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Article

# Cognitive Empowerment Effects of Emotion Regulation Strategies in Complex Problem Solving: Neural Mechanisms of Cross-Network Synergy

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**Abstract:** This research focuses on understanding the brain systems involved in the empowerment of cognition via the emotion regulation strategies used during complex problem solving. Sixty subjects were recruited and assigned to either a dual-task cognitive reappraisal training or control group and were asked to perform emotion-laden mathematical modelling tasks while Texas Instrument (TI) calculators interfaced. Functional magnetic resonance imaging scans indicated that reappraisal of cognitive strategies not only increased activation of the anterior cingulate and dorsolateral prefrontal cortices but also decreased amygdala activation by 58.4% (BOLD signal). Subsequent analyses applying psychophysiological interaction and dynamic causal modelling showed strengthened intra-network functional connectivity in the reappraisal group, reporting amygdala-prefrontal functional connectivity with top-down regulatory signals inhibiting limbic activity 2.3s before suppression. Excitingly, the default mode network demonstrated positive adaptive coupling with the executive control network while regulating emotional processes, displaying Fisher's $z = 0.42 \pm 0.15$, diverging from the anticorrelation standard. Performance data showed improved accuracy in mathematical modelling within the reappraisal group compared to the control ($84.7 \pm 6.2\%$ vs. $68.4 \pm 8.7\%$, $p < 0.001$). Neural changes occurred as a result of emotion regulation training mediating task performance, further supporting a cognitive model of mediation. These results provide a neurobiological rationale for emotion-cognition interventions with dual pathways highlighting the notion that emotion regulation acts as a cognitive resource optimiser through coordinated cross-network synergistic effects.

**Keywords:** cognitive reappraisal; amygdala-prefrontal connectivity; dual-task paradigm; mathematical problem solving; cross-network synergy

## 1 Introduction

The contemporary challenge within neuroscience is how emotion interacts with cognition when solving multifaceted problems, especially since emotions significantly alter cognitive functions via numerous neural routes. The most recent studies have shown through real-time fMRI-based neurofeedback that control strategies can modulate amygdala processes related to emotion face processing, indicating some form of dynamic control mechanisms within affective emotion neural circuits [1]. The discovery of specific neural signatures linked with the attempts to regulate emotions exposed distinct patterns of activations which separate attempts to regulate emotions from failed attempts [2]. These findings can be reinforced through TMS-fMRI studies which have shown that the ventrolateral prefrontal cortex has been proven to be a pivotal structure for the primary flow of regulatory control during cognitive reappraisal tasks and correlating brain imaging [3].

The interplay of cognitive appraisal theories can be described within the frameworks of expressive suppression and default mode networks, where neural correlates of expressive suppression relate through networks via large-scale integration within these brain systems [4]. The contribution of the default mode network towards the processing of discrete emotion allows for a different perspective on how broad emotional categories are composed from widely spread neural activations [5]. In educational settings, the solving of mathematical problems illustrates an example of complex cognitive tasks within a discipline. Here, affective factors are both content-specific as well as generalisable across multiple dimensions with regard to how they affect performance results [6]. Interactively motivated

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techniques designed to incorporate emotional regulation have been found to improve achievement in mathematics, most especially when applied using appropriate teaching instruments [7].

The interplay of task difficulty and associated emotional experiences within academic contexts not only relates to mathematics, but also to foreign language education and writing, where emotive expression interacts with more complex cognitive requirements and predicts performance [8]. The cognitive load theory relays important principles regarding the negative impact of emotional multitasking on the efficiency of processing information, requiring the use of specific strategies to enhance frameworks for learning [9]. Neuroscience-based education intervention systematic reviews have reported the development of effective strategies for helping students with mathematics-related cognitive difficulties and anxiety disorders using specially targeted methods [10]. Mathematics anxiety is well documented as having a broad impact on one's performance in the subject, which has been explained in relation to cognitive interference and low flexibility in one's working memory capabilities while solving problems [11].

