Inhibition of Return Arises from Inhibition of Response Processes: An Analysis of Oscillatory Beta Activity

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Abstract

■ In the orienting of attention paradigm, inhibition of return (IOR) refers to slowed responses to targets presented at the same location as a preceding stimulus. No consensus has yet been reached regarding the stages of information processing underlying the inhibition. We report the results of an electroencephalogram experiment designed to examine the involvement of response inhibition in IOR. Using a cue–target design and a target–target design, we addressed the role of response inhibition in a location discrimination task. Event-related changes in beta power were measured because oscillatory beta activity has been shown to be related to motor activity. Bilaterally located sources in the primary motor cortex showed event-related beta desynchronization (ERD) both at cue and target presentation and a rebound to event-related beta synchronization (ERS) after movement execution. In both designs, IOR arose from an enhancement of beta synchrony. IOR was related to an increase of beta ERS in the target–target design and to a decrease of beta ERD in the cue–target design. These results suggest an important role of response inhibition in IOR. ■

INTRODUCTION

Selective attention mechanisms are required for the proper functioning of behavior in everyday life. A good example is the daily way to work, which is an episode full of relevant and irrelevant objects and signs. Attentional mechanisms are necessary to spotlight traffic signs and to fade out uninformative or even distracting objects, such as advertising signs. Such an adaptive, goal-directed behavior is realized by mechanisms that enhance attention for relevant information at the expense of that for irrelevant information.

One way to study such selective attention mechanisms is the orienting of attention paradigm (Posner, 1980), which elicits mechanisms of an adaptive orienting behavior. Using a cue–target design, the central finding is that, immediately following a task-irrelevant and uninformative cue displayed at a peripheral location, processing of a task-relevant target at the same location is facilitated. This validity effect is supposed to reflect a reflexive shift of attention towards the source of stimulation. In contrast, after attention is removed from the exogenous cue's location, there is delayed responding to the task-relevant target subsequently displayed there. This phenomenon was first described by Posner and Cohen (1984) and was later labeled ''inhibition of return'' (IOR) (Posner, Rafal, Choate, & Vaughn, 1985). The crossover point, where facilitation changes to inhibition, is at about 250 msec following cue onset (see Klein, 2000, for an overview). Importantly, inhibition is only found if the cue is uninformative for target presentation. Otherwise, the inhibitory after-effect is abolished (Hillyard & Anllo-Vento, 1998).

Since its discovery, the phenomenon has attracted a great deal of research interest and scientists have been interested in ''what is inhibited in inhibition of return'' (Reuter-Lorenz, Jha, & Rosenquist, 1996). No consensus has yet been reached regarding the stages of information processing underlying the inhibition. It has been suggested that inhibition may arise from early perceptual processes (Handy, Jha, & Mangun, 1999; Posner & Cohen, 1984), the disconnection between stimulus and response processing (Fuentes, Vivas, & Humphreys, 1999), and late response processes (Ivanoff & Klein, 2001) such as oculomotor processes (Ro, Farnè, & Chang, 2003; Godijn & Theeuwes, 2002) or manual motor processes (Wilson & Pratt, in press; Taylor & Klein, 1998).

Arguably, in a simple target-detection task, ''genuine'' IOR as measured in the cue–target design may be confounded by the effect of manual response inhibition (Spence & Driver, 1998; Maylor & Hockey, 1985). When a cue is presented, participants must suppress any tendency to execute a motor response. If a keypress must be made in response to the detection of a target but not to the preceding cue at the same location, the inhibition of the response to the cue may still be

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present when the target arrives, with the result that the response to the target is slowed down. Thereby, manual response inhibition can produce an IOR-like effect as it is largest when cue and target share similar features such as location (see Harvey, 1980). Such manual response inhibition might be eliminated when using a target–target design, in which IOR is measured between successive targets and participants are not required to withhold a response to the cue. It has been argued that the target–target design provides a more appropriate measure of ''genuine'' IOR, and IOR as measured in the cue–target design may involve an additive combination of manual response inhibition and ''genuine'' IOR (Coward, Poliakoff, O'Boyle, & Lowe, 2004; Spence & Driver, 1998). Comparing the two designs in a simple target-detection task without the need for response selection (all responses with the same hand or foot), researchers found a smaller but still robust IOR effect in the target–target design (Coward et al., 2004). The reduction of the effect was attributed to the elimination of manual response inhibition and an additive combination of manual response inhibition and ''genuine'' IOR in the cue–target task was suggested (Coward et al., 2004; Tassinari, Campara, Benedetti, & Berlucchi, 2002). However, using a location discrimination task with the need for response selection (different responses to the location of a target: e.g., left hand vs. right hand), no difference between IOR magnitudes between designs was found (Taylor & Klein, 2000). The location discrimination task is the same as the detection task except for the need for response selection, and thus, may be a more direct test of the view that responses are biased in IOR. Indeed, a recent study using the location discrimination task suggested that there are processes which initially bias response selection toward cued locations and then subsequently bias response selection away from cued locations (Wilson & Pratt, in press).

Examining the effects of peripheral cuing on event-related brain potential (ERP) components of the electroencephalogram (EEG), several studies suggested that IOR measured in the cue–target design is related to inhibition at relatively early stages of perceptual processing at the cued location (see Prime & Ward, 2006, for an overview). ERP results of these studies provide evidence for a suppression of perceptual processing at the cued location, as indexed by a reduction in the amplitudes of the occipital P1 and N1 components (Prime & Ward, 2004, 2006; Wascher & Tipper, 2004; McDonald, Ward, & Kiehl, 1999). However, these ERP effects have not always been associated with behavioral IOR (McDonald et al., 1999; Hopfinger & Mangun, 1998), suggesting that early stages of perceptual processing cannot fully explain the IOR phenomenon, which may consist of a combination of sensory and response-related factors instead (Kingstone & Pratt, 1999). Thus, Prime and Ward (2004, 2006) examined the effect of nonpredictive cues on the motor-related lateralized readiness potential (LRP). In both studies, no effect on the response-locked LRP was found and researchers suggested that IOR may not be related to response processes. But by measuring evoked, phase-locked LRP activity, Prime and Ward might have missed a response-related effect in IOR as a large portion of motor activity is not phase-locked to an event and therefore does not show up in the LRP. Non-phase-locked oscillatory changes are induced by a stimulus or event with varying onset times or phase jitter, and thus, they are not visible in the averaged LRP. Thus, the present experiment was designed to examine the involvement of response inhibition in IOR by measuring oscillatory changes in induced EEG activity.

