasks being slower ($M = 1143.8$, $SE = 76.4$) than semantic tasks ($M = 1062.0$, $SE = 76.5$). Also, episodic trials were more error prone ($M = 4.9$, $SE = 0.9$) than semantic trials ($M = 2.3$, $SE = 0.6$), $F(1,14) = 12.6$, $MSE = 8.3$, $p = .003$, although accuracy was nevertheless high in all conditions.

There was a significant overall BI effect, $F(1,14) = 5.1$, $MSE = 3739.3$, $p = .04$, with BI runs being slower ($M = 1120.8$, $SE = 78.3$) than control runs ($M = 1085.1$, $SE = 71.9$). The interaction between task type and BI was not significant, $F(1,14) = 0.39$, $MSE = 3360.1$, $p = .54$. However, a priori, we were specifically interested in the difference between semantic and episodic BI effects. Thus, we conducted planned comparisons that demonstrated a significant BI effect for semantic trials, $F(1,14) = 6.4$, $p = .02$, but not for episodic trials, $F(1,14) = 1.1$, $p = .31$. No significant results involving the backward inhibition factor were observed for error rates, $ps > .11$.

Recall that we hypothesized that the transition from S tasks to E tasks (i.e., transition from $n-2$ task to $n-1$ task in SES runs) would require more inhibitory requirements and therefore increased BI, than transitions from E tasks to S tasks (i.e., transition from $n-2$ task to $n-1$ task in ESE runs) because S tasks should be dominant, will linger in working memory, and there-

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[3] Potential effects of laterality were tested by conducting an ANOVA with the factors of BI (BI vs. control), type (semantic vs. episodic), anteriority (anterior: Fz, F3, F4; central: Cz, C3, C4; posterior: Pz, P3, P4), laterality (left: F3, C3, P3; midline: Fz, Cz, Pz; right: F4, C4, P4), and time (for cue-locked waveforms: *t*1: 50 to 250 ms, *t*2: 250 to 450 ms, *t*3: 450 to 650 ms, *t*4: 650 to 850 ms, *t*5: 850 to 1050 ms, *t*6: 1050 to 1250 ms; for response-locked waveforms: *t*1: − 800 to − 600 ms, *t*2: − 600 to − 400 ms, *t*3: − 400 to − 200 ms, *t*4: − 200 to 0 ms, *t*5: 0 to 200 ms). The laterality factor did not interact with backward inhibition in the cue-locked (all $ps > .232$) or in the response-locked epochs (all $ps > .15$).

Table 2. *Mean Reaction Times (RT) and Percent Error Rates (ER) with Their Standard Error (SE) for Semantic and Episodic Repeat and Switch Trials*

	Repeat	Switch	Difference
Semantic			
RT (SE)	911.3 (75.9)	1056.7 (77.8)	145.4
ER (SE)	1.6 (0.4)	2.4 (0.4)	0.8
Episodic			
RT (SE)	1032.8 (73.3)	1137.7 (75.1)	104.9
ER (SE)	4.2 (1.1)	4.7 (0.9)	0.5

fore will require greater inhibitory control to reduce interference. This distal $n-2$ inhibition should be measurable on the current n trial when n and $n-2$ are the same task. Nevertheless, it is possible that differences in BI effects may be due, at least in part, to differences in more proximal task transitions (i.e., the $n-1$ to n transition; e.g., from S to E vs. from E to S). To rule out this possibility, we also compared control trials that had identical current n and $n-1$ tasks but different $n-2$ tasks (e.g., S1–E2–S2 vs. E1–E2–S2). There was no significant difference between $SSE_{control}$ and $ESE_{control}$ runs, $t(14)=1.24$, $SEM=22.7$, $p=.23$, nor $EES_{control}$ and $SES_{control}$ runs, $t(14)=-1.27$, $SEM=39.4$, $p=.22$, indicating that BI differences between high and low interference environments were not due to more proximal task transition differences.

ERP Data

Cue-locked waveforms. Cue-locked waveforms are shown in Figure 3 (left panel: semantic contrast, right panel: episodic contrast). Backward inhibition and control waveforms are shown for six midline sites. Waveforms were characterized by a well-defined N1/P2 complex most evident over centro-posterior sites (see Figure 3). All conditions showed a positive-going complex most evident at central and parietal sites, peaking approximately 350 ms after cue onset. All conditions then showed a sustained posterially distributed negative going wave from approximately 500 ms onward at centro-parietal sites that persisted until target onset.