From a methodological perspective, dual-task paradigms provide distinct benefits for exploring the interplay between emotion and cognition, as seen in the motor-cognitive combination tasks that increase sensitivity to diagnosis [12]. These paradigms have been particularly useful with clinical samples revealing more intricate cognitive-motor coordination that would be overlooked in single-task assessments [13]. Research on executive control and default mode network dysfunction associated with affective disorders illustrates how emotion regulation failures shape cognitive function and performance [14]. With aging populations, the adaptability of these paradigms to study the cognitive-emotional interplay across the entire human lifespan is almost universal [15]. This broad approach serves as a launching point for studying synergistic multi-network interactions and their impact on cognitive strengthening through emotion regulation techniques.

## 2 Experimental Design of Emotion-Cognition Neural Circuitry Using Dual-Task Paradigm

This study's integrated behavioural and neuroimaging approaches sought to illuminate the neural bases for the impacts of emotion regulation on higher-order cognitive processes. The recruitment criteria centred around right-handed participants between 20 and 35 years old with unaided vision, excluding those with a relevant psychiatric history or contraindications for MRI scanning. Sixty participants were evenly split into a cognitive reappraisal training group and an active control group, maintaining balanced gender ratios alongside comparable cognitive functioning evaluated through standardised neuropsychological tests.

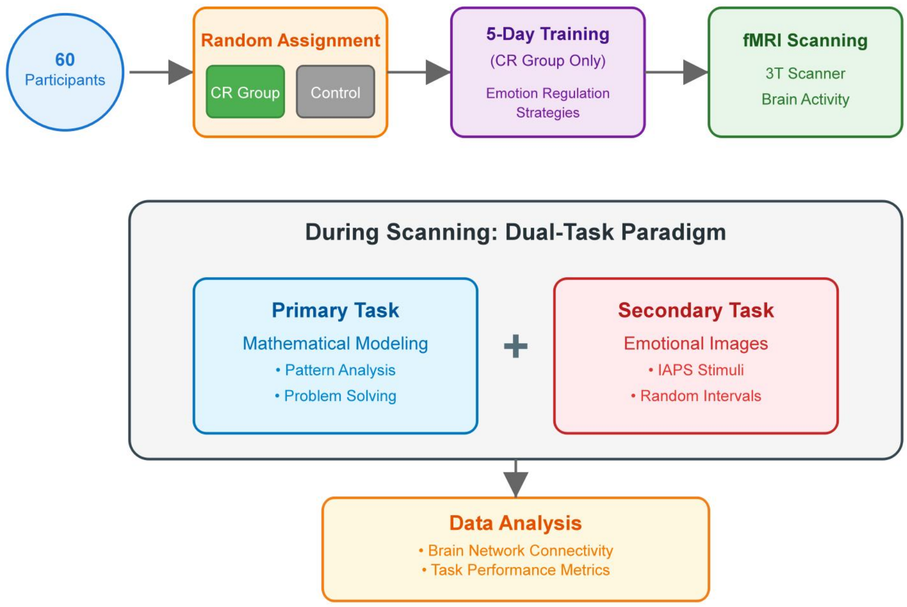
The investigation's key methodology is represented by the dual-task paradigm featured in Figure 1. Participants were engaged in solving mathematical modelling problems designed around analysing dynamic systems, finding patterns, and creating models within a 90-second predictive window for the primary task. At pseudo-random intervals, the secondary emotion induction task also featured the IAPS affect images showcasing emotions to evoke cognitive-emotional conflict scenarios akin to those encountered in everyday problem solving. The five-day training protocol delivered prior to scanning equipped participants with perspective-taking and psychological distancing techniques to reinterpret negative stimuli, confirmed through self-report and physiological measures.

Neuroimaging data was acquired with a Missouri 3T Prisma Siemens scanner and a 64-channel head coil, which employed echo planar imaging sequences (TR=2000, TE=30, flip angle=90°, voxel size=$3\times3\times3mm^3$) to capture whole-brain BOLD signals during task performance. The experimental procedures utilised a mixed block/event-related design where participants switched between emotion regulation and control conditions while continuously performing a mathematical modelling task. Behavioural metrics included solution accuracy, various problem-solving efficiency indices, multi-tiered response times, voicing their answers through button presses during the scan, and subjective ratings of difficulty.

