Cognitive Enhancement of Inhibitory Control and Working Memory Training for Aerial Combat Simulated Shooting

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Abstract

[Objective] To compare the improvement effects of inhibitory control training and working memory training on response inhibition performance in simulated shooting tasks and their underlying behavioral mechanisms. [Methods] A 2 (pre-test, post-test) X 3 (inhibitory control training group, working memory training group, control group) mixed design was adopted. Participants were required to complete data collection for simulated shooting tasks before and after 5 days of structured training. [Results] Compared to the control group, both training groups showed significant improvements in performance on the simulated tasks; however, the changes in the inhibitory control group were superior to those in the working memory group and guided participants to form more cautious behavioral decisions. [Limitations] The current simulation level is limited to a two-dimensional display, which remains distant from real-world scenarios, and the indicators are relatively singular, making it impossible to better quantify the sub-processes of behavioral decision-making changes. [Conclusion] Inhibitory control training, utilizing near-transfer as the path selection, yielded the best performance in this study.

Full Text

Preamble

Cognitive Enhancement of Inhibitory Control and Working Memory Training on Air Combat Simulated Shooting

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摘要

Abstract

Objective: This study aims to compare the effects of inhibitory control training and working memory training on enhancing response inhibition performance during simulated shooting tasks, while exploring the underlying behavioral mechanisms.

Methods: A 2 (Pre-test, Post-test) × 3 (Inhibitory Control Training Group, Working Memory Training Group, Control Group) mixed design was employed. Participants completed data collection for a simulated shooting task before and after a five-day structured training intervention.

Results: Compared to the control group, both training groups demonstrated significant improvements in performance on the simulated task. However, the inhibitory control group showed superior improvement compared to the working memory group and induced more cautious behavioral decision-making strategies among participants.

Limitations: The current simulation is limited to a two-dimensional display, which maintains a gap from real-world scenarios. Furthermore, the metrics used are relatively singular, which limits the ability to fully quantify the sub-processes involved in behavioral decision-making changes.

Conclusion: Inhibitory control training, utilizing a near-transfer pathway, yielded the best performance outcomes in this study.

关键词

Response Inhibition, Cognitive Training, and the Speed-Accuracy Trade-off

Classification Code: B849

Abstract

Response inhibition refers to the cognitive ability of an individual to consciously suppress dominant, automatic, or pre-potent responses according to task demands. As a core component of executive function, it is crucial for goal-directed behavior and emotional regulation. Recent research has increasingly focused on whether response inhibition can be improved through systematic cognitive training and whether such improvements can generalize to untrained tasks. However, the effectiveness of such training remains a subject of intense debate in the field of cognitive psychology. One critical factor often overlooked in these discussions is the Speed-Accuracy Trade-off (SAT). The SAT describes the fundamental relationship where participants can prioritize either speed or accuracy, often at the expense of the other. In the context of response inhibition training, changes in performance may reflect a genuine improvement in inhibitory capacity or merely a strategic shift in the participant' s decision-making threshold. This paper reviews the current state of response inhibition training research, analyzes the theoretical mechanisms of the SAT within inhibitory tasks, and discusses how modeling approaches—such as the Diffusion Model—can help disentangle capacity gains from strategic adjustments.

1. Introduction

Response inhibition is a fundamental cognitive process that allows individuals to adapt to changing environments by withholding inappropriate actions. Deficits in this ability are associated with various clinical conditions, including Attention-Deficit/Hyperactivity Disorder (ADHD), substance abuse, and impulse control disorders. Consequently, developing effective cognitive training protocols to enhance response inhibition has become a priority for both basic research and clinical application.

Traditional training paradigms, such as the Stop-Signal Task (SST) and the Go/No-Go task, have been widely used to measure and train inhibitory control. While some studies report significant training effects, others find that these improvements are task-specific and fail to transfer to broader cognitive domains. A major challenge in interpreting these results is the inherent flexibility of human performance. When participants undergo repeated training, they may learn to optimize their performance by adjusting their response strategies rather than by increasing their underlying neural efficiency or inhibitory capacity.

2. The Role of Speed-Accuracy Trade-off (SAT)

The Speed-Accuracy Trade-off is a ubiquitous phenomenon in cognitive tasks. In response inhibition paradigms, the SAT manifests as a tension between responding quickly to "Go" stimuli and maintaining a high success rate on "Stop" or "No-Go" trials.