The point-by-point *t* tests revealed no significant cue-locked differences (i.e., sustained over 12 consecutive points) between semantic backward inhibition and control waveforms (see Figure 3, left panel). However, significant differences were found for the episodic BI contrast. As shown in Figure 3 (right panel), participants showed enhanced negativity to control relative to backward inhibition waveforms at Cz and CPz electrode sites between 290–430 ms and 270–430 ms, respectively.

Table 3. *Mean Reaction Times (RT) and Percent Error Rates (ER) with Their Standard Error (SE) for Semantic and Episodic Backward Inhibition and Control Conditions*

Semantic	SES_{BI}	SES_{C}	Difference
RT (SE)	1084.5 (82.1)	1039.5 (71.5)	45.1*
ER (SE)	2.1 (0.7)	2.4 (0.7)	– 0.3
Episodic	ESE_{BI}	ESE_{C}	Difference
RT (SE)	1157.1 (77.4)	1130.7 (77.4)	26.4
ER (SE)	4.5 (0.9)	5.4 (1.2)	– 0.9

*$p<.05$.

Response-locked waveforms. Response-locked waveforms are shown in Figure 4 (left panel: semantic contrast, right panel: episodic contrast). Similar to the cue-locked figures, backward inhibition and control waveforms for six midline sites are depicted. Response-locked ERP waveforms were characterized by a slow negative-going wave most evident at central and frontal sites peaking approximately 350 ms preceding the response and followed by a positive going sharp drop preceding response execution.

Significant differences were found for the semantic BI contrast with significant increased negativity on BI waveforms relative to control waveforms at Pz between -240 and -70 ms preceding the response (Figure 4, left panel). However, for the episodic BI contrast, response-locked waveforms showed no significant differences (Figure 4, right panel).

LRP-r. LRP-r peak latency, peak amplitude, and onset were analyzed using within-subject ANOVAs with the factors of task type (semantic vs. episodic) and backward inhibition (BI vs. control) and the results are summarized in Table 4. Four out of 15 participants did not show a reliable LRP-r component and were excluded from analysis. As shown in Figure 5, LRP-r waveforms showed the characteristic negative-going wave starting approximately 300 ms before the response and peaking just before response execution.

LRP-r peak amplitude was significantly larger for semantic waveforms ($M=3.9$, $SE=0.43$) relative to episodic waveforms ($M=-3.4$, $SE=0.47$), $F(1,10)=4.7$, $MSE=0.49$, $p=.05$. The main effect of BI, the interaction between BI and task type (semantic vs. episodic), and planned comparisons of episodic and semantic contrast, were not significant (all $F\text{s}<1.9$, all $p\text{s}>.2$).

LRP-r onset latency data showed no significant main effects or interaction (all $F\text{s}<2.6$, all $p\text{s}>.14$). However, planned comparisons revealed a trend toward significance for the semantic contrast, $F(1,10)=4.1$, $p=.07$, with BI trials showing an earlier onset ($M=-322.7$, $SE=33.3$) than control trials ($M=-275.5$, $SE=34.0$), whereas the episodic contrast showed no difference in LRP-r onset between BI and control waveforms, $F(1,10)=.01$, $p=.96$. LRP-r latency data showed no significant effects (all $F\text{s}<1.61$, all $p\text{s}>.23$).

Discussion

The first goal of this study was to test the hypothesis that inhibitory control in task switching is a form of reactive inhibition whereby greater inhibitory control is exerted on tasks with high interference potential. By asking participants to switch between tasks of varying difficulty, we expected to find larger backward inhibition (BI) effects when interference from the previous task was high. RT results showed a statistically reliable backward inhibition effect (BI vs. control) in high interference environments (semantic contrast) and a smaller and statistically nonsignificant effect in low interference environments, supporting the hypothesis that BI is a form of reactive inhibition and indicating that our task manipulation was successful.