On a neural basis, information processing depends on the functioning of assemblies of neurons organized in networks. The activation and deactivation of such neural populations can be detected through changes in ongoing oscillatory EEG activity in different frequency bands. Event-related changes in ongoing EEG activity in a given frequency band can consist of either decreases or increases in signal power. These changes are considered to be due to a decrease or an increase in synchronous firing of the underlying neuronal populations. The former case is called event-related desynchronization (ERD) (Pfurtscheller & Aranibar, 1977) and the latter event-related synchronization (ERS) (Pfurtscheller, 1992). There is strong evidence that oscillatory changes in beta power (15–25 Hz) of sources in the sensorimotor and primary motor cortex are related to motor activity (Jurkiewicz, Gaetz, Bostan, & Cheyne, 2006; Pfurtscheller & Lopes da Silva, 1999; Salmelin, Hämäläinen, Kajola, & Hari, 1995) by regulating cortical activation (ERD) and cortical deactivation (ERS) (Neuper & Pfurtscheller, 2001). Beta ERD begins contralaterally from the onset of movements and becomes bilateral around movement execution (Pfurtscheller, Graimann, Huggins, Levine, & Schuh, 2003; Leocani, Toro, Zhuang, Gerloff, & Hallett, 2001). After movement execution beta ERD typically rebounds to beta ERS (Pfurtscheller, Stancak, & Neuper, 1996). Thereby, beta ERD and ERS are not mutually dependent and somewhat differ in their sources (Jurkiewicz et al., 2006). Very similar to the execution of real movements, imaginary movements and no-go cues elicit event-related changes of the beta rhythm (Pfurtscheller, Neuper, Brunner, & Lopes da Silva, 2005; Leocani et al., 2001). Synchrony in the beta band is known to be modulated by inhibition insofar as an increase in beta synchrony is associated with an increase of GABA-mediated inhibition among inhibitory interneurons (Jensen et al., 2005). Accordingly, synchronization processes at both beta ERD and beta ERS have been related to an inhibitory function (Pfurtscheller et al., 2005; Kühn et al., 2004; Leocani et al., 2001; Leocani, Cohen, Wassermann, Ikoma, & Hallett, 2000). Assuming that beta ERD reflects cortical activation and beta ERS reflects cortical

deactivation, both being mediated by GABAergic inhibition, detrimental effects on motor activity should arise from an enhancement of relative beta synchrony showing up in either less beta ERD or more beta ERS.

The present IOR experiment was designed to examine the involvement of response inhibition in both the target–target design and cue–target design in a location discrimination task, which is a more direct test of the view that responses are biased in IOR compared to a simple detection task. If response inhibition mediates the pattern of the IOR effect, delayed responding to targets presented at the same location as a preceding stimulus should arise from an increase in beta synchrony leading to less cortical activation (smaller ERD) or more cortical deactivation (larger ERS). In the cue–target design, an increase in beta synchrony could reflect a combination of manual response inhibition and ''genuine'' response inhibition. In the target–target design, an increase in beta synchrony should mainly reflect ''genuine'' response inhibition in IOR. Comparing relative power changes in the beta band between the target–target task and the cue–target task then should shed light on the involvement of ''genuine'' response inhibition and manual response inhibition in IOR.

METHODS

Participants

After giving informed consent, 36 volunteers (14 men and 22 women) accomplished either the target–target task or the cue–target task. All participants reported normal to corrected-to-normal vision. With the exception of three volunteers, all subjects were right-handed. Mean age was 23 years with a range of 19 to 38 years ($SD = 3.4$).

Experimental Design

Participants viewed a computer monitor from a distance of 150 cm and were instructed to maintain fixation on a centrally located gray fixation cross throughout the whole experiment and to not move the eyes. The screen background was black and displayed at all times two gray square outline boxes (2.5° * 2.5°) centered 6.5° above and below fixation. After an intertrial interval of variable duration between 1950 and 2050 msec, each of the 80 trials began with a 200-msec onset of the first stimulus (S1). S1 consisted of a brightening of one of the two square boxes and was equally likely to occur at either location. After a variable delay of 750 to 1000 msec, the second stimulus (S2) was presented for 1000 msec. The total stimulus onset asynchrony (SOA) ranged between 950 and 1200 msec. S2 was a red cross (1.25°) and was presented with equal probability within one of the two peripheral boxes with chance coincidence of S1 and S2 locations. Forty trials on which S1 and S2 occurred at the same location were classified as valid trials, whereas 40 trials on which S1 and S2 occurred at opposite locations were classified as invalid trials. In the target–target task, participants responded based on the spatial location of both S1 and S2. In the cue–target task, participants only responded based on the location of S2. Two response keys were marked on the computer keyboard, one on the upper left side and one on the upper right side. Participants were instructed to press the left key with the index finger of their left hand for targets that appeared above fixation and to press the right key with the index finger of their right hand for targets that appeared below fixation (Figure 1A). Both speed and accuracy were stressed in the instruction.

EEG Recordings

EEG was recorded from mostly equidistant 62 Ag/AgCl scalp electrodes arranged according to the extended 10-20 system and mounted in an elastic cap (BrainCap64, Easycap). Vertical and horizontal eye movements were recorded from two additional channels. Electrode FCz served as common reference. Bioelectrical signals were digitalized with a sampling rate of 500 Hz and amplified between 0.3 and 70 Hz (BrainAmpMR plus, Brain Products). EEG recordings were off-line re-referenced against average reference and electrooculogram-corrected using calibration data to generate individual artifact coefficients and the PCA method (Ille, Berg, & Scherg, 2002; Lagerlund, Sharbrough, & Busacker, 1997). Impedance was kept below 5 kΩ.

