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Review

Electroencephalography of response inhibition tasks: Functional networks and cognitive contributions

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ABSTRACT

Response inhibition paradigms, as for example stop signal and go/no-go tasks, are often used to study cognitive control processes. Because of the apparent demand to stop a motor reaction, the electrophysiological responses evoked by stop and no-go trials have sometimes likewise been interpreted as indicators of inhibitory processes. Recent research, however, suggests a richer conceptual background. Evidence denotes an association of a frontal-midline N200/theta oscillations with premotor cognitive processes such as conflict monitoring or response program updating, and an anterior P300/delta oscillations with response-related, evaluative processing stages, probably the evaluation of motor inhibition. However, the data are still insufficient to unambiguously relate these electroencephalographic measures to specific inhibitory functions. Beta band activity only recently has become a focus of attention in this task context because of its association with the motor system and regions involved in inhibitory control. Its functional role in response inhibition tasks needs further exploration though. Hence, as things stand, any deduction of differences regarding actual inhibitory capabilities or loads between subject groups or conditions based on electroencephalographic measures has to be treated with caution.

1. Introduction

Human cognition and behavior vary dramatically from one moment to the other. These variations of course are not exclusively driven by the outcome of a random process, but rather reflect our ability, and the necessity, to adapt to an ever-changing environment and to adjust or maintain our goals accordingly. A broad class of processes, altogether often referred to as cognitive control, render such flexibility possible by supporting goal and stimulus-response representations, issuing task processing strategies or attentional allocation, or by managing interferences in information processing and inhibition of inappropriate response tendencies. Inhibitory mechanisms, especially, have gained much interest due to their putative relevance for a variety of mental disorders such as attention deficit/hyperactivity disorder, schizophrenia or psychopathy. Response inhibition paradigms are often used to study inhibitory control in both healthy subjects and patient groups. Here, not only behavioral performance measures but also electroencephalographic variables are often considered immediate indicators of inhibitory processes.

This review summarizes studies utilizing go/no-go and stop signal tasks and electroencephalography (EEG) to explore the cognitive processes underlying response inhibition. First, the electrophysiological phenomena associated with these tasks will thoroughly be assessed, accompanied by a description of anatomical networks contributing to the generation of these EEG signals. Then, we will examine EEG effects from experiments that investigated motor inhibition and will assess their behavioral relevance. A number of theories already exist that try to link event-related potentials (ERP) and EEG oscillations to cognition and behavior; thus, a section of this review is devoted to these frameworks. Integrating the reviewed information, we arrive at the conclusion that commonly postulated associations of EEG measures and inhibitory mechanisms are only insufficiently supported. Relevant implications for cognitive and clinical neuroscience are shortly discussed and some recommendations for future ventures are provided.

1.1. Go/no-go and stop signal task characteristics

Most response inhibition paradigms impose the need to adjust response strategies in a multi-tasking situation. Subjects are required to

Abbreviations: aMCC, anterior midcingulate cortex; BA, Brodmann area; CPT, continuous performance test; EEG, electroencephalography; ERP, event-related potential; fMRI, functional magnetic resonance imaging; HD, Huntington's disease; IFC, inferior frontal cortex; MCC, midcingulate cortex; PD, Parkinson's disease; pMCC, posterior midcingulate cortex; preSMA, pre-supplementary motor area; SSRT, stop signal reaction time; TMS, transcranial magnetic stimulation.

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respond with high pace to one sort of stimulus while they are instructed to withhold responses to a second type of stimulus. The most common paradigms employed to study response inhibition without doubt are go/no-go and stop signal tasks, which are depicted in Fig. 1. Although similar in nature, these tasks differ in one important aspect: while in the go/no-go task a stimulus on a given trial is unambiguously indicating to either respond or not, stop-trials in the stop signal task first elicit a response by presenting a go-stimulus that is subsequently followed by a stop-signal indicating the necessity to withhold the already initiated response.

Typical behavioral dependent variables derived from both tasks are the average reaction time to go-trials as well as the number of false alarms, i.e., the number of responses made in context of no-go or stop signal presentation. The stop signal task furthermore allows the calculation of the stop signal reaction time (SSRT) that aims at the quantification of the latency of the inhibition mechanism (e.g., Band et al., 2003a; Logan et al., 1984). SSRT estimation rests on the assumption that processes to produce and to stop a response, triggered by the presentation of a go and a stop signal, respectively, independently race for execution. Hence, when the stop process finishes before the go process does, the response is successfully inhibited. With respect to electrophysiological responses, both no-go and stop conditions evoke two event-related potentials: frontal-midline N200 and P300, often together referred to as the N2/P3-complex (e.g., Simson et al., 1977; De Jong et al., 1990). When subjected to time-frequency decompositions, augmented power in theta (4–8 Hz) and delta (0–4 Hz) frequencies is reliably discernible. More recent studies also found activity in the beta band (12–30 Hz) at fronto-central electrodes to be of relevance (e.g., Alegre et al., 2008; Krämer et al., 2011). These electrophysiological responses evoked in response inhibition paradigms have always been of special interest, because they were expected to more directly relate to inhibitory processes.