The second goal was to examine the electrophysiological correlates of backward inhibition to determine whether BI is associated with preparatory (i.e., cue-locked) and/or response (i.e., response-locked) processes. Results showed significant differences between backward inhibition and control waveforms in both the cue-locked (preparatory processes) and response-locked (response related processes) periods. However, these effects

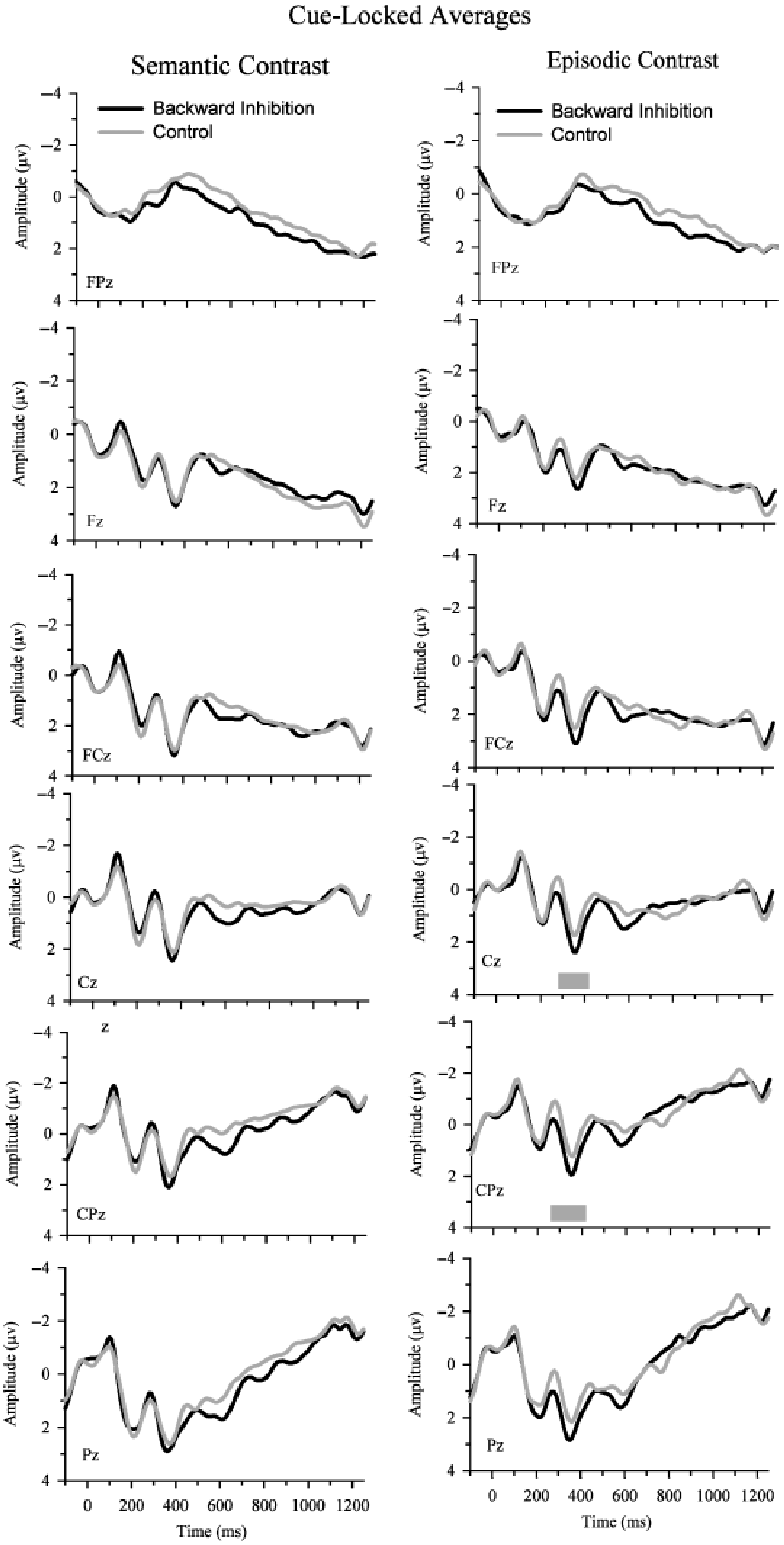

Figure 3. Cue-locked ERP grand average waveforms. Left panel: Semantic contrast. Right panel: Episodic contrast. Backward inhibition waveforms are represented in black, control waveforms are represented in gray. Shaded area over time axis represents significant differences between BI and control episodic conditions.