If a participant

Cognitive Enhancement in Simulated Air Combat Shooting through Inhibitory Control and Working Memory Training

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Abstract

[Objective]This study compares the effectiveness of inhibitory control training versus working memory training on enhancing response inhibition performance in a simulated shooting task and investigates the underlying behavioral mechanisms. [Methods] A 2 (pre-test, post-test) × 3 (inhibitory control training group, working memory training group, control group) mixed design was employed. Participants completed a simulated shooting task before and after five structured training sessions. [Results] Compared to the control group, both training groups showed significant improvements in performance on the simulated task. However, the inhibitory control training group demonstrated greater improvements than the working memory training group, along with the development of more prudent behavioral decision-making.

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[Limitations]The simulation was presented in a two-dimensional format, which remains distant from real-world scenarios. Additionally, the metrics used were relatively limited, making it difficult to fully quantify the subprocesses underlying changes in behavioral decisionmaking. [Conclusions]Inhibitory control training, selected based on a neartransfer pathway, yielded the best performance in this study.

Keywords

Response inhibition Cognitive training Speed-Accuracy tradeoff

1 引言

Introduction

Tactical decision-making is often fraught with challenges, requiring soldiers to be capable of both rapid response and accurate inhibition—essentially achieving the discipline of “acting when ordered and refraining when forbidden.” Driven by technological innovation, modern aerial combat scenarios have been scaled down into the cockpit. The high degree of automation in aircraft operations and weapon systems has placed new demands on pilots based on “cognitive advantage” [?, ?, ?, ?, ?]. As a core component of executive function, response inhibition has become a central cognitive building block that determines “shoot/don’t-shoot” decision performance and even influences mission success and survival rates. For instance, the U.S. Army has deployed combat robots to the battlefield to replace soldiers, allowing personnel to determine whether to attack simply by pressing a button from the rear. While this reduces soldier casualties, it increases the risk of “friendly fire or civilian collateral damage.” Consequently, in the marksmanship training of soldiers (including pilots), the enhancement of response inhibition should be treated as a critical combat power multiplier on par with physical conditioning and equipment upgrades. In fact, a substantial body of research has demonstrated that cognitive enhancement training can improve response inhibition [?, ?, ?, ?, ?, ?, ?, ?, ?], thereby enhancing performance in "shoot/don' t-shoot" tasks.

Inhibition control, along with working memory updating and task switching, constitutes the three factors of executive function [?, ?]. Response inhibition and interference inhibition are both sub-components of inhibitory control. Response inhibition refers to an individual' s ability to control dominant or automated responses when faced with conflict or inappropriate stimuli [?, ?, ?]. Logan' s horse-race model [?, ?] likens this to a competition between "go" and "stop" processes; response inhibition is successfully achieved only when the "stop" process wins. Behaviorally, this internal competition manifests as a speed-accuracy tradeoff (SAT) [?, ?]. Specifically, while increased response readiness can accelerate reaction speed, it also heightens impulsivity, thereby complicating the inhibitory mechanism [?, ?, ?].

Therefore, the efficacy of any intervention aimed at improving response inhibition, such as cognitive training, likely lies in its ability to improve an individual' s tradeoff strategy [?, ?], which in turn influences the competitive landscape of the underlying "horse race."

There are currently two mainstream theoretical pathways for enhancing response inhibition through training. The first pathway is based on the principle of cognitive specificity, asserting that training effects are highly dependent on the similarity between the training task and the target task in terms of specific cognitive components and situational characteristics [?, ?]. To directly improve response inhibition performance in simulated shooting, the most effective approach would be training on tasks that are highly consistent with the cognitive processes of "ceasing fire," such as inhibitory control training (e.g., Go/No-Go or Stop-Signal tasks). By repeatedly practicing the inhibition of dominant responses in conflict situations, this type of training is believed to precisely strengthen target cognitive components, thereby achieving near-transfer of training effects to complex tasks. The second pathway is based on process overlap theory, which posits that training transfer occurs because the training and target tasks invoke overlapping general cognitive processes—such as information monitoring, updating, and conflict resolution—without requiring similarity in surface features [?, ?, ?]. According to this view, although working memory training (such as the n-back task) appears vastly different from shooting decisions on the surface, it can effectively strengthen general processes like working memory updating and cognitive control [?, ?]. These processes serve as the fundamental cognitive resources necessary for completing response inhibition tasks. Consequently, the effects of working memory training can indirectly transfer to response inhibition performance by strengthening this shared "process overlap" foundation, which is regarded as far-transfer.