EEG Data Analysis

EEG data were visually inspected for artifacts and thereafter segmented into 4000-msec epochs (ranging from 2000 msec preceding S2 onset to 2000 msec following S2 onset). All single trials were time-locked to S2 onset. Due to the variable SOA, S1 onset was jittered from −1200 msec to −950 msec before S2 onset. Trials outside the range of 100 msec to 1000 msec in reaction time (RT) and trials with localization errors were excluded from the analysis. The mean number of single trials remaining for each participant for analysis was 74.9 with a minimum of 50 out of 80 trials.

By means of temporal spectral evolution analysis (Hari & Salmelin, 1997), ERD/ERS values over electrodes in the beta frequency domain were calculated by band-pass filtering (15 to 25 Hz), rectifying of samples, referencing, and subsequent averaging over single trials (implemented in Brain Electrical Source Analysis MEGIS Software BESA v5.1.6). The ERD/ERS is defined as percentage power decrease (ERD) or power increase (ERS) in relation to a reference interval. We chose a 500-msec reference interval preceding S1 onset, namely, −1750 to −1250 msec before S2 onset.

To localize the sources of ERD/ERS, the Multiple-Source Beamformer (MSBF, Brain Electrical Source

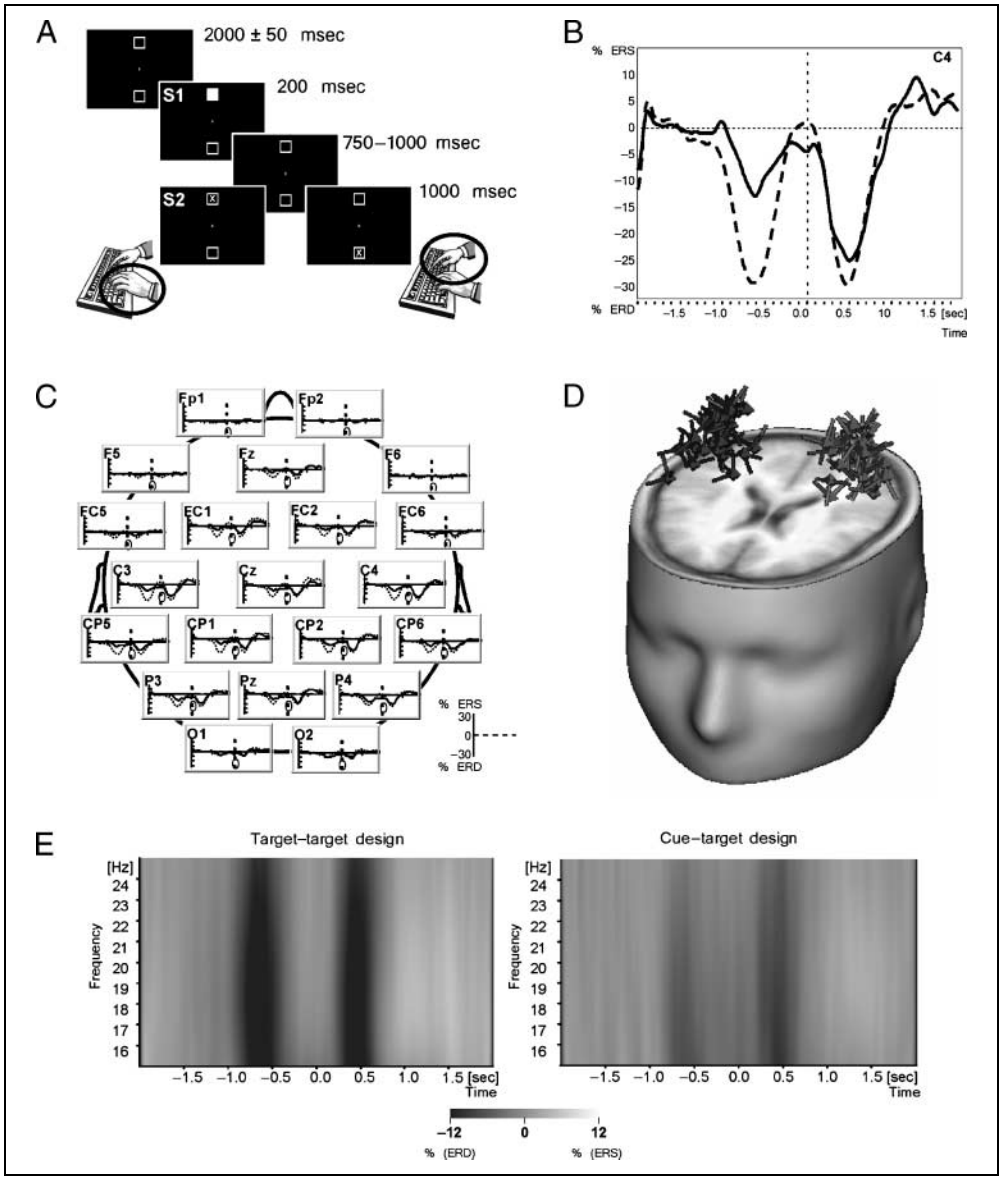

Figure 1. Both in the target–target design and cue–target design, typical movement-related beta ERD/ERS was observed. (A) Location discrimination task: depiction of a valid trial and an invalid trial with S1 presentation above fixation. S1 consisted of a brightening of one of the two square boxes positioned above and below fixation. S2 was a red cross that was presented in one of the square boxes. In the target–target design, participants were instructed to respond both to S1 and S2 with the index finger of their left hand (targets above fixation) and right hand (targets below fixation). In the cue–target design, participants were instructed to only respond to S2. (B) Mean beta ERD/ERS for electrode C4 in the target–target design (dashed line) and cue–target design (solid line). Beta ERD both at S1 and S2 presentation and beta ERS after movement execution (movement prevention) was observed. (C) Mean beta ERD/ERS for a sample of electrodes in the target–target design (dashed line) and cue–target design (solid line). In both designs, beta activity was mostly pronounced over centro-parietal electrodes. For all statistical analyses, four separate time intervals were chosen: S1-ERD (−800 to −500 msec), S1-ERS (−300 to 0 msec), S2-ERD (200 to 500 msec), and S2-ERS (700 to 1000 msec). (D) Beamformer sources of individual-subjects beta ERD on the standard BESA head model are shown. To localize the sources of beta ERD/ERS, the bilateral Multiple Source Beamformer (MSBF, Brain Electrical Source MEGIS Software BESA v5.1.6) was used. MSBF revealed the sources of maximum beta activity following target onset in the left and right primary motor cortex. (E) Time–frequency representations of beta power in the target–target and cue–target design: Localized sources showed most evident ERD/ERS in a fairly wide beta band ranging from 15 to 25 Hz. Beta ERD is indicated by black coloring and beta ERS by white coloring.