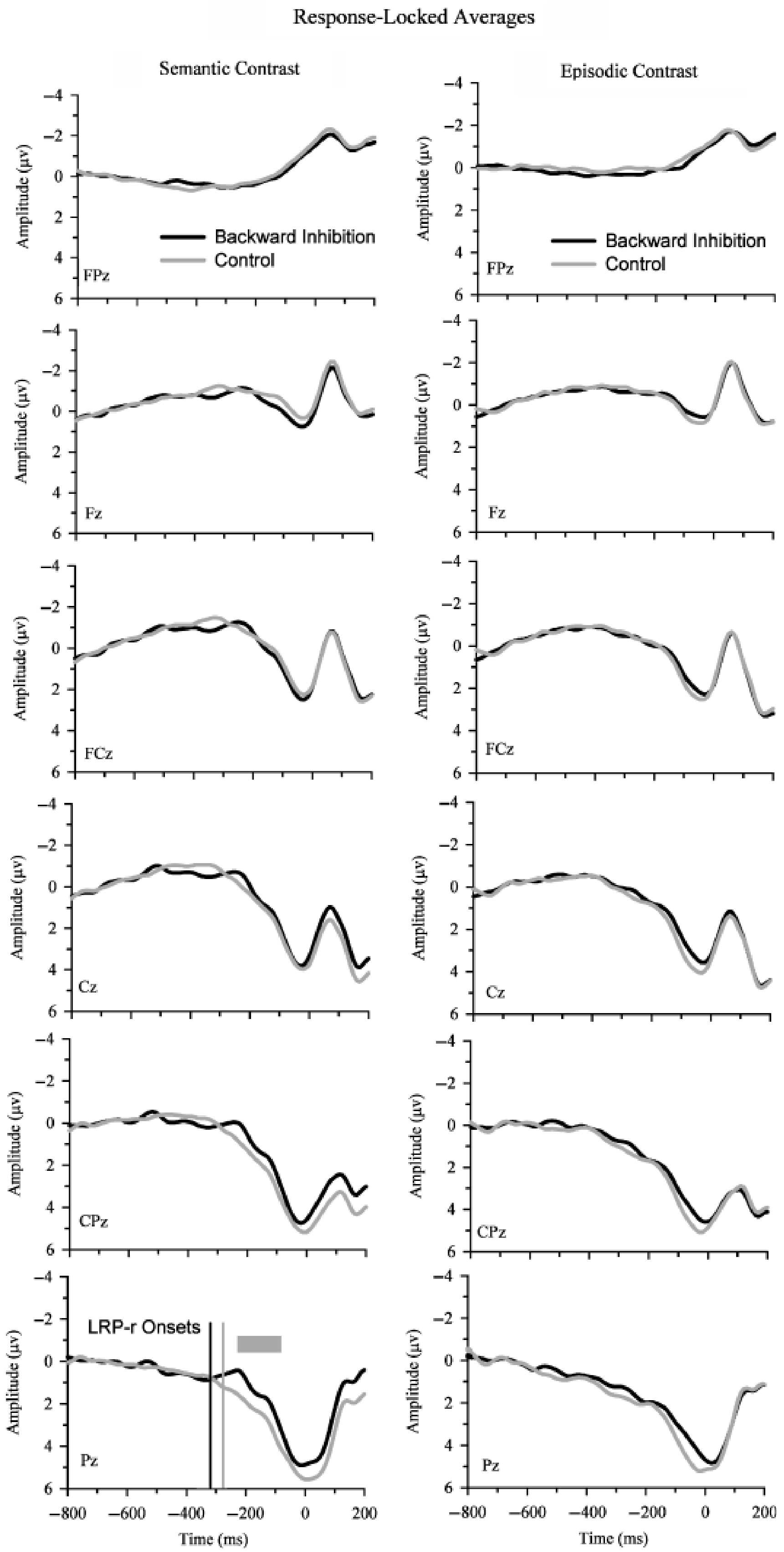

Figure 4. Response-locked ERP grand average waveforms. Left panel: Semantic contrast. Right panel: Episodic contrast. Backward inhibition waveforms are represented in black, control waveforms are represented in gray. Shaded area over time axis represents significant differences between BI and control conditions. The vertical bars represent LRP-r onset (black for BI and gray for control; note that in the Episodic contrasts, these two time points are overlapping; therefore, only one line is visible).

