The Global Nature of Motor System Inhibitory Effects in Response Control: Evidence, Mechanisms, and Debate

Authors: Wang Lihui, Wang Lihui

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Abstract

In research on response control, the long-standing theoretical perspective has held that only effectors interfering with the current goal exhibit inhibitory effects. However, a summary of recent research findings reveals that during response control processes, inhibitory effects emerge not only in interfering effectors but also in both task-irrelevant and task-required effectors; furthermore, inhibitory effects related to response control are not confined to tasks involving response conflict, but are widely observed in tasks involving response execution, indicating that the entire motor system demonstrates global inhibition across multiple contexts. The dual-process model posits that inhibition of different effectors is controlled by distinct brain regions, whereas the spotlight model suggests that inhibition of different effectors originates from a common system, the latter being consistent with the normalization model in computational neuroscience. The global characteristic of inhibitory effects in response control facilitates examination of cognitive processing from a synergistic and holistic perspective. Simultaneously, current research exhibits ongoing debates regarding the conditions under which this global inhibition emerges. Future research should differentiate between distinct effectors, and in conjunction with computational models, elucidate the synergistic mechanisms among effectors, the computational mechanisms of each effector in the motor cortex, and the relationship between abnormalities in these mechanisms and response control dysfunction in individuals with mental and psychiatric disorders.

Full Text

The Global Inhibitory Effect within the Motor System in Response Control: Evidence, Mechanisms, and Controversies

WANG Lihui1,2

1 Institute of Psychology and Behavioral Science, Shanghai Jiao Tong University, Shanghai 200030, China
2 Shanghai Mental Health Center, Shanghai Jiao Tong University School of Medicine, Shanghai 200030, China

Abstract

Traditional theories of response control have long maintained that inhibitory effects are selectively applied only to effectors that interfere with current task goals. However, recent research demonstrates that during response control, inhibition occurs not only at interfering effectors but also at task-irrelevant effectors and even at task-required effectors. Moreover, these inhibitory effects are not confined to tasks involving response conflict; they appear broadly across tasks that involve response execution, revealing a global inhibition of the entire motor system across multiple contexts. The dual-process model posits that inhibition of different effectors is controlled by distinct brain regions, whereas the spotlight model argues that inhibition across effectors originates from a single system—the latter aligning with the normalization model in computational neuroscience. The global nature of inhibitory effects in response control encourages a conceptualization of cognitive processing from the perspectives of coordination and integration. Nevertheless, current research exhibits ongoing debate regarding the conditions under which global inhibition emerges. Future studies should differentiate among various effectors and employ computational modeling to elucidate the coordination mechanisms between effectors, the computational mechanisms within the motor cortex, and how abnormalities in these mechanisms relate to response control deficits in psychiatric populations.

Keywords: response control, global inhibition, motor system, cognitive flexibility

Human thought and action exhibit remarkable adaptability and flexibility. As a healthy, functioning organism, humans can flexibly adjust perceptual and motor functions to achieve goals in constantly changing environments. A core manifestation of this adaptive capacity is response inhibition—the ability to suppress inappropriate or task-irrelevant behaviors to ensure effective execution of goal-directed actions (Logan, 1994). Response inhibition is involved in numerous everyday situations. For instance, when driving, we must continuously monitor safety information in our surroundings and stop promptly and accurately at red lights or when sudden hazards appear (such as pedestrians jaywalking) to ensure our own and others' safety. Furthermore, many psychiatric and neurological disorders, including Parkinson's disease, attention deficit hyperactivity disorder (ADHD), obsessive-compulsive disorder, and substance addiction, are characterized by deficits in response inhibition (Chambers et al., 2009; Zhao et al., 2015; Su & Zheng, 2019). Therefore, studying response inhibition not only advances our understanding of how humans adapt to environments through flexible behavior but also enhances our knowledge of mental and neurological disorders, holding significant theoretical and clinical importance.