However, most existing studies follow a single theoretical framework, exploring the effects of either inhibitory control training or working memory training in isolation. There is a lack of empirical research that systematically compares the relative effectiveness and underlying mechanisms of these two training pathways within the same high-ecological-validity complex task environment [?, ?, ?]. Such a comparison is crucial for identifying which theoretically guided training regimen is more suitable for military training applications.

Although cognitive training research generally indicates that near-transfer effects are typically superior to far-transfer effects [?, ?, ?, ?], which supports the potential advantage of inhibitory control training in the present study,

working memory training may still demonstrate unique value in complex, multitasking combat scenarios by strengthening shared neural processes related to cognitive control, conflict monitoring, and information updating [?, ?]. Therefore, this study utilizes a self-developed, high-ecological-validity simulated shooting task to examine the differences in effectiveness between different training pathways for improving response inhibition. By comparing the performance changes of inhibitory control training and working memory training groups against a control group, and employing a speed-accuracy tradeoff model, we explore the underlying behavioral mechanisms of these interventions.

2 方法

This study employs a 2×3 mixed experimental design, with Testing Time (Pretest vs. Post-test) as the within-subjects factor and Training Group (Inhibitory Control group, Working Memory group, and Control group) as the between-subjects factor. The primary behavioral metrics include reaction times and inhibitory accuracy during a simulated shooting task. These data will also be utilized to construct scatter plots illustrating the speed-accuracy tradeoff functions.

2.1 被试

The sample size was determined through an a priori power analysis using G*Power software (version 3.1). With the effect size set at $f = 0.25$, the significance level at $\alpha = 0.05$, and the statistical power at 0.80, the results indicated that a minimum of 42 participants was required for the training experiment.

Ultimately, 75 participants (25 females and 50 males) aged between 17 and 28 years ($M = 19.91, SD = 2.03$) were recruited to participate in the cognitive training. All participants were right-handed and had normal or corrected-to-normal vision. The experiment was approved by the Ethics Committee of the School of Psychology at Shaanxi Normal University.

2.2 程序与材料

All visual stimuli for the experiments were presented on a Lenovo monitor with a screen resolution of 1600×900. The simulated shooting task was developed using the Unity3D engine (version 2022.3.50f1). The Stop-Signal Task (SST), Go/No-Go (GNG) task, n-back task, and visual search task were all programmed and administered using E-Prime software (version 3.0.3.9). Statistical data analysis was conducted using SPSS (version 24.0) and JASP (version 0.95.4).

2.3 流程

All participants ($N = 75$) first completed a simulated shooting task. The code for this task is open-source and available at (https://osf.io/au3pd). The task procedure is illustrated in the figures. In the shooting task [Figure 1: see original paper], participants were required to complete a "search-lock-shoot" sequence, and their shooting reaction times were recorded. In the inhibitory shooting task [Figure 2: see original paper], participants were required to inhibit the shooting action and cancel the lock-on when a specific signal appeared; their inhibition accuracy was recorded. The task parameters were set as follows: the inter-stimulus interval was 3 seconds, shooting trials accounted for 75% of the total 100 trials, the stop-signal delay was 300 ms, and the decision window for both shooting and inhibition signals was 700 ms. Any response exceeding the decision window was recorded as a task failure.

During the decision window, pressing "S" while the target was identified resulted in a successful attack. The trial was marked as a failure if no response was made within the decision window or if the mouse was released before the required response. (See the online version for color figures).

After the signal delay, the "locking" indicator changed to a "locked" indicator. At this point, participants were required to refrain from pressing the "S" key to attack and instead release the mouse within the decision window; otherwise, the task was considered a failure. (See the online version for color figures).

Following the initial test, participants were randomly assigned to one of three groups to undergo different structured training programs for a period of five days. All tasks were graded by difficulty and dynamically adjusted based on participant performance; participants advanced to the next difficulty level once their accuracy at the current level reached 80%.