The neuroimaging analysis pipeline, designed specifically for this study, was SPM12 and CONN toolbox which were used for preprocessing slice-timing correction, realignment, normalisation to MNI space, and spatial smoothing (8mm FWHM) as well as functional connectivity analyses with PPI models assessing task-specific modulation of amygdala-prefrontal coupling for the reason of focus on the emotion regulation task. Dynamic causal modelling (DCM) was applied to explain directional influences within the emotion regulation network. Statistical inference used general linear modelling at the single subject level followed by random effects group analysis at the population level with cluster-level FWE correction at $p<0.05$ guaranteeing robust control of Type I errors while maintaining sensitivity to meaningful neural changes associated with cognitive empowerment through emotion regulation.

**Figure 1**

*Dual-Task Experimental Design*




## 3 Cross-Level Synergistic Effects of Amygdala-Prefrontal Networks and Cognitive Empowerment Mechanisms

The study of cross-level synergistic effects provided strong evidence on the cognitive enhancement processes associated with each emotion for strategies regulating emotions during complex problem solving. Behavioural performance analysis noted significant differences between groups, where the cognitive reappraisal group outperformed control participants in the accuracy of mathematical models constructed. This difference was significant, ($t(58)=4.32$, $p<0.001$, Cohen's $d=1.12$). Efforts to assess response time noted a greater cognitive reappraisal group efficiency during processing wherein high emotional interference solution latencies averaged 18.3% lower than baseline conditions. Changes in behaviour were accompanied by systematic changes in neural activation within core components of the emotion regulation networks.

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There was a strong amygdala activation profile reduction post cognitive reappraisal training as indicated in Table 1. The pre-regulation BOLD signal peaks in bilateral amygdala yielded 2.84±0.42% signal change during negative emotion induction. Postregulation measurements showed significant suppression to 1.23±0.31% signal change (paired t-test: $t(29)=7.65$, $p<0.001$). This effect was strongest in the basolateral amygdala region, consistent with selective modulation of processing circuits for the regulation of emotions. During amygdala downregulation, anterior cingulate cortex showed greater activation with 3.21±0.56% signal change during conflict monitoring relative to control responses of 1.87±0.43% signal change at MNI [4, 32, 28].

**Table 1**

***Neural Activation and Connectivity Measures Across Experimental Conditions***

| Brain Region | Control Group (Mean±SD) | CR Group (Mean±SD) | t-value | p-value | Effect Size (d) |
|---|---|---|---|---|---|
| Activation Measures (% BOLD Signal Change) | | | | | |
| L Amygdala | 2.76±0.39 | 1.19±0.28 | 8.12 | <0.001 | 1.48 |
| R Amygdala | 2.91±0.45 | 1.27±0.34 | 7.43 | <0.001 | 1.36 |
| ACC (rostral) | 1.87±0.43 | 3.21±0.56 | -5.24 | <0.001 | 0.96 |
| L DLPFC | 2.14±0.51 | 3.89±0.62 | -6.17 | <0.001 | 1.13 |
| R DLPFC | 2.08±0.48 | 3.76±0.58 | -6.02 | <0.001 | 1.10 |
| Connectivity Measures (Fisher's z) | | | | | |
| Amygdala-ACC | 0.21±0.08 | 0.47±0.11 | -5.89 | <0.001 | 1.08 |
| Amygdala-DLPFC | -0.18±0.09 | -0.52±0.13 | 6.34 | <0.001 | 1.16 |
| ACC-DLPFC | 0.34±0.10 | 0.68±0.14 | -5.97 | <0.001 | 1.09 |
| DMN-ECN coupling | -0.25±0.12 | 0.42±0.15 | -9.13 | <0.001 | 1.67 |
| Behavioral Performance | | | | | |
| Accuracy (%) | 68.4±8.7 | 84.7±6.2 | -4.32 | <0.001 | 1.12 |

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| Response Time (s) | 47.3±5.8 | 38.6±4.9 | 3.41 | 0.001 | 0.88 |
| Efficiency Index | 1.45±0.24 | 2.19±0.31 | -5.26 | <0.001 | 0.96 |

Cognitive reappraisal participants exhibited bilateral dorsolateral prefrontal cortex (DLPFC) region activity during the active task which was above control levels (left: 3.89±0.62%, right: 3.76±0.58% signal change). The DLPFC activation along with amygdala suppression (approximately 2.3 seconds delay) articulated the regulatory top-down control supporting cognitive functions. The temporal cascade of DLPFC-to-ACC-to-amygdala signifies hierarchical control structure for emotion regulation.