Traditional theories posit that responses required by current task goals compete with responses or response tendencies that interfere with these goals, necessitating inhibition of the interfering responses to ensure goal achievement (Logan, 1994; Ridderinkhof, 2002; Wang & Cai, 2010). Research on response inhibition has a long history, with investigators proposing various theoretical models emphasizing different aspects. Early race models based on the Go/NoGo paradigm (Logan, 1994) suggested that response and response inhibition processes are independent and compete in the initial processing stage, with whichever process reaches threshold first determining the final behavioral outcome. Boucher et al.'s (2007) interactive competition model proposed that these processes are no longer independent in later stages, with response inhibition suppressing the response as it approaches threshold. The activation-suppression model based on conflict control (Ridderinkhof, 2002) posited that response inhibition involves two stages: first, activation of the inappropriate response, followed by its suppression. These processes are not independent, as suppression efficiency influences the activation strength and time course of the inappropriate response, with substantial individual differences. Aron (2011) noted that early models of response inhibition focused exclusively on "reactive inhibition"—the passive suppression of already-activated inappropriate responses—and further proposed "proactive inhibition," which involves active, advance suppression of potential, not-yet-activated inappropriate responses.

Despite disagreements regarding the proactivity and temporal dynamics of response inhibition, these theories unanimously agree that only responses interfering with current task goals need to be suppressed during implementation (Aron, 2011; Salzer et al., 2017). For example, in the classic Go/NoGo paradigm commonly used to study response inhibition, the response to NoGo stimuli is suppressed; in the Stroop task, the response triggered by incongruent color words is suppressed. However, mounting evidence indicates that inhibitory effects are not limited to responses that interfere with current task goals; rather, they involve global suppression of the entire motor system. Moreover, these effects are not exclusive to contexts involving response conflict and selection but extend broadly to contexts involving general response output and execution. Because multiple effectors exhibit inhibitory effects, researchers have proposed the concept of "global inhibition" (Wessel et al., 2013; Duque et al., 2017).

This article provides a systematic review of global inhibitory effects based on recent research developments. We first introduce the manifestations of global inhibition, then elaborate on its cognitive and neural mechanisms. Building on this foundation, we present different perspectives and controversies regarding the global nature of inhibitory effects with critical commentary, and conclude by summarizing the significance of global inhibition at both cognitive processing and neural computation levels while proposing directions for future research.

Global Manifestations of Inhibitory Effects

The core characteristic of global inhibition is suppression of the entire motor system, encompassing not only inhibition of responses that interfere with current goals but also inhibition of potential responses that do not interfere with current goals, as well as inhibitory processing of responses that must currently be executed. To differentiate these three types of responses, this article defines three categories of response effectors: (1) *task-required effectors*, which execute the responses demanded by the current task; (2) *interfering effectors*, which produce interference or conflict with task completion (task-required and interfering effectors together constitute *task-relevant effectors*); and (3) *task-irrelevant effectors*, which are unrelated to the current task but remain part of the entire motor system. In a Stroop task, for example, if participants are required to respond to red stimuli with a left-hand button press and to green stimuli with a right-hand button press, when the word "green" is presented in red ink, the left hand is the task-required effector, the right hand is the interfering effector, and all other effectors (such as the left foot) are task-irrelevant effectors.

Traditional research on response inhibition has primarily focused on two categories. The first includes response inhibition in Stop-signal and Go/NoGo paradigms, where participants inhibit responses from a particular effector when a signal appears (e.g., a stop signal or NoGo stimulus). Although task-required and interfering responses share the same effector in these paradigms, the effector is only considered interfering under conditions requiring response stopping. The second category includes response inhibition in conflict control tasks, such as the effector corresponding to the semantic meaning in incongruent conditions of the Stroop paradigm, or the effector on the same side as the spatial location in incongruent conditions of the Simon paradigm. In both categories, traditional research has defined response inhibition as suppression of interfering effectors, without examining whether inhibitory effects exist in other effectors, thereby overlooking the global nature of inhibition. Furthermore, both categories involve conflict control: classic paradigms like Stroop, Flanker, and Simon feature direct conflict between different effectors, while Stop-signal and Go/NoGo tasks involve conflict between executing and stopping a response, which is also essentially a conflict control paradigm. However, recent findings reveal that the global nature of inhibitory effects persists even in contexts not involving conflict control. Below, we discuss inhibitory phenomena in different effectors separately for conflict control and non-conflict control contexts.