Table 4. *LRP-r Peak Amplitude, Peak Latency, and Onset with Their Standard Error (SE) for Semantic and Episodic Backward Inhibition and Control Conditions*

Semantic	SES_{BI}	SES_C	Difference
Onset (ms) (SE)	322.7 (33.3)	275.5 (34.0)	47.2^+
Peak amplitude (μV) (SE)	– 4.0 (0.4)	– 3.7 (0.5)	0.3
Peak latency (ms) (SE)	– 27.3 (12.8)	– 12.7 (10.1)	14.5
Episodic	ESE_{BI}	ESE_C	Difference
Onset (ms) (SE)	261.8 (28.7)	260.0 (31.1)	1.8
Peak amplitude (μV) (SE)	– 3.6 (0.5)	– 3.2 (0.5)	0.4
Peak latency (ms) (SE)	– 28.2 (7.2)	– 28.2 (12.3)	0

$^+p = .07$.

depended on the degree of task interference. That is, the cue-locked effects were found only in the episodic contrast (i.e., the low-interference environment), whereas response-locked effects were found only in the semantic contrast (i.e., the high-interference environment). These are now discussed in turn.

Task Difficulty Effects on Backward Inhibition

Behavioral performance results showed a reliable backward inhibition effect consistent with previous research (Arbuthnott & Frank, 2000; Dreher & Berman, 2002; Hubner et al., 2003; Koch et al., 2004; Mayr, 2001; Mayr & Keele, 2000; Schuch & Koch, 2003). By asking participants to switch between easy and difficult tasks, we created high (semantic BI, SES runs) and low interference (episodic BI, ESE runs) environments. We reasoned that if BI is a reactive inhibition mechanism (i.e., tasks that can cause high interference will be inhibited to a greater extent than low-interference task sets), results should show large BI effects in high interference situations and small BI effects in low interference situations. Our results confirmed this hypothesis. There was a significant BI effect of 45 ms for semantic contrasts and a non-significant BI effect of 26 ms for episodic contrasts, which was demonstrated through a priori planned comparisons (although the BI × Task Type interaction was not significant). There is a note of caution that should be raised at this point in interpreting null findings (in the case of the episodic contrast). Thus, it is most accurate to discuss the present results as demonstrating a greater and more reliable BI effect invoked by semantic trials transitions than by episodic trial transitions. It remains to be determined whether reliable BI effects can be demonstrated on episodic task manipulations under other conditions.

The finding that backward inhibition is a reactive inhibition mechanism is in broad agreement with Mayr and Keele's (2000) and Hubner et al.'s (2003) results that were obtained by varying the degree of interference afforded by a target distractor and showing increased alternation costs in situations of high interference. This property of backward inhibition is also consistent with efforts to explain switch cost asymmetry between dominant and nondominant tasks. A dominant task will be inhibited to a greater extent than a less dominant task to guard against increased interference from the dominant task. When performed again shortly thereafter, the dominant task must consequently overcome greater inhibition resulting in larger switch costs than for nondominant tasks (Allport et al., 1994; Gilbert & Shallice, 2002).

Timing of Backward Inhibition

Recent studies using behavioral measures have reached contradictory conclusions regarding the processes associated with BI, with some studies showing evidence in favor of inhibitory control being related to task preparation (Dreisbach et al., 2002; Hubner et al., 2003; Mayr & Keele, 2000, Experiment 3) and others to response selection (Koch et al., 2004; Schuch & Koch, 2003). Because ERPs provide an online measure of the time course of the brain's response to a particular stimulus event, they are ideally suited to address the question of whether BI is associated with preparatory and/or response-related processes. We reasoned that if we found a difference between backward inhibition and control waveforms in the cue-locked interval, this would be evidence that BI is invoked during task preparation stages whereas BI effects in response-locked epochs would suggest that BI is applied during response selection and/or response preparation.