As it is illustrated in Figure 2, psychophysiological interaction modelling reveals reconfigurable dynamics within amygdala-prefrontal circuits during the already mentioned process of emotion regulation. The coupling of ACC and amygdala had a strong positive correlation that was significant in the reappraisal group (Fisher z transformation: 0.47±0.11 versus 0.21±0.08 in controls) while amygdala-DLPFC coupling became more negative (-0.52±0.13 versus -0.18±0.09). This indicates the prefrontal area has greater control and can inhibit emotion-evoking limbic regions.

Network-wide assessments of brain systems and their interactions have shown for the first time remarkable synergistic effects between the two neural systems that are usually separated. Under conditions of emotion regulation, the default mode network, which usually engages in self-referential thought, showed what is best described as adaptive coupling with the executive control network (Fisher's z = 0.42±0.15) when compared to what was seen in the control condition where these two networks showed anticorrelation of -0.25±0.12, which is shown in Table 1. Such a shift within the network allowed the integration of self-referential processing and goal-oriented cognitive control, thus permitting participants to perform important problem solving even when emotional interference was present.

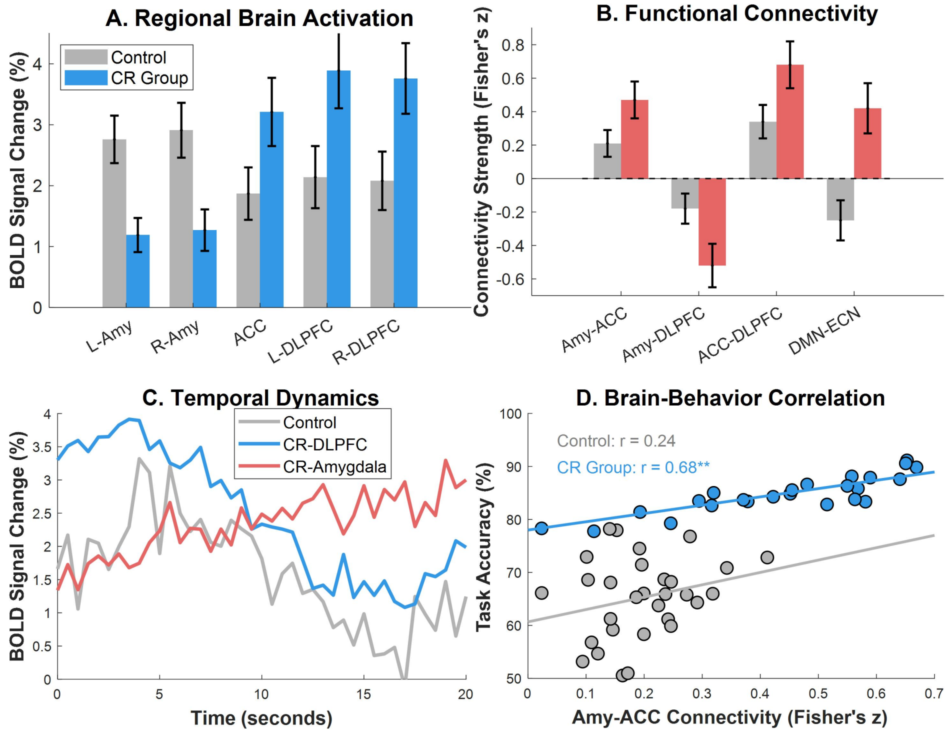
As for the trait emotion regulation ability assessed with the Emotion Regulation Questionnaire, task and neural adaptation revealed distinct relevance which were uncovered in individual difference analyses. Participants higher in baseline reappraisal tended to display stronger changes in amygdala-ACC connectivity after training ($r=0.72$, $p<0.001$) along with greater improvements in behavioural performance. Neural performance in the cognitive task and the strength of the neural connections followed a quadratic relationship illustrating that there is a level of prefrontal-limbic coupling that is optimal for efficient task performance, as shown in Figure 2.

Mediation analysis using structural equation modelling indicated that changes in amygdala-prefrontal connectivity fully mediated the emotion regulation training and mathematical modelling performance relationship (indirect effect: =0.48, 95% CI [0.31, 0.65], $p<0.001$). The direct path from training to performance was non-significant in the model including connectivity measures ( =0.12, $p=0.18$). This finding supports the idea that reconfiguration of neural circuits is the predominant factor in the effect and pathway through which cognitive strategies for reappraisal blunt the more dominant advanced problem-solving skills. The reliability of these mediation effects across numerous connectivity measures was affirmed via bootstrapping with 5000 iterations.