Analysis MEGIS Software BESA v5.1.6) was used. This method images oscillatory sources in a user-defined time–frequency domain. In accordance to ERD/ERS calculation, the beamformer computes changes of power in a poststimulus interval relative to a prestimulus baseline. As a default, MSBF uses a bilateral beamformer, where specifically contributions from the homologue source in the opposite hemisphere are taken into account. This allows for imaging of highly correlated bilateral activity in the two hemispheres that commonly occurs during processing of external stimuli or motor activity. For reliable beamformer results, it is important to assign the same duration to the target and the baseline interval. Therefore, we defined a 500-msec interval following target onset that was contrasted with the 500-msec precue reference interval in the beta frequency domain (15 to 25 Hz). Based on the chosen baseline and target interval, the MSBF revealed the locations of the bilaterally simulated sources of maximum beta ERD in the cortex for each participant. The EEG data were transformed from electrode space to individual source space. Because MSBF uses individual-subject EEG data, the ongoing EEG activity of the individual sources was averaged over dipole orientations and analyzed. The mean locations of the sources were calculated using the Talairach coordinates obtained from the analysis of

maximal beta ERD for each participant. Anatomic labeling of sources was feasible using the WFU Pickatlas v2.0 software toolbox (Maldjian, Laurienti, Kraft, & Burdette, 2003).

Statistical Design

Mean median RT of responses to S2 was used as a behavioral-dependent variable and entered into repeated measures analyses of variance (ANOVAs) with the within-subjects factors S1-POSITION (above, below) and S2-POSITION (above, below) and the between-subjects factor design (target–target, cue–target). For both designs, behavioral IOR indices were calculated (difference in RT; valid minus invalid) and median splits on this measure formed high- and low-inhibition groups of participants. This was done although a recent study by Berger (2006) suggested a reliability problem in IOR, which might diminish the likelihood of finding differences between groups. Mean beta ERD/ERS was used as a physiological-dependent variable and entered into repeated measures ANOVAs with the within-subjects factors S1-POSITION (above, below), S2-POSITION (above, below) and source (left, right), and the between-subjects factor design (target–target, cue–target). For both designs, Pearson correlations between behavioral RT and physiological ERD/ERS were calculated. For statistical analysis, we chose four separate time intervals: S1-ERD (−800 msec to −500 msec), S1-ERS (−300 msec to 0 msec), S2-ERD (200 msec to 500 msec), and S2-ERS (700 msec to 1000 msec).

RESULTS

Behavioral Data

Analyzing RT of responses to S2, ANOVA revealed an S1-POSITION × S2-POSITION interaction [$F(1, 34) = 28.1$, $p < .001$] and a main effect of design [$F(1, 34) = 4.6$, $p < .05$]. The interaction was due to the expected IOR effect with slower responses on valid trials than on invalid trials. The effect of design was due to faster responses in the target–target design than in the cue–target design. In the target–target design, RT was 375 msec on invalid trials and 397 msec on valid trials. In the cue–target design, RT was 412 msec on invalid trials and 432 msec on valid trials (Table 1). IOR magnitude did not differ between designs [$F(1, 34) < 1$]. Regarding responses to S1 in the target–target design, mean median RT was 380 msec for stimuli presented above fixation and 382 msec for stimuli presented below fixation.

Physiological Data

In both designs, beta activity was mostly pronounced over centro-parietal electrodes. Mean beta ERD/ERS is shown for electrode C4, exemplarily (Figure 1B), and for a sample of electrodes (Figure 1C). Source localization revealed the locations of two sources of maximum beta activity in the left and right precentral gyrus (Brodmann's area 4) (Figure 1D). The left source ($x = -38$, $y = -20$, $z = 58$) was symmetrically located to the right source ($x = 41$, $y = -21$, $z = 58$), tested by two-tailed t tests for each coordinate axis [all $t(35) < 1$]. Sources showed most evident ERD/ERS in a fairly wide beta band ranging from 15 to 25 Hz (Figure 1E). Figures 2A and 3A show mean beta ERD/ERS for sources in the target–target design and the cue–target design. Further analysis was restricted to the two bilateral sources. For each time interval, separate ANOVAs were calculated.

In the S1-ERD interval, ANOVA revealed a S1-LOCATION × Source interaction [$F(1, 34) = 16.3$, $p < .001$] and a main effect of design [$F(1, 34) = 19.6$, $p < .001$]. The interaction was due to laterality of beta ERD with a larger drop in power contralateral to the (anticipated) movement side to S1. The main effect arose from less relative power in the cue–target design, reflecting the prevention of a response to S1 in this design.

In the S1-ERS interval, ANOVA revealed an S1-LOCATION × Source × Design interaction [$F(1, 34) = 4.6$, $p < .05$]. This interaction was due to a difference in laterality of ERS between designs. Post hoc analysis showed that the interaction arose from a larger increase in power in the target–target design [$F(1, 17) = 5.7$, $p < .025$] (Figure 2B).