The inhibitory control group ($n = 25$) underwent intensive training targeting the cognitive components of response inhibition. The training protocol combined a Go/No-Go (GNG) task [Figure 3: see original paper] and a Stop-Signal Task (SST) [Figure 4: see original paper]. Participants trained for 40 minutes daily, completing a total of 320×4 (1280) trials, with inhibition trials accounting for 30%. The stop-signal delay (SSD) in the SST task was adjusted using a staircase procedure: within each difficulty level, the SSD remained fixed and gradually increased from 100 ms to 200 ms and 300 ms as the training levels progressed.

As training advanced, the response time windows for both GNG and SST were gradually shortened (1000 ms, 850 ms, and 700 ms) to increase time pressure.

In the GNG task, aircraft icons appeared randomly within a 3×3 grid to prevent attentional fatigue. Following a fixation point, an aircraft icon appeared, followed by a signal light on the periphery of the aircraft. Participants were instructed to press "S" upon seeing a green light and to withhold their response upon seeing a red light.

In the SST, an aircraft icon appeared after the fixation point, followed by a green signal light on the periphery. Participants were required to press the "S" key when the green light appeared. However, with a certain probability, the green light would change to red after a specific interval (SSD), at which point participants were required to cancel their response.

The working memory group ($n = 25$) aimed to indirectly enhance response inhibition by increasing working memory resources. The training utilized a dual-dimensional (color and orientation) n-back task [Figure 5: see original paper]. Participants trained for 40 minutes daily, completing 600×2 (1200) trials, with match trials accounting for 30% and each stimulus presented for 1000 ms. When a participant' s accuracy on the 2-back task reached 80%, they progressed to 3-back training.

The control group ($n = 25$) completed only 40 minutes of a visual search task daily [Figure 6: see original paper] to control for the placebo effect. Participants were required to press the corresponding key based on the position of an orange block: "q" if the orange block was in the top-four positions on the left, "z" for the bottom-left, "p" for the top-right, and "m" for the bottom-right.

3.1 基线水平同质性检验

One-way analysis of variance (ANOVA) revealed no significant differences among the three groups of participants in the simulated shooting task (shooting reaction time: $F(2, 72) = 1.33, p = 0.271, BF_{10} = 3.20 \times 10^{-1}$; inhibition accuracy: $F(2, 72) = 1.35, p = 0.703, BF_{10} = 1.50 \times 10^{-1}$). Furthermore, post-hoc comparisons using the LSD method for both dependent variables (shooting reaction time and inhibition accuracy) indicated that no pairwise comparisons reached statistical significance (all $p > 0.05$). Additionally, the 95% confidence intervals for all inter-group comparisons included zero, further confirming that there were no significant baseline differences between the groups prior to training.

3.2 训练效应

To investigate the impact of different training methods on the improvement of response inhibition capacity, this study employed multivariate analysis of variance (MANOVA) and Bayesian analysis of variance. Shooting reaction time and inhibition accuracy from the pre-test data were used as covariates, with group assignment as the fixed factor. The differences in shooting reaction time and inhibition accuracy served as the dependent variables for the analysis.

The results revealed a significant main effect of group on the overall change in behavioral performance (Wilks' $\Lambda = 0.34$, $F(4, 138) = 24.59$, $p < .001$, partial $\eta^2 = 0.416$). Regarding shooting reaction time, a significant main effect of group was observed ($F(2, 70) = 14.58$, $p < .001$, partial $\eta^2 = 0.294$, $BF_{10} = 2.50 \times 10^2$). Similarly, significant effects were found for inhibition accuracy ($F(2, 70) = 54.55$, $p < .001$, partial $\eta^2 = 0.609$, $BF_{10} = 9.09 \times 10^8$).

Post-hoc analysis indicated significant differences between the inhibitory control group and the control group in both reaction time ($p < .001$, $d = 1.30$, $BF_{10} = 5.92 \times 10^2$) and accuracy ($p < .001$, $d = 2.364$, $BF_{10} = 1.46 \times 10^7$). The working memory group also differed significantly from the control group in reaction time ($p = .002$, $d = 0.66$, $BF_{10} = 3.72 \times 10^0$) and accuracy ($p < .001$, $d = 1.70$, $BF_{10} = 2.35 \times 10^4$). Furthermore, the differences between the inhibitory control group and the working memory group reached statistical significance for both reaction time ($p = .030$, $d = 0.64$, $BF_{10} = 1.61 \times 10^0$) and accuracy ($p = .029$, $d = 0.66$, $BF_{10} = 4.82 \times 10^0$), reflecting distinct outcomes between the two interventions. Additionally, descriptive statistics showed that the mean improvement in accuracy for the inhibitory control group ($\Delta = 0.361$) was 10.7% higher than that of the working memory group ($\Delta = 0.254$), representing a relative increase of 42.09% (using the working memory group as the baseline).