Response Inhibition in Conflict Control Contexts

The most intuitive way to elicit response inhibition is through conflict control paradigms, and numerous such tasks have demonstrated the global nature of inhibitory effects. Inhibition of task-irrelevant effectors was first observed by Badry et al. (2009). Using a Stop-signal paradigm that required manual button presses to specific stimuli, they found that when participants had to inhibit their response upon stop-signal presentation, inhibitory effects were observed not only in the responding hand (the interfering effector) but also in the leg (a task-irrelevant effector), as evidenced by motor-evoked potential signals in the leg that were lower than baseline levels measured during resting states without task demands. Another study using a Go/NoGo paradigm requiring manual responses also observed inhibitory effects in the leg (Majid et al., 2012). In this study, the responding hand served as the interfering effector and the leg as the task-irrelevant effector, with results showing that motor-evoked potentials in the leg were lower during conditions requiring hand response stopping compared to resting baseline levels. Wessel et al. (2013) required participants to perform a Stop-signal task using eye movements, making saccades to stimulus locations when no stop signal appeared and stopping saccades when a stop signal appeared. Approximately 50 ms before successful saccade stopping, inhibitory effects appeared in the hand, with motor-evoked potential signals lower than those during saccade execution conditions and unsuccessful stopping conditions. Because this task did not involve hand responses (making the hand a task-irrelevant effector), these results indicate that suppression of the oculomotor system is accompanied by suppression of the somatomotor system, demonstrating global inhibitory effects across the entire motor system (Wessel et al., 2013). Additionally, research has shown that inhibitory effects appear in the hand during speech stopping (Cai et al., 2012), with motor-evoked potentials lower during successful speech stopping compared to speech execution and unsuccessful stopping conditions.

Beyond inhibition of interfering and task-irrelevant effectors, some studies have demonstrated inhibitory effects in task-required effectors (Klein et al., 2014; Bundt et al., 2016; Wang et al., 2021). For example, Klein et al. (2014) used a Flanker paradigm requiring participants to respond to the direction of a central arrow among a row of arrows (left-hand button press for leftward arrows, right-hand button press for rightward arrows), where the central arrow direction could be congruent or incongruent with the flanking arrows. Results showed that the task-required effector exhibited inhibitory effects upon stimulus presentation in both congruent and incongruent conditions, with motor-evoked potentials lower than resting baseline levels. Moreover, this inhibitory effect was stronger when participants were better prepared for inhibition, specifically when most trials in a block were incongruent (requiring greater inhibitory preparation) (Klein et al., 2014). Using a Simon paradigm, Wang et al. (2021) similarly found that both interfering and task-relevant effectors showed inhibitory effects during resolution of spatial-response conflict, with these two inhibitory effects exhibiting a negative correlation in magnitude. Collectively, although inhibiting the task-required effector may seem detrimental to correct response execution, it may be essential for resolving response conflict.

Response Inhibition in Non-Conflict Control Contexts

In experimental contexts not involving conflict control, Duque et al. (2010) examined inhibitory effects during response preparation and selection using a cue-response selection paradigm. In this paradigm, participants first viewed a cue indicating that a response task would follow, and after a delay, a target stimulus appeared on either the left or right side of the screen. The cue provided no predictive information about target location, and participants had to respond to the target. The experiment included different task contexts: a bilateral response context requiring left and right index finger responses to left and right stimuli, respectively (making one hand the task-required effector and the other the interfering effector), and a unilateral response context requiring responses from different fingers of the same hand (left little finger for left stimuli and left index finger for right stimuli, or right index finger for left stimuli and right little finger for right stimuli). Results showed that in the bilateral response context, the task-required effector exhibited significant inhibition during the time window closest to target appearance following cue presentation, whereas in the unilateral context, only the left-hand task-required effector showed significant inhibition, with the right-hand effect not reaching significance. After target presentation in the bilateral context, the interfering effector (right index finger) showed significant inhibition when the left hand was the responding hand. In another experiment, the cue was still presented, but the target was a central arrow requiring a single-hand response (e.g., left index finger only). Results revealed that during the time window closest to target appearance following cue presentation, both the task-required effector (left index finger) and a task-irrelevant effector (right index finger) showed significant inhibition, while another more neurally distant task-irrelevant effector (right little finger) did not show significant inhibition (Duque et al., 2010). Based on these differential inhibition patterns, the authors proposed that the function of global inhibition is to resolve response competition. Although the second task only required a left index finger response, when the arrow pointed rightward, it activated a stronger response tendency in the right index finger than in the right little finger, creating greater response competition that required stronger inhibition to ensure correct execution.