Prior to discussing the results, an important nuance in the interpretation of the temporal effects must be made. The current design allows for the measurement of brain activity on trial *n*, the just-performed task, and is therefore not a direct measure of the

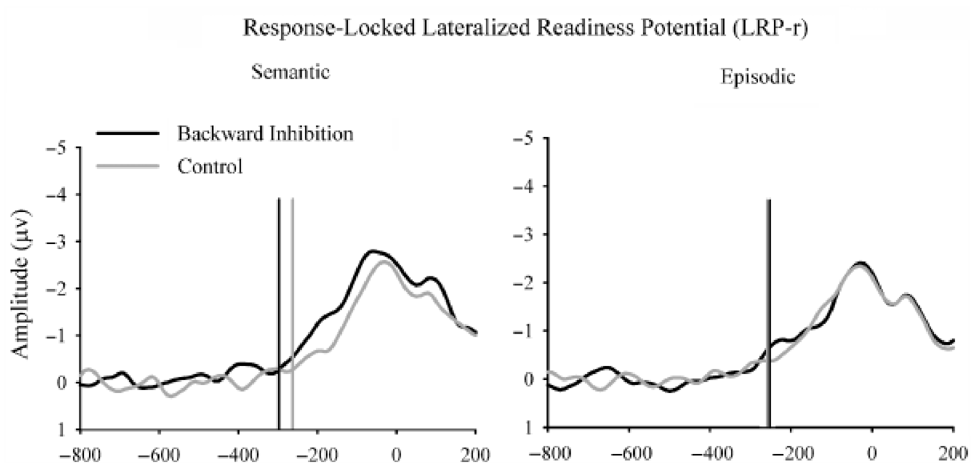

Figure 5. Response-locked lateralized readiness potential (LRP-r) for BI (black line) and control (gray line) conditions for semantic (left) and episodic (right) tasks. The vertical bars represents LRP-r onset.

inhibitory process that occurs at the transition between the $n-2$ and $n-1$ tasks. What is measured, then, are the processes exerted to *overcome* inhibition on trial n, and not inhibitory control itself (Dreher & Berman, 2002).

Cue-locked results. Although no significant effects were noted in semantic runs, episodic runs showed a significant effect over centroparietal sites across the 270–430-ms interval that reflects either reduced N2 or enhanced P3 activity in BI waveforms relative to control waveforms (see Figure 3, right panel). We were surprised to see this modulation in the episodic but not in the semantic contrasts because we hypothesized that any backward inhibition effects would be larger in high interference environments. The following are two possible interpretations of these results.

First, the observed reduction in cue-locked N2 activity on BI trials relative to control trials in the episodic contrast may reflect the recency and the degree of activation of a task set and/or its word cue. In visual tasks, N2 enhancement has been associated with orientation to an infrequent or deviant stimulus (Renault, Ragot, Lesevre & Remond, 1982; Näätänen & Picton, 1986). In terms of the ongoing representation of the environment, a less recent event can be regarded as a deviant stimulus. Thus, in the context of this study, it can be argued that the same cue presented on a control trial (i.e., a task performed more than two trials back: *A* . . . CBA) is less recent than the same cue presented on backward inhibition trial (i.e., a task performed two trials back: *A*BA). This relatively less recent cue may therefore evoke a larger N2. Why, then, would this effect be found only on episodic tasks and not on semantic tasks? One possibility is that episodic tasks are not lingering in working memory, are more difficult to activate than semantic tasks, and thus elicit a stronger orientation.

An alternative interpretation would view the cue-locked effect noted on episodic contrasts as a P3-like enhancement to backward inhibition relative to control waveforms. We can rule out any oddball or frequency accounts of this possible P3-like modulation because backward inhibition and control trials had equal frequency of occurrence (see Table 1 for frequencies related to all run conditions). Cue-locked P3-like enhancement in task switching designs has been observed in switch trials relative to repeat trials (Barcelo, Munoz-Cespedes, Pozo, & Rubia, 2000; Kieffaber & Hetrick, 2005; Moulden et al., 1998; West, 2004) and has been interpreted as an index of processes engaged in updating the environmental context (Donchin & Coles, 1988) as would be required when switching task sets. Following similar thinking, the enhanced positivity to BI episodic trials observed in this experiment may reflect increased attentional resources necessary to update the environmental context when a switch to an inhibited task is required relative to a noninhibited task. The reason why this effect is seen only in the episodic contrast and not in the semantic one may be due to the fact that episodic tasks are more difficult to activate than semantic ones and may therefore require more attentional resources as indexed by the P3b-like modulation. Moreover, it is possible that this BI effect observed in the cue–target interval may be associated with the small and nonsignficant episodic BI effect observed in the RT data. In other words, because episodic tasks are more difficult, there may be more efficient allocation of attentional resources during the cue–target interval leading to minimal behavioral BI effects.