These results demonstrate that both training modalities are effective and can transfer to simulated tasks, with inhibitory control training yielding more prominent effects.

3.3 反应抑制行为机制

The results described above indicate that the training was effective; however, the underlying behavioral mechanisms remain unclear. To further elucidate how training influences decision-making strategies, we analyzed changes in the speed-accuracy tradeoff. Using the mean and standard deviation of shooting reaction times and inhibition accuracy from all 75 participants in the pre-test as a baseline, we calculated Z-scores for each participant' s pre- and post-test data. Scatter plots for the three groups across pre- and post-tests were generated, with reaction time Z-scores on the vertical axis and inhibition accuracy Z-scores on the horizontal axis, as shown in [Figure 7: see original paper] and [Figure 8: see original paper].

As illustrated in the figures, the data points for the three groups during the pre-test are dispersedly distributed across all four quadrants, reflecting the diverse strategies individuals employ regarding the speed-accuracy tradeoff at baseline. Following cognitive training, the post-test data points for both the inhibitory control group and the working memory group shifted significantly toward the first quadrant. This quadrant corresponds to higher inhibition accuracy Z-scores and longer reaction time Z-scores. These findings suggest that, in shooting scenarios requiring the immediate cancellation of automated responses, trained individuals actively reduce their response speed to secure a sufficient time window for monitoring and inhibiting inappropriate shooting impulses.

To further examine the differences between the two training modalities in shaping behavioral patterns, we calculated the Euclidean distance from each data point to its respective group mean in the post-test and compared their coefficients of variation (CV). The results showed that the mean intra-group Euclidean distance for the inhibitory control group was 0.74 with a coefficient of variation of $CV = 0.47$, which was smaller than the mean intra-group Euclidean distance of 0.94 and coefficient of variation of $CV = 0.53$ observed in the working memory group. This suggests a higher degree of behavioral consistency within the inhibitory control group. However, independent samples t-tests and Bayesian t-tests revealed that the difference in mean Euclidean distances between the two groups did not reach statistical significance ($p = .313, d = 0.29, BF_{10} = 8.64 \times 10^{-1}$), indicating that further investigation with a larger sample size is required to confirm this difference in consistency.

4 讨论

This study aims to compare the effectiveness of two cognitive training modalities—inhibitory control and working memory—in enhancing response inhibition performance during simulated shooting tasks, while exploring their underlying behavioral mechanisms. The results indicate that, compared to a control group that performed only visual search tasks, participants who received either inhibitory control training or working memory training demonstrated significant improvements in inhibition accuracy during shooting decisions. Notably, the improvement in the inhibitory control training group was more pronounced, with an enhancement in shooting inhibition accuracy that was 42% higher than that of the working memory group. These findings provide preliminary empirical evidence for developing military cognitive training programs aimed at technology-driven troop preparation. Furthermore, they confirm that laboratory-based cognitive training possesses significant transfer potential for application in complex, real-world task scenarios.

4.1 抑制控制训练通过近迁移强化了反应抑制的行为机制

The inhibitory control group demonstrated a significant improvement in inhibition accuracy during the post-test, accompanied by a notable prolongation of shooting reaction times. This behavioral pattern reflects a strategic adjustment in the speed-accuracy tradeoff (SAT) [?, ?, ?]. According to the "horse race model" proposed by Logan and Cowan (1984), response inhibition is not a singular "stop" process, but rather a dynamic competition between "go" and "stop" processes. Consequently, the extension of reaction time following training can be understood as the individual raising their decision threshold for response execution, thereby gaining a temporal advantage for the inhibitory process.