A subsequent study further investigated the global nature of inhibitory effects in non-conflict control contexts and observed inhibition across task-required, interfering, and task-irrelevant effectors (Greenhouse et al., 2015). Compared to Duque et al. (2010), Greenhouse et al. (2015) added a condition without preparatory cues and a condition requiring no response. Results showed that in both unimanual and bimanual response tasks, task-required and task-irrelevant effectors both exhibited inhibition, and this inhibition occurred regardless of whether preparatory cues were present, though it appeared earlier when cues were provided. However, no inhibition was observed when no response was required. Based on these findings, the authors argued that the function of global inhibition is to serve general response output and execution, appearing whenever the current context demands a response as an integral part of response preparation and output.

Although the evidence indicates inhibitory effects across multiple effectors, important distinctions must be made. For interfering and task-irrelevant effectors, inhibitory effects include both reductions in neural signals (e.g., motor-evoked potentials) and prevention of response output (e.g., successfully stopping interfering and task-irrelevant effectors). In contrast, for task-required effectors, inhibitory effects generally refer to reductions in neural signals without preventing response output, as the purpose is to control the timing and execution of the required response.

Cognitive and Neural Mechanisms of Global Inhibitory Effects

Because behavioral measures typically reflect only the efficiency of inhibition implementation without revealing inhibitory effects across different effectors, physiological or neural measures are necessary to provide evidence for global inhibition. The most commonly used technique for measuring inhibitory effects is motor-evoked potentials (MEPs). This method involves applying transcranial magnetic stimulation (TMS) to a specific region of primary motor cortex while recording electromyography from the contralateral effector. The resulting electromyographic signal, known as the motor-evoked potential, reflects neural excitability along the response output pathway from motor cortex (central nervous system) to spinal cord (peripheral nervous system) (Bestmann & Krakauer, 2015; Bestmann & Duque, 2016). MEPs measured during resting states without task demands establish an individual's baseline potential level, and MEPs significantly lower than baseline during task performance are interpreted as indicating inhibitory effects. Numerous studies have used this measure to observe inhibition in task-required effectors (Duque et al., 2012; Klein et al., 2014), interfering effectors (van den Wildenberg et al., 2010; van Campen et al., 2014), and task-irrelevant effectors (Majid et al., 2012; Wessel et al., 2013). This technique offers several advantages: First, MEPs can be measured at different time points before and after response initiation or stopping, better revealing the temporal characteristics of inhibitory effects (van Campen et al., 2014; Freeman & Aron, 2016). Second, it can reflect molecular-level neural activity, such as inhibitory neurotransmitter GABA activity detected through paired-pulse TMS (Coxon et al., 2006). When the interval between two TMS pulses is 2–3 ms, the second pulse activates low-threshold GABA neurons in primary motor cortex, producing intracortical inhibition (Fisher et al., 2002).

Although global inhibition is more extensive than the traditional view of response inhibition, both share similar cognitive-level influencing factors, including attention, top-down control, reward, and motivation (Klein et al., 2014; Botvinick & Braver, 2015; Wang, Braver et al., 2019). Studies have manipulated these factors (e.g., high vs. low reward, degree of top-down attentional involvement) while observing how neural signals corresponding to different effectors change as supporting evidence. These neural signals include surface electromyography from effectors, electroencephalography and blood oxygen level-dependent signals from primary motor cortex, and motor-evoked potentials. Reward, as an easily manipulated experimental variable, is frequently used to investigate response inhibition (Freeman et al., 2014; Freeman & Aron, 2016; Wang, Chang et al., 2019). Beyond these factors, event abruptness represents a special factor influencing global inhibition, with some researchers arguing that global inhibition is more readily observed when inhibitory control is suddenly required or when inhibition occurs rapidly (Majid et al., 2012; Wessel & Aron, 2017).