In sum, the unexpected pattern of cue-locked results, with significant effects in the episodic contrasts but not in the semantic contrasts, could be interpreted either as a noninhibitory mechanism (i.e., more difficult orientation to episodic control cues relative to episodic backward inhibition cues) or as indicative of increased attentional resources allocated in the reactivation of an inhibited task set.

Response-locked and LRP-r results. The ERP results associated with participants' responses were very illuminating. LRP-r data measured over the motor cortex showed increased LRP-r peak amplitudes on semantic trials relative to episodic trials. Given that LRP-r peak amplitude can be interpreted as an index of the amount of activation required to trigger response execution (Falkenstein, Yordanova, & Kolev, 2006), this suggests that response codes on semantic trials may be in a more inhibited state than on episodic trials and may therefore be more difficult to activate.

Response-locked waveforms showed two distinct effects present on the semantic BI contrast but not on the episodic BI contrast. First, LRP-r data showed a trend toward an earlier onset (relative to the response as measured by RT) on backward inhibition trials relative to control trials for the semantic contrast only. The time interval between LRP-r onset (i.e., the end of response selection) and response execution can be interpreted as the time required to prepare the overt response. The longer time elapsing between LRP-r onset and response execution on backward inhibition trials may indicate additional time required to activate an overt response. It is very interesting to note that the difference between BI and control trials in LRP-r onset (47 ms) is almost identical to the difference between BI and control trials in RT (45 ms), raising the possibility that the behavioral cost associated with backward inhibition may be due to the additional time required to prepare a response. In other words, the extra time required to execute a response on semantic BI trials relative to semantic control trials may be due to the extra time needed to activate inhibited response codes. Following the same reasoning, this effect was not found in the episodic contrast because response codes associated with episodic tasks are not inhibited to the same extent as response codes associated with semantic tasks.

Second, semantic backward inhibition trials showed increased negativity over parietal sites from 240 ms to 70 ms preceding the response. The timing of this effect began shortly before the response and suggests that backward inhibition acts at the level of the response set. As discussed next, both the parietal topography and timing of this effect are noteworthy.

The parietal lobe has been implicated in most imaging studies of task switching (Brass & von Cramon, 2004; Braver, Reynolds, & Donaldson, 2003; Dove, Pollmann, Schubert, Wiggins, & von Cramon, 2000; Sohn, Ursu, Anderson, Stenger, & Carter, 2000; Wylie, Javitt, & Foxe, 2004). There is growing evidence of cooperation between frontal and parietal cortices in task switching. Although one must be cautious when making direct comparisons between results from fundamentally different neuroimaging methods, the electrophysiological results are consistent with fMRI evidence that the selection of the appropriate response activates frontal brain regions, whereas parietal regions are involved in the representation of the candidate S–R associations (Brass & von Cramon, 2004; Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Corbetta & Shulman, 2002). To account for their data, Schuch and Koch (2003) suggest that BI is associated with inhibition of the response set that they call category-response rules (e.g., small = left button; large = right button). It is tempting to draw a parallel between category-response rules specific to task switching and the more general concept of S–R associations, and speculate that they could both be stored in parietal areas.