From an applied perspective, this strategic shift toward "high accuracy at a moderate cost of speed" holds substantial practical value. In high-risk decision-making environments, such as aviation safety and military operations, the cost of failing to inhibit an erroneous action—such as friendly fire—is typically far higher than the cost of a decision delay [?, ?]. Therefore, guiding pilots toward a more deliberate decision-making style through inhibitory control training may represent an effective cognitive enhancement pathway.

It is noteworthy that the stop-signal task employed in inhibitory control training and the "inhibited shooting trials" in simulated shooting tasks are highly consistent in their core cognitive process of "stopping a pre-initiated response." Thus, the performance advantage observed in the inhibitory control group may partially stem from near-transfer or practice effects resulting from this task similarity [?, ?]. The successful transfer of training effects, based on the principle of cognitive specificity, to a simulated task with higher ecological validity further demonstrates the directness and efficacy of this approach in enhancing response inhibition capabilities within specific contexts.

4.2 工作记忆训练通过远迁移泛化影响了反应抑制的行为机制

The working memory group also demonstrated a significant improvement in inhibition accuracy, suggesting that n-back training can indirectly enhance response inhibition performance by strengthening working memory updating and information monitoring capabilities (Dahlin et al., 2008; Szmalec et al., 2011). Scatter plots revealed that the post-test data points for this group also shifted toward the first quadrant, indicating that working memory training similarly prompted individuals to adopt a more cautious "speed-accuracy tradeoff" decision-making strategy. However, the pattern of behavioral change differed from that of the inhibition control group. On one hand, both the magnitude of accuracy improvement and the extent of reaction time prolongation in the working memory group were smaller than those in the inhibition control group, with these differences reaching statistical significance. On the other hand, descriptive statistics

indicated that the intra-group coefficient of variation for the working memory group was slightly higher than that of the inhibition control group. This suggests greater individual variability in behavioral patterns within the working memory group, although the difference in Euclidean distance between the two groups did not reach statistical significance. This discrepancy may reflect differences in the underlying mechanisms of the two training pathways: inhibition control training likely directly reinforces the core cognitive components of response inhibition, leading to a highly consistent "slow but accurate" pattern among group members. In contrast, working memory training may produce a more generalized transfer effect by enhancing general cognitive resources, the manifestation of which may vary more widely depending on an individual' s baseline cognitive capacity. Process Overlap Theory (Dahlin et al., 2008) provides an explanatory framework for this far-transfer effect, suggesting that working memory training may strengthen shared neural circuits associated with cognitive control, such as the frontoparietal network, thereby generalizing to response inhibition tasks that also require cognitive control involvement. In complex tasks requiring sustained situational awareness, frequent task switching, or the processing of multiple information streams, this generalized enhancement of cognitive resources may hold greater ecological value.

4.3 创新与局限

This study simultaneously compares the differences between near-transfer and far-transfer training in enhancing complex shooting decision-making performance. By employing a highly ecological simulated shooting task as a benchmark for evaluating transfer effects [?, ?, ?, ?, ?], this research provides a methodological template for related studies. Furthermore, the findings offer empirical evidence for the development of military cognitive training curricula. This research also incorporates prospective ergonomic design philosophies—specifically, optimizing design and cognitive empowerment [?, ?, ?, ?]—to enhance operator capabilities as a means of mitigating the inherent risks of complex human-machine systems.

However, several limitations of this study must be acknowledged. Although the ecological validity of the simulated task far exceeds that of simple laboratory tasks, its complexity still does not fully match that of real-world operational environments. Additionally, relying solely on behavioral metrics such as reaction time and accuracy makes it difficult to strictly distinguish changes in the underlying cognitive processes. While current speed-accuracy analyses can indicate overall shifts in strategy, they cannot precisely quantify the independent contributions of these specific subprocesses.

5 结论

This study compared the differences in performance enhancement between inhibitory control training and working memory training within a simulated shooting task. The results indicate that both types of cognitive training significantly improve inhibitory shooting performance and demonstrate successful transfer to dynamic, complex simulated tasks. However, inhibitory control training proved more effective, outperforming working memory training by 10 percentage points.

Furthermore, this research validated the behavioral mechanisms underlying response inhibition; specifically, the key to successful inhibition may lie in increasing the decision threshold to gain sufficient time for monitoring and responding to inhibitory signals. Future research should involve long-term tracking of professional populations within more authentic combat environments to verify the ecological validity and durability of these findings.

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