Two theories currently explain global inhibition: the dual-process model and the spotlight model, both supported by neural evidence. The dual-process model proposes two independent inhibitory mechanisms—one controlling activation of the task-required effector to prevent premature threshold crossing and ensure timely execution, and another resolving competition between the task-required effector and non-task-required effectors by suppressing activation of interfering and task-irrelevant effectors to prevent erroneous responses. Regarding neural mechanisms, the former is controlled by dorsal premotor cortex, while the latter is controlled by lateral prefrontal cortex (Duque et al., 2012; Labruna et al., 2014). In a study using repetitive TMS (rTMS) to disrupt activity in specific brain regions, Duque et al. (2012) found that rTMS applied to lateral prefrontal cortex weakened inhibition of interfering effectors, whereas rTMS applied to dorsal premotor cortex weakened inhibition of task-required effectors. According to this model, although multiple effectors show inhibitory processing that appears "global," the inhibition of different effectors actually belongs to different processes controlled by distinct brain regions.

The spotlight model proposes that inhibition of task-relevant and task-irrelevant effectors originates from a single inhibitory system that enhances the signal-to-noise ratio of the motor system through global inhibition (Greenhouse et al., 2015). In this process, simultaneous activation and inhibition of the motor system create gain modulation, whereby the gain of motor system neural signals increases proportionally as background noise decreases (Chance et al., 2002; Baca et al., 2008). An analogous example would be a teacher instructing a class to be quiet while one student is answering a question: although all students' voices (including the answering student) are reduced, the answering student's voice becomes more salient. Recent findings based on surface electromyography from responding hands support the spotlight model. Using a Simon paradigm, Wang et al. (2021) also found that stronger inhibition of interfering effectors was associated with weaker inhibition of task-required effectors and faster resolution of response conflict.

The primary distinction between the dual-process and spotlight models concerns whether inhibitory processing across different effectors shares a common origin, though they do not substantially disagree about the brain network involved in implementing response inhibition. According to traditional theory, response inhibition primarily involves a network from prefrontal cortex to basal ganglia, with key prefrontal regions being the pre-supplementary motor area and right inferior frontal cortex. Numerous systematic reviews have addressed this network (Bari & Robbins, 2013; Aron et al., 2016; Wang & Cai, 2010), so this article will not elaborate further.

The spotlight model is consistent with the normalization model in computational neuroscience (Carandini & Heeger, 2012). According to this model, a neuron's output strength is achieved through a normalization computation across the activity of an entire neural population. One variant of this model is shown in Equation (1). In this formula, In represents the activity of the neuron of interest, such as the neural signal corresponding to the task-required effector, while Im represents the activity of other neurons, such as the sum of neural signals corresponding to interfering and task-irrelevant effectors. When the activity of the entire neural population decreases (e.g., through inhibition), the denominator becomes smaller (both Im and In in Equation (1) decrease). Simultaneously, because the task-required effector must cross the motor threshold to generate a response, the magnitude of neural activity corresponding to the task-required effector is much higher than that of other effectors, causing the denominator to decrease proportionally more than the numerator. Under these conditions, the neuron corresponding to the task-relevant effector shows stronger activity after normalization (the normalized output value R of In).

Understanding global inhibition from the perspectives of the spotlight model and normalization computational model holds important psychological and cognitive neuroscience significance. First, both models consistently reflect that response control is not an isolated cognitive component or neural process but rather a coordinated cognitive processing mechanism. This coordinated processing is particularly evident in tasks involving multiple effectors, manifesting as a trade-off between the degree of inhibition applied to interfering or task-irrelevant effectors and that applied to task-required effectors—a "neural dynamics" characteristic (Wang, Chang et al., 2019; Wang et al., 2021). This has important implications for inhibitory training, providing more comprehensive explanations for existing training findings. For example, training response inhibition using Go/NoGo tasks has been found to not only improve inhibition accuracy in NoGo conditions but also significantly speed up responses in Go conditions (Benikos et al., 2013), indicating that inhibitory training enhances not only stopping efficiency but also motor output efficiency. Additionally, this coordinated interaction prompts consideration of the "costs and benefits" of inhibitory training: What effects does inhibitory training for one effector have on other effectors? How can we balance the different effects training produces across multiple effectors? Such considerations enable the design of better, more targeted training tasks based on task goals.