In the S2-ERD interval, ANOVA revealed three interactions, two of them due to laterality of relative beta power and one due to validity of S1. The S2-LOCATION × Source interaction [$F(1, 34) = 15.8$, $p < .001$] resulted from a larger drop in power contralateral to the movement side respecting S2. The S1-LOCATION ×

Table 1. Mean Reaction Times (Standard Errors, msec) to S2 as a Function of Design and Validity of S1

	Target–Target Design			*Cue–Target Design*		
	All	*Highs*	*Lows*	*All*	*Highs*	*Lows*
Valid	397 (10.4)	375 (11.7)	418 (14.4)	432 (11.8)	444 (12.0)	420 (20.3)
Invalid	375 (14.0)	336 (11.6)	414 (17.7)	412 (11.6)	409 (11.3)	416 (21.0)

All = all participants; Highs = high-inhibition group; Lows = low-inhibition group.

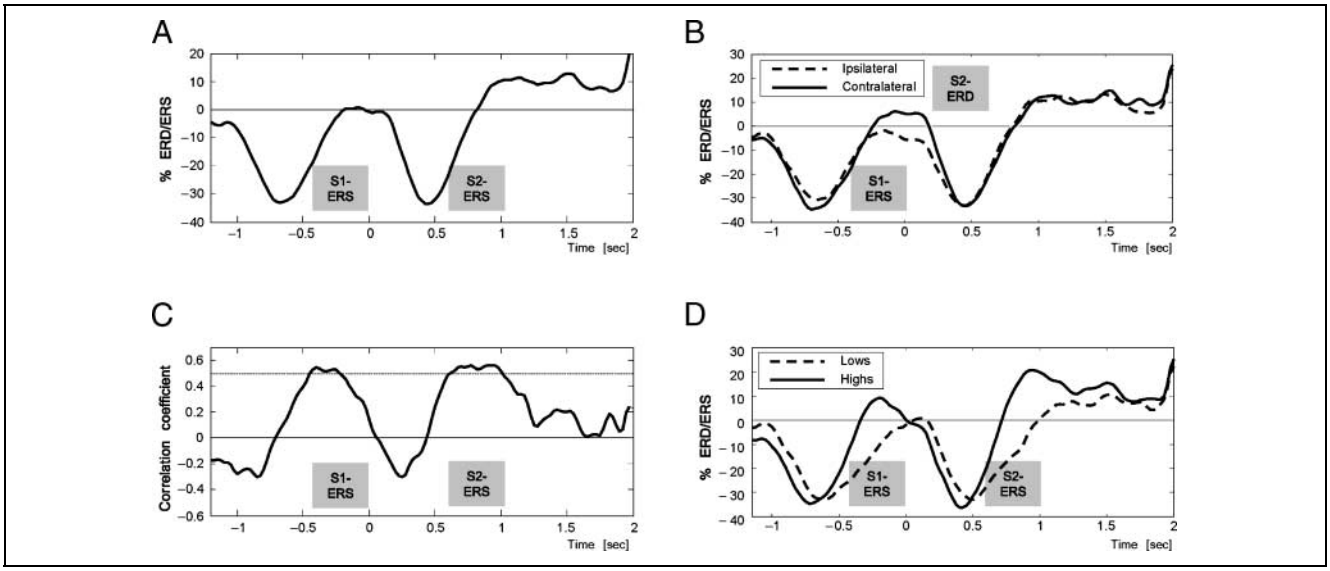

Figure 2. Target–target design. Gray areas illustrate the separate time intervals of statistical analysis. (A) Mean relative beta power: Sources showed beta ERD at presentation of targets and beta ERS following movement execution. (B) Laterality of ERS: Sources showed an enhancement of ERS contralateral to the movement side respecting S1 location. (C) Point-to-point Pearson correlations between relative beta power and the behavioral IOR effect (difference in RT; valid-cue minus invalid-cue trials). The dashed line corresponds to a significant correlation with $p < .05$. (D) Median split on the behavioral inhibition index: In both sources, S1-ERS and S2-ERS were larger in the high-inhibition group (Highs) compared to the low-inhibition group (Lows).

Source × Design interaction [$F(1, 34) = 5.7$, $p < .025$] was due to a difference in laterality of ERD between designs depending on S1 location. Post hoc analysis showed that the interaction arose from less contralateral ERD in the target–target design [$F(1, 17) = 22.6$, $p < .001$]. The S1-LOCATION × S2-LOCATION × Design interaction [$F(2, 34) = 10.1$, $p < .005$] resulted from a difference in beta ERD between designs depending on the validity of S1 location. Post hoc analysis showed that the interaction arose from a smaller drop in power in