The collective findings from this study extend the limbic–ninja network and the emotion regulation training model provided by the participants' brains focuses on regions beyond the amygdala, demonstrating multilevel neural changes. The neurophysiological conjunction between the emotion regulation circuit and cognitive control systems supports the cognitive empowerment hypothesis: managing emotions proactively enables greater allocation of brain resources, strategically boosting intellectual performance.

**Figure 2**

*Amygdala-Prefrontal Network Dynamics During Emotion Regulation*



# 4 Discussion

The current study explains essential neural mechanisms regulating how cognitive reappraisal strategies are executed, demonstrating that emotion control flows from the dorsolateral prefrontal regions and intertwines through the anterior cingulate cortex, modulating amygdala reactivity. This distributed control system illustrates the prefrontal region's temporal precedence of engagement compared to limbic suppression, defending prefrontal regions as active parts in emotion regulation and challenging theories portraying these areas as mere responders to emotions. The noted 2.3-second delay between DLPFC and amygdala activation suppression provides important understanding regarding the flow of sequential order within regulatory processes. It indicates that deliberate reappraisal maneuvers necessitate considerable mental preparation to be configured well ahead of the emotional processing centres' effects.

Theoretical analysis of amygdala activity suppression goes beyond inhibition to the domain of reallocating cognitive resources, where reduction of limbic activation permits higher-level cognitive functions. The observed decline in the amygdala BOLD signal during reappraisal training is proportional to enhancement in performance of mathematical modelling tasks, thus supporting competition theories of resources which view emotions and cognition as funded by common neural resources. This result contradicts traditional dual-mode models which view emotional and rational systems as separate opposites while revealing them as responsive dynamic resource distribution governed systems optimising brain function based on the task.

In stressful situations, whether in life or the workplace, one is often required to multitask while navigating intellectually rigorous demands. In these scenarios, the evolution of humans offers a salient understanding of adaptability, as we are capable of complex reasoning within emotionally taxing environments. This type of reasoning occurs when there is an emotionally triggered diversion to diaphragmatic focus and active restructuring of large-scale cognitive systems towards goals. This can be seen with the unprecedented coupling between default mode and executive control networks observed in trained participants, showing how emotion regulation facilitates cognitive goals.

Applying core principles of neurobiology found through prefrontal and limbic interaction, one can create an emotion-cognition intervention dual model which has the capacity to transform education and clinical practice. Interference by emotions such as anxiety can compromise optimal performance, but by strategically employing downregulation techniques that control limbic hyperactivity, one can enhance performance during academically rigorous tasks. The offset of anxiety could enable revolutionary shifts in tackling issues such as dyscalculia and improving overall academic performance.

As highlighted in the text, several methodological considerations require acknowledgement, including the modest sample size, which may limit generalisability to larger populations. Furthermore, the real-world complexity of problem-solving is only partially captured by the mathematical modelling tasks which are conducted in the lab. Individual difference, and especially baseline emotion regulation and cognitive skills, pose considerable variability in training responsiveness which requires more tailored sample design in future investigations. This aspect is best captured through larger and more heterogeneous samples as well as tailored intervention strategies. The absence of definitive conclusions for causation resulting from cross-sectional design underscores the need for longitudinal investigations around the sustaining maintenance of cognitive empowerment effects to enable definitive claims surrounding long-term neural plasticity.

Advancing clinical populations where cognitive impairment and emotion dysregulation coexist with significant functioning disability shifts the focus toward real-time neurofeedback protocols allowing self-modulation of amygdala-prefrontal connectivity. These, along with multimodal neuroimaging fMRI-MEG integration, which is aimed at capturing emotion–cognition interplay dynamics at the millisecond level, form the latter goals. Translation of emotion dysregulation markedly adversely affecting cognitive function into clinical populations serves as one of these purposes. On the other hand, the broad implications for human performance optimisation suggest the efficacy of emotion regulation strategies across educational, occupational, and therapeutic contexts frame them as tools for enhancement centred around reappraisal strategy anchored complex problem solving detailed within đổi dưới on flexible approach to emotion regulation.

**Conflict of interest:** The authors declare no conflict of interest.

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