Another significant implication is the demonstration of shared neural computational principles across different cognitive processes. From a neural computation perspective, global inhibition of inhibitory effects involves computational processes across multiple neural populations corresponding to different effectors, rather than simply suppressing activity in neural populations corresponding to task-irrelevant effectors. This normalization computation pattern of overall neural activity is not unique to the motor system but is also evident in visual attention (Denison et al., 2021), olfactory processing (Zhu et al., 2013), multisensory integration (Ohshiro et al., 2017), and value representation and decision-making (Louie et al., 2013). In visual attention, for instance, selective attention to certain information involves not just suppression of neural activity corresponding to distracting information but normalization computation across the entire visual receptive field (Reynolds & Heeger, 2009). In value representation and decision-making, neural activity representing a particular option is not simply a function of that option's value but is normalized relative to the values of multiple alternative options, with decisions based on normalized rather than absolute values (Louie et al., 2013). While numerous empirical studies have validated the normalization model as an important neural mechanism in visual attention, olfactory processing, multisensory integration, and value representation, research on response control has thus far only produced factorial experimental results consistent with normalization model predictions. Computational modeling studies are still lacking, and filling this gap would not only advance research on the neural mechanisms of response control but also demonstrate the fundamental and widespread nature of the normalization model in neural computation (Reynolds & Heeger, 2009).

Comparison of Different Classification Criteria for Inhibitory Processing

To explicate the global nature of inhibitory effects, this article employs two classification schemes: one categorizing effectors and the other categorizing whether the cognitive context involves conflict. Notably, these classifications differ markedly from those in published review articles. To comprehensively introduce inhibitory effects, Duque et al. (2017) detailed several categories: standard stopping versus selective stopping, proactive inhibition versus reactive inhibition, and preparatory inhibition. Standard stopping involves only one effector without requiring effector selection (as in the classic Stop-signal task), whereas selective stopping requires inhibiting one of two or more effectors. Proactive versus reactive inhibition differs in that proactive inhibition can predict upcoming inhibition needs based on contextual cues and implement inhibition actively, whereas reactive inhibition cannot. Preparatory inhibition is proposed relative to non-preparatory inhibition, with its core being cognitive preparation for the effector to be inhibited—for example, preparing to inhibit the right hand when a trial requires a left-hand response.

These classification schemes are not oriented around whether inhibition is global;

their purpose is to comprehensively introduce and summarize inhibitory effects. However, these subcategories lack clear boundaries and logical relationships, with some exhibiting unresolvable overlap. For instance, both selective and preparatory inhibition can be either proactive or reactive, depending on whether the current context provides predictive information about upcoming inhibition needs. The authors do not provide explicit, quantifiable classification models for determining what constitutes proactive selective inhibition. Moreover, proactive inhibition can be achieved through training, meaning the same experimental context might shift from reactive to proactive inhibition due to repetition of similar trial types (Braver, 2012). Consequently, one cannot a priori assume which type of inhibition a given context involves but must infer it post-hoc from results, undermining scientific rigor.

In contrast, this article's classification by effector type and conflict context offers advantages: different effectors have objective, clear boundaries, and the degree of conflict determines the level of competition between effectors. These features facilitate clear, a priori predictions for testing theoretical reliability, rather than presupposing participants' degree of proactive inhibition. However, this classification's limitation is its failure to capture the distinction between top-down response inhibition (e.g., proactive and preparatory inhibition) and bottom-up response inhibition (e.g., reactive and non-preparatory inhibition). Different classification standards serve different purposes; this article's core focus is the global nature of inhibitory effects, which manifests in multiple effectors and multiple task contexts, hence the classification by effector and task context. Future research should integrate and critically consider different classification methods, examining their different emphases in revealing inhibitory mechanisms and what theoretical questions each classification is best suited to address.

Debate on Whether Global Inhibitory Effects Are Independent of Task Context

A controversy related to the global nature of inhibitory effects concerns whether they are broadly involved across various contexts. Duque et al. (2017) argue that global inhibition is conditional and does not appear in selective stopping tasks, which instead exhibit targeted inhibition of the specific effector requiring suppression. For example, when a cue indicating which finger to inhibit was presented before inhibition initiation, no inhibitory effect was observed in leg muscles (task-irrelevant effectors) during inhibition (Aron & Verbruggen, 2008). Duque et al. (2017) thus propose that different inhibitory mechanisms exist: global inhibition is more likely employed when the task emphasizes speed, whereas selective inhibition is more likely when the task emphasizes control over a specific response. This perspective treats global and selective inhibition as distinct, non-overlapping categories employed in different task contexts.

