Growth Mindset Influences Behavioral and Neural Response Patterns in Learning: A Self-Regulated Learning Theory Perspective

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Abstract

Growth mindset refers to individuals' beliefs in the malleability and enhancement of their own attributes. In recent years, fostering growth mindset among adolescents has become a prominent topic in education. However, whether growth mindset regarding intelligence and related interventions can enhance academic performance remains controversial, and future research urgently requires transformation and breakthroughs in research perspectives, paradigms, and metrics. Grounded in self-regulated learning theory, this study addresses the question of whether growth mindset influences the learning process, adopting a self-regulated learning paradigm within a metacognitive framework to reveal the behavioral and neural response patterns through which growth mindset affects the learning process in feedback-learning contexts via behavioral experiments, event-related potentials, and functional magnetic resonance imaging experiments, thereby attempting to advance research on this topic from persistent controversy toward gradual clarification and to provide practical foundations for the precise cultivation of growth mindset among adolescents.

Full Text

The Behavioral and Neural Response Patterns of Growth Mindset Affecting the Learning Process: A Perspective from Self-Regulated Learning Theory

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Abstract: Growth mindset refers to an individual's belief that personal attributes such as intelligence are malleable and can be improved. In recent years, cultivating a growth mindset among adolescents has become a prominent educational priority. However, whether growth mindset and related interventions can genuinely promote academic performance remains controversial, and future research urgently requires transformation and breakthrough in perspectives, paradigms, and measurement indicators. Grounded in self-regulated learning theory, this study addresses the question of whether growth mindset influences the learning process by employing a metacognitive framework of self-regulated learning paradigms. Through behavioral experiments, event-related potential (ERP), and functional magnetic resonance imaging (fMRI) techniques, we reveal the behavioral and neural response patterns through which growth mindset affects the learning process in feedback-based learning contexts. This work attempts to shift the research trajectory from persistent controversy toward gradual clarification and provide a practical foundation for the precise cultivation of growth mindset in adolescents.

Keywords: growth mindset, self-regulated learning, metacognitive monitoring, feedback, neural response patterns

1 Research Significance

Growth mindset refers to an individual's belief that personal attributes such as intelligence and personality are malleable and can be improved [?]. Since this concept was introduced, numerous researchers have investigated the relationship between growth mindset and adolescents' academic, psychological, and social adaptation from various perspectives. The Programme for International Student Assessment (PISA) has incorporated growth mindset as a key indicator for predicting adolescents' academic achievement and social adaptation. Cultivating growth mindset in adolescents is regarded as a transformative change in reshaping the educational ecosystem [?] and has extended into educational policy discussions [?]. Two large-scale cohort studies published in *Nature* found that growth mindset interventions promote adolescents' academic achievement and stress reduction [?, ?].

However, multiple meta-analyses have found that the effect of growth mindset interventions on academic achievement is minimal [?, ?, ?, ?]. Evaluating the true effectiveness of growth mindset and its interventions on adolescents' academic performance has become a critical issue and an international frontier topic that urgently requires further investigation. Existing research has overemphasized evaluating the promoting effects of growth mindset and interventions based on academic achievement or outcomes, while neglecting the learning process itself. This approach obscures valuable assessment information and represents a key source of current controversies [?, ?]. Future research urgently needs to transform and break through in research perspectives, paradigms, and indicators.

In light of this, the present study is grounded in self-regulated learning theory and utilizes cognitive neuroscience methods to investigate the influence of growth mindset and interventions on adolescents' self-regulated learning processes and the underlying neural plasticity mechanisms from three dimensions: behavioral performance, neural activity, and brain plasticity. The core innovations are: (1) highlighting the process-oriented nature of learning [?] by reflecting the effects of growth mindset and interventions on various aspects of the learning process; (2) based on self-regulated learning theory [?], employing learning process paradigms to characterize the influence of growth mindset on learning processes from a metacognitive level, thereby overcoming the content and methodological limitations of previous research based on motivational social-cognitive theory; and (3) constructing and integrating behavioral indicators, neural activity indicators, and brain plasticity indicators of growth mindset's influence on learning processes to provide multi-angle assessment tools for scientifically evaluating growth mindset and intervention effects, thereby compensating for assessment biases caused by single-outcome indicators.