1.2. Comparability of response inhibition paradigms

The basic concepts behind go/no-go and stop signal tasks and the phenomenology of electrophysiological responses are highly similar and hence corresponding effects are interpreted virtually the same irrespective of the precise task context. There are only few studies that directly compared go/no-go and stop signal tasks and they do not generally argue against such a comparability. Using ERP methodology van Boxtel et al. (2001) showed similar ERP patterns in no-go- and stop trials, which suggests similar underlying mechanisms. Rubia et al. (2001) were the first to use functional magnetic resonance imaging (fMRI) to assess common and specific patterns of activations with go/no-go and stop signal variants. They found the majority of activation maxima in conditions associated with response inhibition to be congruent. A common network was spanned by bilateral middle and inferior frontal gyri, midcingulate and parietal cortices as well as the pre-supplementary motor area (preSMA). Minor differences were observed in middle and medial frontal as well as inferior parietal regions. Can we, however, actually expect to have zero differences in fMRI when comparing tasks with varying stimulus contexts, presentation times or interstimulus intervals, even though they indeed assess the same cognitive concept? Whether stop signal and go/no-go tasks are based on the same cognitive processes has also been addressed on a more conceptual level. Verbruggen and Logan (2008a), for example, argue that the inhibitory process in the go/no-go task is automatic due to consistent stimulus-response mappings, whereas successful stop signal inhibition may rely on a more controlled process. Still, their experimental data show that even in the stop signal task automatic inhibition does occur. Hence, let us for now put our doubts aside and accept the notion that both tasks basically rely on the same cognitive constructs. We will revisit this issue in the discussion after having reviewed experimental findings of both tasks.

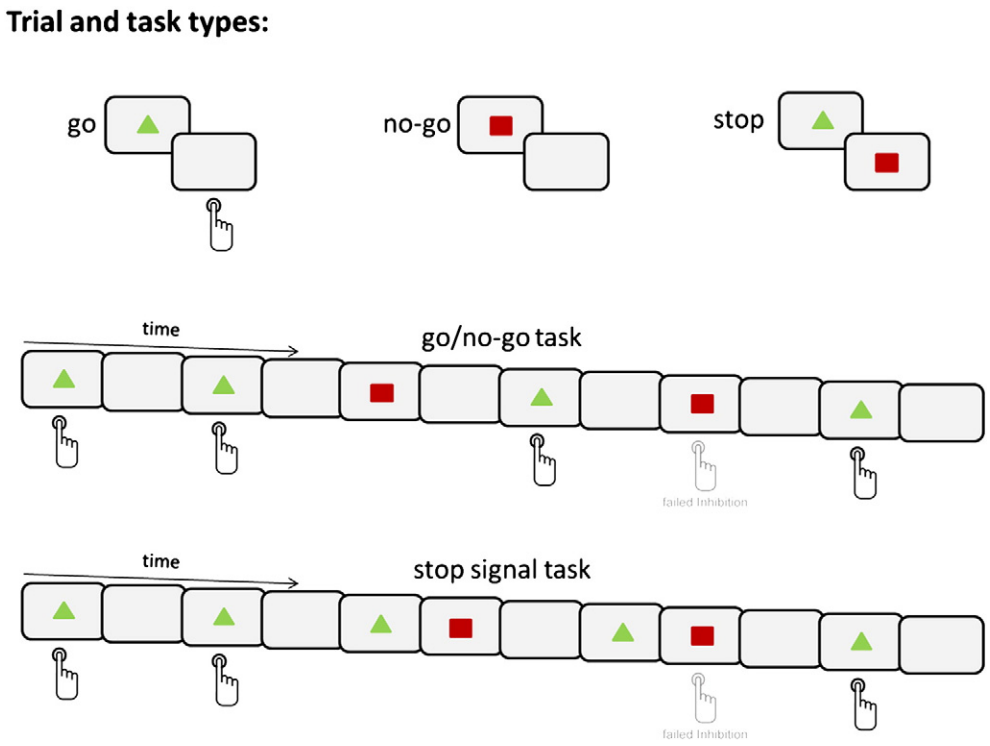

Fig. 1. Basic characteristics of go/no-go and stop signal tasks. Both tasks contain go trials that usually consist of the presentation of a single stimulus (e.g., a green triangle). Participants are instructed to respond to this stimulus (e.g., via button press). The go/no-go task additionally incorporates no-go trials, during which a stimulus distinct from the go stimulus is presented (e.g., a red square). Here, participants are instructed not to respond; failed inhibition occurs if the participant produces a response. Stop signal tasks consist of go and stop trials. During stop trials first the go stimulus is presented, followed by a delayed presentation of the stop stimulus. Although a go stimulus has been presented first, the successively presented stop stimulus calls for response suppression in a given trial; failure to do so also indicates failed inhibition.