In contrast, Wessel and Aron (2017) review global inhibition as a universal mechanism of the motor system, merely more observable under certain conditions, such as those requiring rapid responses. The former view tends to assume different mechanisms underlie different phenomena, while the latter considers global inhibition a universal mechanism with varying elicitation strength across experimental contexts.

Summarizing these perspectives, we can currently only conclude that whether global inhibition is observable with existing methods and technologies is conditional, not that the existence of global inhibition itself is conditional. This issue relates to the bottleneck problem of current empirical research's reliance on p-values for statistical inference (Benjamin et al., 2018). Most current studies base statistical inference on p-value significance testing, where "non-observation" of a phenomenon is typically based on null results (non-significant p-values). However, null results do not directly support a conclusion of "does not occur" but rather "no evidence yet." Therefore, determining whether global inhibition broadly involves various tasks requires not only more empirical evidence but also integration of multiple statistical methods, such as Bayesian factor analysis in addition to traditional statistical analysis (Hu et al., 2018).

Unlike traditional statistical methods, Bayesian factor analysis does not rely on p-values but quantifies the relative probability of the null hypothesis ("no effect") versus the alternative hypothesis ("effect exists"). A standard criterion suggests that if the Bayes factor exceeds 3 (meaning the null hypothesis is at least three times more probable than the alternative), there is statistical evidence supporting the null hypothesis, allowing a "no effect" conclusion (Wagenmakers et al., 2018). For example, if traditional statistics yield a non-significant p-value for global inhibition, we cannot determine whether this null result stems from insufficient statistical power or genuine absence of effect. If subsequent Bayesian factor analysis yields BF = 4, the statistical inference would be "the null hypothesis is four times more probable than the alternative," 倾向于得出"这个效应不存在"的结论。If BF = 1/4, the inference would be "the null hypothesis is one-fourth as probable as the alternative," suggesting insufficient statistical power rather than absence of effect, providing justification for further verification.

Additionally, in studies that failed to observe inhibition in task-irrelevant effectors, this phenomenon may result from tasks being too simple or participants being over-trained, rendering effects too weak for traditional measures to detect. For instance, Xu et al. (2015) found that selective inhibition could be better accomplished with sufficient training, thereby reducing additional cognitive costs associated with inhibiting task-irrelevant effectors. This suggests that selective inhibition does not inherently weaken or eliminate global inhibition; rather, the efficiency of completing selective inhibition influences the manifestation of global inhibition.

Theoretical Comparison Between "Holistic View" and "Local View"

The global nature of inhibitory effects is not merely a phenomenological description but offers a new "holistic view" for understanding response control, challenging the traditional "local view." This holistic view captures the integrated and coordinated characteristics of the motor system, challenging the "local" and "isolated" perspectives of previous research. Furthermore, from the principle of Occam's razor, the holistic view offers theoretical parsimony (law of parsimony): the more untestable presuppositions a theory contains, the less scientific it becomes. Under the global inhibition framework, the entire motor system is inhibited, with only differential degrees of inhibition across motor neuron populations—assumptions that can be measured through neural signals without introducing additional hypothetical variables. This represents a "monistic" approach where computational simulation involves different values of a single variable. If we assume global inhibition sometimes exists and sometimes does not, with some effectors being inhibited and others not, new presuppositions are required to explain "which effectors need inhibition and which do not, which contexts require it and which do not." This represents a "pluralistic" approach involving multiple variables with multiple values, leading to excessive model degrees of freedom and reduced predictive power. Compared to "local view" theories, "holistic view" theories emphasize relationships among components within a system and how these relationships affect the entire system. However, from an applied perspective, designing application systems (such as the aforementioned inhibitory training protocols) requires full consideration of mutual influences and constraints among components, increasing design difficulty and complexity.