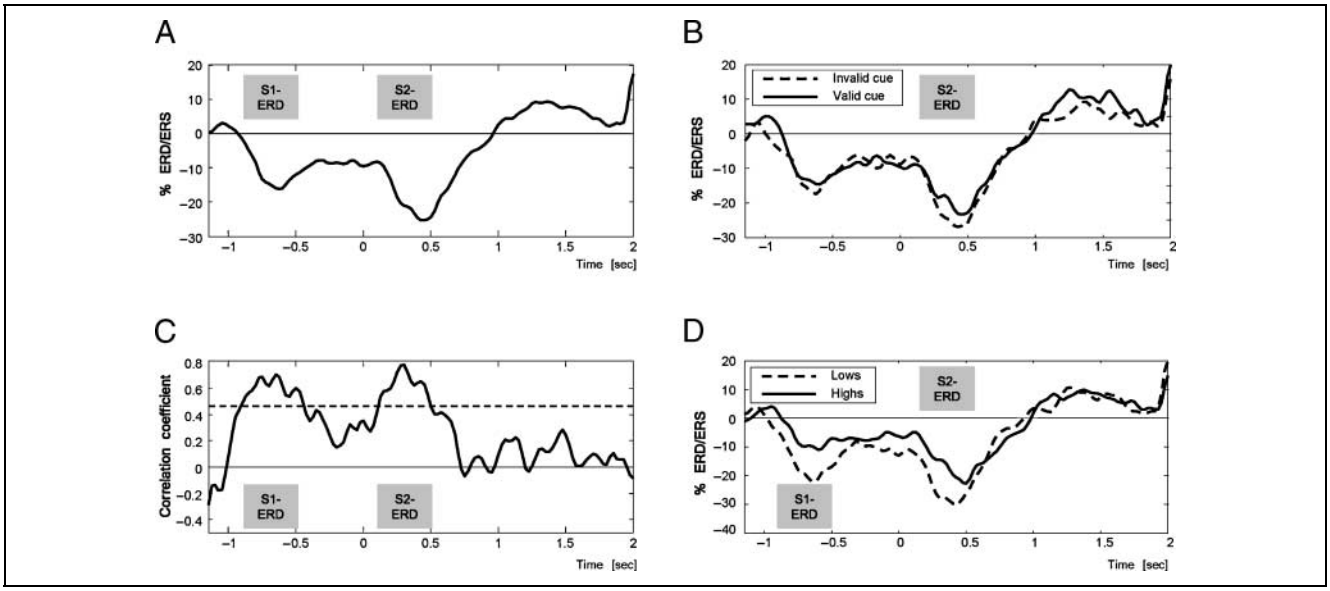

Figure 3. Cue–target design. Gray areas illustrate the separate time intervals of statistical analysis. (A) Mean relative beta power: Sources showed beta ERD at presentation of targets and beta ERS following movement execution. (B) Validity of cue: Sources showed a decrease of S2-ERD if a valid cue (S1) preceded target presentation (S2) compared to an invalid cue. (C) Point-to-point Pearson correlations between relative beta power and the behavioral IOR effect (difference in RT; valid-cue minus invalid-cue trials). The dashed line corresponds to a significant correlation with $p < .05$. Scatterplots of significant correlations in the S1-ERD and S2-ERD interval are shown separately. (D) Median split on the behavioral inhibition index: In both sources, S1-ERD and S2-ERD were smaller in the high-inhibition group (Highs) compared to the low-inhibition group (Lows).

valid trials compared to invalid trials in the cue–target design [$F(1, 17) = 4.9, p < .05$] (Figure 3B).

In the S2-ERS interval, ANOVA revealed no significant effects.

Combination of Behavioral and Physiological Data

Examining the relationship between beta activity and the behavioral IOR magnitude in the target–target design, we found significant correlations between relative power in the beta band and the difference in RT. IOR was related to an increase in ERS (Figure 2C; see scatterplots in Figure 4A). More beta ERS was accompanied by a larger behavioral IOR effect, both in the S1-ERS interval ($r = .49, p < .05$) and S2-ERS interval ($r = .56, p < .025$). Beta ERS in the S1-ERS and S2-ERS interval were highly correlated ($r = .85, p < .001$). Based on the behavioral IOR magnitude, a median split formed a high- and a low-inhibition group of participants. Behavioral RT (Table 1) differed in the high-inhibition group [$t(8) = 9.8, p < .001$], but did not reach significance in the low-inhibition group [$t(8) < 1$]. Figure 2D shows the contrast of beta activity with the between-subjects factor of inhibition group. Comparing groups, the high-inhibition group showed more beta ERS, both in the S1-ERS [$t(16) = 2.5, p < .025$] and S2-ERS interval [$t(16) = 3.0, p < .01$] (Figure 2D). Similarly, an analysis of the individual ERD/ERS maxima in the separate time intervals showed that the high-inhibition group showed more maximum ERS [$F(1, 16) = 5.4, p < .05$] but no difference in maximum ERD [$F(1, 16) < 1$] compared to the low-inhibition group.

Examining the relationship between beta activity and the behavioral IOR magnitude in the cue–target design, IOR was related to a decrease in beta ERD (Figure 3C; see scatterplots in Figure 4B). Less beta ERD was accompanied by a larger behavioral IOR effect, both in the S1-ERD ($r = -.66, p < .005$) and S2-ERD interval ($r = -.71, p < .001$). Beta ERD in the S1-ERD and S2-ERD interval were highly correlated ($r = .90, p < .001$). A median split formed a high- and a low-inhibition group of participants. Behavioral RT (Table 1) differed in the