The second interesting aspect of the response-locked ERP data has to do with the timing of the parietal effect relative to response selection. Our results clearly show that the increased negativity measured at parietal sites on semantic backward inhibition trials occurs after response selection (i.e., measured by the onset of the LRP-r), suggesting that processes involved in recovering from backward inhibition are associated with response preparation and execution. To account for our results, a description of the logical order of events required in response selection is needed. First, all category-response rules stored in the parietal lobes are activated in a bottom-up fashion. For example, in the present experiment, the word "lion" will activate all the possible competing category-response rules associated with the four tasks: size, existence, color, and position (e.g., large = left button; living = right button; red = left button; top = left button). Second, frontal brain areas would be involved in the selection of the appropriate response set (i.e., if the cue was "size," the response set would be large = left button; small = right button). Third, the selected response set will be biased and competing sets will be inhibited. To account for the possibility that BI is exerted at the level of category-response rules (i.e., the response set) we have to assume that, in the event that the relevant response set (e.g., large = left button; small = right button) begins the trial in an inhibited state, it will be activated enough to be considered in the selection process but still at a "disadvantage" relative to competing response sets. Once selected, the inhibited category-response rule will require longer and stronger activation than a noninhibited response set to trigger an overt response. This account fits nicely with our data. That is, the increased negativity to BI trials over parietal sites may reflect increased effort required to activate the inhibited category-response rule (i.e., the inhibited response set) whereas the trend toward an earlier LRP-r onset for BI trials suggests that more time is required to prepare and execute a response when the category-response rule in inhibited. The fact that response-locked effects and behavioral BI effects are not observed in the episodic contrast are likely due to the fact that episodic tasks tend to decay quickly from working memory, affording less interference potential and, therefore, less need to be inhibited to the same extent as semantic tasks.

It is a well-established fact that advanced preparation reduces switch costs (Meiran, 1996; Rogers & Monsell, 1995). The interpretation of the current study's results described above suggests that advanced preparation is not associated with activation of category-response rules per se but with the task set. That is, category response rules (e.g., large = left button) are not activated by the presentation of the cue. It seems, rather, that a valid cue facilitates processing by biasing attentional resources to the relevant task dimension (e.g., size classification). It appears, however, that the activation of category-response rules requires the presentation of the target. This interpretation is consistent with current models of task-switching discussed next.

Relation to Models of Task Switching

The results of this study fit well with two-step models of task switching. There is a strong consensus that control processes in task switching can be divided into two broad categories. Rogers and Monsell (1995) were first in proposing this dichotomy with the distinction between endogenous processes that can be prepared ahead of the target and exogenous processes that require the target's presentation. Rubinstein, Meyer, and Evans's (2001) model also calls for two distinct executive mechanisms. The first process, which is called goal shifting, can occur before target onset and may be seen as a mechanism that biases attention toward the relevant task. The second process is called rule activation. It occurs after target presentation and its role is to enable the rules required to select the appropriate response and disabling the rules relevant to the previous trial. Although not explicitly stated in their model, disabling the previous task rules may persist over time and require extra processing if the task was to be reactivated again a short time later. In a similar vein, Rushworth, Passingham, and Nobre (2002) make a distinction between attentional processes involved in the selection of the stimulus dimensions and intentional processes involved in the selection of motor responses. Finally, the model proposed by Meiran (2000) also states that task switching comprises two mechanisms. The first is the stimulus set that can and should be prepared ahead of the stimulus and acts as a sort of filter, analogous to selective attention, to bias attention in favor of the appropriate stimulus dimension. The second mechanism is responsible for the reconfiguration of the response set (stimulus–response translation rules) and occurs after response selection.

Our results suggest that BI may act on both attentional (cue-locked) and on intentional (response-related) processes (Schuch & Koch, 2003). Although there are several possible interpretations of the cue-locked ERP difference between backward inhibition and control waveforms on the episodic contrast (i.e., low interference environment), it may suggest that, under certain circumstances (i.e., when switching from a nondominant to a dominant task), BI may be associated with preparatory processes (cue-locked). In contrast, the response-locked increased activity on semantic BI trials relative to control trials strongly suggests that BI acts at the level of the response set, biasing one set of competing S–R rules over the other. These response-locked results are particularly relevant to Meiran's model of task switching because they are compatible with a mechanism that reconfigures the response-set after response selection.

Summary and Conclusion

We sought to examine the effects of task difficulty on backward inhibition as well as the time course of backward inhibition. Behavioral results provided evidence that backward inhibition is a reactive inhibition mechanism that is exerted to the extent that a just-performed task can interfere with current performance. The pattern of cue-locked ERP results maybe interpreted as evidence for increased attentional resources being allocated during the reactivation of an inhibited nondominant task. Also, several features of the response-locked ERP results show that BI is associated with response processes and occurs after response selection. Our response-locked and LRP-r data are consistent with Schuch and Koch's (2003) proposal that BI is associated with inhibition of response-category rules. We conclude that efforts to resolve response set inhibition are associated with both task and response preparation and may recruit both frontal and posterior areas.

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