Summary and Outlook

In summary, response control involves not inhibition of a single effector but inhibitory processing of the entire motor system. Moreover, inhibitory effects are not exclusive to response conflict contexts but are broadly present in contexts involving response output and execution. This global and widespread nature is crucial for understanding response output. First, any response output, regardless of whether explicit response conflict exists, requires suppression of task-irrelevant responses or response tendencies from other effectors and control of the task-required effector to prevent premature responding. Second, from an evolutionary perspective, organisms have a tendency to respond to any external stimulus, with different effectors differentiating from a common motor system. During human evolution and development, mechanisms emerged for inhibiting responses and selectively inhibiting according to current contexts. Therefore, the global nature of inhibitory effects reflects at the cognitive level the coordinated interactions among components of the motor system, and at the neural level reflects computational processing efficiency, thereby ensuring efficient implementation of response output and execution for current tasks.

Although the global nature of inhibitory effects appears robust across different experimental contexts and multiple effectors, the relationships among inhibitory effects manifested by different effectors remain unclear. As noted earlier, evidence shows that inhibition of one effector (e.g., the right hand) is accompanied by inhibition of another neurally homologous effector (e.g., the right leg), and inhibition of one motor subsystem (e.g., the oculomotor system) is accompanied by inhibition of another subsystem (e.g., the somatomotor system). However, the relationships among these inhibitory effects await further investigation. From a cognitive perspective, one hypothesis suggests that the stronger the interference an effector poses to the task-required effector, the stronger its inhibition, with interference degree determined by current task demands. If the task only requires bimanual button presses without requiring other effectors, the interfering hand receives stronger inhibition than other effectors. From a neural perspective, another hypothesis proposes that the closer an effector's neural representation is to that of the task-required effector, the stronger its inhibition, enabling more efficient neural processing. In real-world contexts, cognitive and neural factors likely interact, awaiting future verification.

Existing research on global inhibition has focused on factorial experiments, revealing global inhibitory features by comparing inhibition strength across different levels of influencing factors (e.g., reward). While these factorial results provide qualitative evidence, they cannot specify the precise functional relationships among inhibitory effects across effectors. Future research should combine highly quantitative computational models to establish these functional relationships. Computational modeling can more accurately reflect how components of the motor system coordinate to improve response efficiency, offer high predictive power for inhibitory effects in novel contexts, and integrate inhibitory effects across different processing levels—revealing common principles across molecular-level GABA activity, cortical-level primary motor cortex activity, and behavioral-level inhibition efficiency based on reaction time and accuracy.

Currently, the normalization model best fits the various phenomena observed. As previously discussed, the normalization model aligns with the spotlight model, and research manipulating reward levels has produced results consistent with its predictions (Wang et al., 2021). The normalization model is a classic model in computational neuroscience that is not specific to particular cognitive components or experimental contexts (Salinas & Sejnowski, 2001; Carandini & Heeger, 2012) but is broadly evident in visual selective attention (Reynolds & Heeger, 2009), multisensory integration (Ohshiro et al., 2017), and value computation and representation (Louie et al., 2013). Investigating whether the normalization model serves as the computational mechanism for global inhibition can reveal common computational mechanisms across different cognitive processes.

Response control is closely related to multiple psychological and psychiatric disorders, and behavioral and neural markers of global inhibition can effectively predict symptom severity and relapse rates in these populations. Characterizing global inhibition in clinical populations can also enhance our overall understanding of motor system processing principles and efficiency. However, only a few addiction studies have examined global inhibition (Huang et al., 2017; Shen et al., 2017; Quoilin et al., 2018), with no research yet addressing other disorders such as OCD and ADHD. Future studies should increase investigations of clinical populations to construct more comprehensive, targeted, and predictive models by comparing inhibitory effects across different disorders. Additionally, traditional response inhibition-based training tasks show poor transfer across contexts and limited therapeutic efficacy (Bowley et al., 2013). The global inhibition perspective offers new insights for training and intervention: first, training design must consider potential impacts on multiple effectors rather than isolated effects on a single effector; second, tasks reflecting cognitive flexibility and response coordination should be used to improve inhibitory dysfunction, rather than focusing solely on response inhibition training for specific stimuli (e.g., addiction cues). Recent research has found bimanual drumming training effective for autism and dementia intervention (Miyazaki et al., 2020; Cahart et al., 2022), and advances in virtual reality and digital health can provide better conditions and application prospects for developing training protocols that reflect motor system flexibility, enhancing therapeutic efficacy.

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Note: Figure translations are in progress. See original paper for figures.