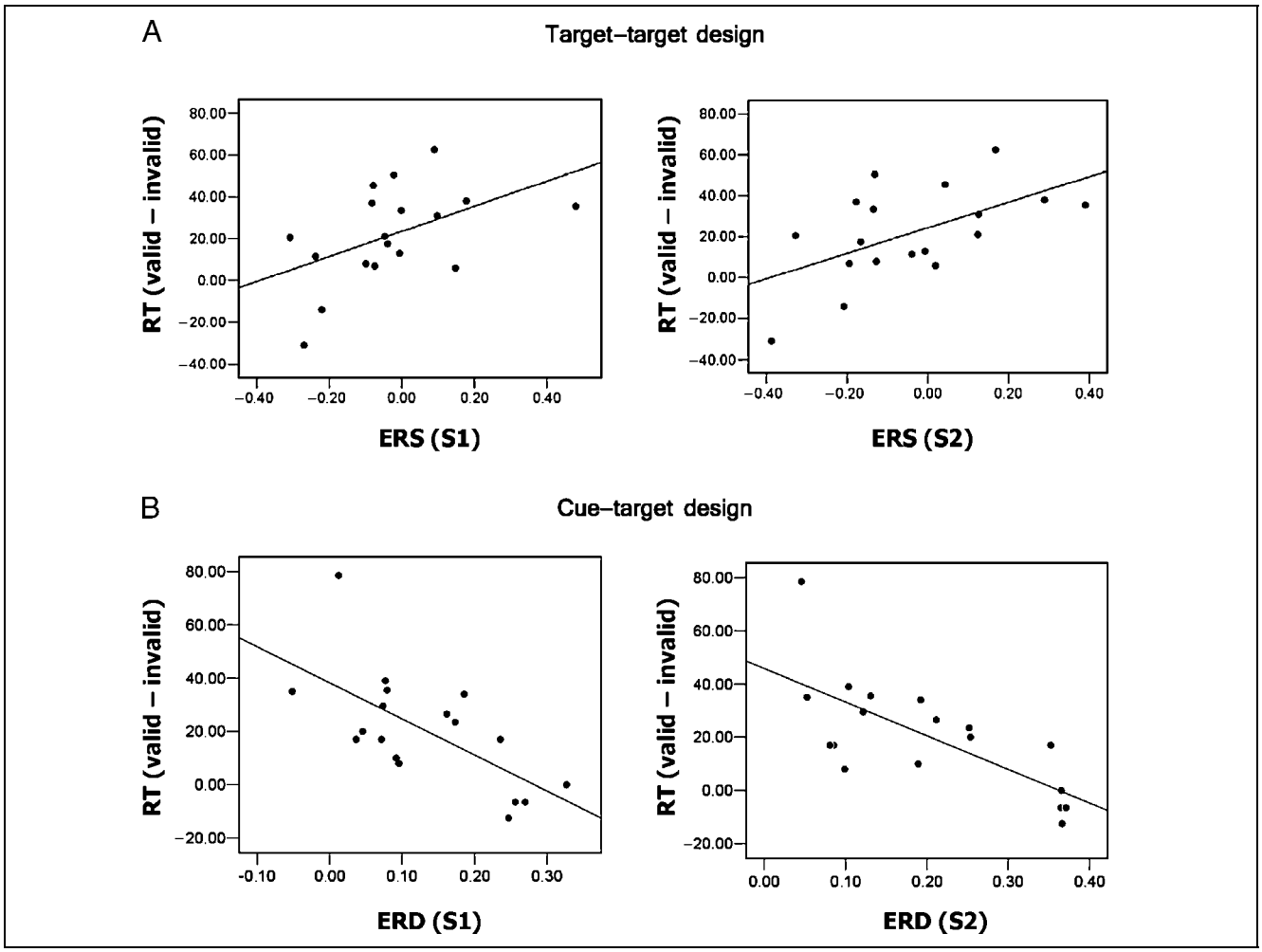

Figure 4. IOR was selectively associated with beta ERS in the target–target design or beta ERD in the cue–target design. (A) In the target–target design, IOR is positively correlated with beta ERS, both with S1-ERS ($p < .05$) and S2-ERS ($p < .025$). (B) In the cue–target design, IOR is negatively correlated with beta ERD, both with S1-ERD ($p < .001$) and S2-ERD ($p < .001$).

high-inhibition group [$t(8) = 6.2, p < .001$], but did not reach significance in the low-inhibition group [$t(8) = 1.3$, $p = .24$]. Comparing groups, the high-inhibition group showed less beta ERD, both in the S1-ERD [$t(16) = 2.2$, $p < .05$] and S2-ERD interval [$t(16) = 1.9, p = .07$], and was marginally significant (Figure 3D). Similarly, an analysis of the individual ERD/ERS maxima in the separate time intervals showed that the high-inhibition group showed less maximum ERD [$F(1, 16) = 4.8, p < .05$] but no difference in maximum ERS [$F(1, 16) < 1$] compared to the low-inhibition group.

DISCUSSION

Both in the target–target design and cue–target design, the expected behavioral IOR effect—slower responses on valid trials than on invalid trials—was obtained (Table 1). In contrast to studies comparing both designs in a simple detection task (Coward et al., 2004; Tassinari et al., 2002), our results correspond to the finding that no difference in IOR is found between designs in a location discrimination task (Taylor & Klein, 2000). The location discrimination task is the same as a detection task except for the need for response selection (Wilson & Pratt, in press). Although the detection of a peripheral event might produce an implicit categorical coding of target location (see Harvey, 1980), we think that a task that includes response selection provides a more direct test of the view that responses might be biased against the inhibited location.

Calculations of relative beta power over electrodes revealed beta ERD upon presentation of stimuli and beta ERS after movement execution (target) and movement prevention (cue), mostly pronounced over centroparietal electrodes. The bilateral beamformer located the sources of maximum beta activity in the primary motor cortex, namely, the left and right precentral gyrus (Figure 1D). The locations of the bilateral sources are in accordance with regard to both neuromagnetic data (Bauer, Ostenveld, Peeters, & Fries, 2006; Jurkiewicz et al., 2006; Salmelin et al., 1995) and hemodynamic data (Mayer, Seidenberg, Dorflinger, & Rao, 2004; Rosen et al., 1999).

Assuming that beta ERD reflects cortical activation and beta ERS reflects cortical deactivation, inhibitory effects on motor activity should arise from an increase in beta synchrony showing up in either less beta ERD or more beta ERS. This interpretation is consistent with the view that oscillatory synchrony might reflect some form of inhibition (Klimesch, Sauseng, & Hanslmayr, 2007; Jensen et al., 2005; Cassim et al., 2001). In contrast to the additive-combination model of ''genuine'' IOR and manual response inhibition in the simple target-detection task, the present findings suggest a special role of response inhibition in IOR in the location discrimination task. Here, two response-related but separate and nonadditive processes mediate the pattern of IOR in the target–target design and cue–target design. This conclusion arises partly on the basis of the failure to observe any differential IOR effect between designs. More crucially, however, it arises because two separate physiological correlates were identified, which supposedly mediate IOR unique to the different designs: Beta ERS was selectively associated with IOR in the target–target design and beta ERD was selectively associated with IOR in the cue–target design. The view of different functional roles of beta ERD and ERS is in accordance with the finding that they are not mutually dependent and somewhat differ in their sources (Jurkiewicz et al., 2006).

A relationship between postmovement beta ERS and IOR was only observed in the target–target design. Both the correlational data and the results based on the median split, contrasting a high- and a low-inhibition group, indicate an ERS-based explanation of IOR in the target–target design. Delayed responding to S2 targets presented at the same location as the preceding S1 targets arose from enhanced beta synchrony with larger ERS. Because the median split was based on the behavioral validity effect and small IOR was also associated with longer and more variable response times (Table 1), one could argue that slow and variable responding could be associated with more variability in the ERD, such that the ERD could be smaller and more broadly distributed. The longer-lasting ERD would overlap with the ERS interval, making the ERS smaller and later. By this account, increased ERS would not lead to more IOR. Instead, more variable responding might lead to less IOR, more variability in ERD, which in turn affects the timing and amplitude of the subsequent ERS. However, this alternative can be ruled out by examining the individual ERD/ERS maxima in the separate time intervals.

Postmovement beta ERS has been suggested to represent some form of passive inhibition, in terms of immobilization (Salmelin et al., 1995), deactivation of motor cortex (Pfurtscheller et al., 2005), or resetting of underlying cortical networks (Pfurtscheller et al., 2005). Ipsilateral and contralateral ERS have been shown to contribute differently to motor control as increases in beta band power correspond to a time of increased inhibition in the contralateral motor cortex (Leocani et al., 2001; Chen, Yaseen, Cohen, & Hallett, 1998), whereas no change in inhibition during this time period is found in the ipsilateral motor cortex (Rau, Plewnia, Hummel, & Gerloff, 2003; Leocani et al., 2001). In the target–target design of the present experiment, increased ERS was only observed in the contralateral motor cortex based on S1 location (Figure 2B). Because S1-ERS and S2-ERS were highly correlated, ERS differences seem to have been sustained throughout the target–target interval accompanied by less S2-ERD and a larger IOR effect. These results are in line with a passive response-inhibition explanation of IOR in the target–target design. In contrast to the cue–target design

(see below), we did not observe a decrease of beta ERD at target presentation based on the validity of the cue.

A relationship between beta ERD and IOR was only observed in the cue–target design. Both the correlational data and the results based on the median split indicate an ERD-based explanation of IOR in the cue–target design. Delayed responding to S2 targets presented at the same location as the preceding S1 cues arose from enhanced beta synchrony with smaller ERD at both cue and target presentation, leading to less activation. Again, the alternative explanation of different response time variability leading to differences in beta ERD between low- and high-inhibition group can be ruled out by examining the individual ERD/ERS maxima in the separate time intervals.

Beta ERD has been suggested to underlie some form of active response inhibition. Researchers suggested that after a no-go stimulus, there is not only a lack or an interruption of motor activation but also an early active response inhibition that prevents an action from occurring (Waldvogel et al., 2000; Hoshiyama et al., 1997). Consistently, an intracranial study by Kühn et al. (2004) provided evidence that beta ERD may be a feature of active response inhibition. The authors suggested that the subthalamic nucleus is involved in the preparation of externally paced movements in humans. More precisely, the degree of beta ERD in the subthalamic nucleus may be an important determinant of whether motor programming and movement initiation is favored or suppressed. Leocani et al. (2000, 2001) compared beta ERD in go and no-go RT tasks with the time course of corticospinal excitability. The authors proposed that beta ERD may indicate active corticospinal inhibition, whereas beta ERS corresponds to cortical removal of excitation or idling. In the cue–target design of the present experiment, beta ERD at target presentation depended on the validity of the cue with less ERD after a valid cue compared to an invalid cue (Figure 3B). As cue-ERD and target-ERD were highly correlated, ERD differences seem to have been sustained throughout the cue–target interval. These results are in line with an active response-inhibition explanation of IOR in the cue–target design. In contrast to the target–target design, we did not observe an increase of contralateral beta ERS.

Studies that looked at the effects of peripheral cuing on ERP components suggested that IOR is related to inhibition at relatively early stages of perception as indexed by a reduction in the amplitudes of the occipital P1 and N1 components (Prime & Ward, 2004, 2006; Wascher & Tipper, 2004; McDonald et al., 1999). However, early stages of perceptual processing may not fully explain the IOR phenomenon, which may consist of a combination of sensory and response-related factors (Kingstone & Pratt, 1999; McDonald et al., 1999; Hopfinger & Mangun, 1998). Being a critical node in the visual orienting pathway, the primate superior colliculus has been suggested to be involved in the generation of IOR (see Klein, 2000, for an overview). The superior colliculus is not itself inhibited when IOR is present and perceptual inhibition may occur before reaching the superior colliculus (Dorris, Klein, Everling, & Munoz, 2002). The activity of superior colliculus neurons during the SOA period is actually higher in a valid trial compared to an invalid trial, and thus, might be a structure to generate inhibition of later processes (Houghton & Tipper, 1994, 1996). In fact, animal studies showed a connection between the superior colliculus and the subthalamic nucleus (Bressand et al., 2002; Tokuno, Takada, Ikai, & Mizuno, 1994; Carpenter, Carleton, Keller, & Conte, 1981), in which beta ERD seems to be a feature of movement control (Kühn et al., 2004).

Using simple target-detection tasks, it has been argued that the target–target design provides a more appropriate measure of ''genuine'' IOR, and IOR as measured in the cue–target design may involve an additive combination of manual response inhibition and ''genuine'' IOR (Coward et al., 2004; Spence & Driver, 1998). In this experiment, we chose a location discrimination task that is the same as the detection task except for the need for response selection and may be a more direct test of response inhibition in IOR. In contrast to the additive-combination model of ''genuine'' IOR and manual response inhibition in the target-detection task, the present findings suggest a different role of response inhibition in IOR in a location discrimination task. Two separate physiological correlates were identified, which mediate IOR unique to designs: Beta ERS was selectively associated with IOR in the target–target design and beta ERD was selectively associated with IOR in the cue–target design. In the target–target design, IOR arose from beta ERS, which was more pronounced contralaterally after movement execution. We suggest that the rebound to beta ERS represents some form of passive cortical inhibition following activation at movement execution. In the cue–target design, IOR arose from beta ERD which was—just like RT—cue dependent. We suggest that beta ERD reflects some form of active response inhibition, which might be generated in another structure, perhaps in the superior colliculus. Thus, in the location discrimination task, ''genuine'' IOR, which is cue-dependent and response-related, can be observed in the cue–target design, whereas a passive form of response inhibition seems to be responsible for the IOR effect in the target–target design.

To summarize, using a location discrimination task with the need for response selection, two response-related but separate and nonadditive mechanisms mediated the pattern of IOR in the target–target design and cue–target design. In the target–target design, passive response inhibition arose from an increase in beta synchrony with larger contralateral beta ERS following movement execution. In the cue–target design, active

response inhibition led to an increase in beta synchrony with smaller ERD following a valid cue. Extending the findings of differential processing at relatively early stages of perception in IOR, these results suggest that IOR arises from inhibition of response processes.

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