2.1 The Meaning and Measurement of Growth Mindset

"Mindsets" originally derived from implicit theories [?] and was later renamed as "mindset" [?]. In recent years, Chinese scholars have tended to use "thinking patterns" as an alternative translation [?, ?, ?]. Dweck [?] defined individuals' tendency to view personal attributes as malleable or fixed as "mindsets," which are classified into growth mindset and fixed mindset. Grounded in classic educational psychology theories such as achievement goals and attribution of success and failure, the connotation and extension of mindsets have been continuously enriched. At the connotative level, growth mindset refers to an individual's belief that personal attributes can be shaped and improved through effort, serving as the source of autonomous growth. At the extensional level, growth mindset can manifest in various domains including intelligence [?], personality [?], interpersonal relationships [?], race [?], emotion [?], and creativity [?, ?]. This study primarily focuses on growth mindset regarding intelligence.

Mindset not only represents a trait difference [?] but can also be manipulated and intervened upon through experimental means [?]. Researchers commonly use the Implicit Theories of Intelligence Scale to assess individuals' trait-like mindset types, including 8-item [?], 3-item [?], and 20-item versions [?]. At the intervention level, there are two main approaches: laboratory priming (such as using quotes from famous people or story texts [?]) and educational context interventions (such as brain plasticity courses and mindset training strategies [?]).

2.2 Research Progress on the Relationship Between Growth Mindset and Academic Performance

Motivational social-cognitive theory posits that mindsets create a motivational interpretive framework that influences individuals' goal orientation, cognitive performance, and behavioral patterns [?]. For instance, achievement goal orientation, as a core component of the motivational system, has been found to be influenced by individuals' mindsets [?, ?]. Individuals with a fixed mindset believe that ability is innate and unchangeable, tending to pursue performance goals by seeking evidence to prove their ability and avoiding failure that might negate their competence. In contrast, individuals with a growth mindset believe that ability is malleable and can be developed through effort, tending to pursue mastery goals, embracing challenges without fear of failure, and investing more effort to master knowledge and improve ability [?, ?].

In recent years, the relationship between mindsets and academic performance has gradually become a research hotspot. A series of studies have found that mindsets influence academic achievement by affecting intrinsic motivational systems such as learning goals, self-efficacy, attitudes toward setbacks, and attribution styles [?, ?, ?]. Additionally, the relationship between growth mindset and academic achievement is moderated by several variables [?, ?]. The promoting effect of growth mindset on academic achievement is stronger for left-behind students and students from low socioeconomic status backgrounds [?, ?, ?, ?], as well as for STEM majors [?, ?]. However, some studies have found no significant correlation between mindsets and academic performance [?, ?].

Under the mainstream guidance that growth mindset benefits adolescents' academic performance, researchers have focused on priming or training adolescents' growth mindset through online/offline methods in laboratory/educational contexts, with the core being the promotion and popularization of brain science knowledge to convince adolescents that the brain can be changed through training [?, ?]. Blackwell et al. [?] used mindset induction methods (text materials stating "the brain is plastic, you can become smarter") to prime participants' growth mindset and found it could effectively reduce the risk of academic performance decline. Numerous researchers have developed growth mindset intervention programs involving knowledge of "neuroplasticity" [?], explanations of motivation and learning strategies [?], and "saying is believing" practices [?]. Intervention studies have found that growth mindset interventions can significantly improve students' academic performance [?, ?]. However, some survey data have found no significant association between growth mindset interventions and students' academic performance [?, ?].

Currently, whether growth mindset and its interventions affect adolescents' academic performance has become a highly controversial issue within the field. Recent meta-analyses indicate that the relationship between growth mindset and academic performance exhibits high heterogeneity [?, ?, ?]. The mindset-context interaction theory suggests that the effect of growth mindset on academic performance has boundary conditions [?, ?], involving psychological affordances (supportive social environments) and vulnerability factors (such as impoverished students and students with learning difficulties) [?]. Beyond these factors, we believe two issues warrant careful consideration. First, current research exhibits a status quo of emphasizing learning outcomes while neglecting learning processes. Most studies use test scores as a single assessment indicator of academic performance, ignoring process performance. Shifting the evaluation of adolescents' academic performance from outcome-oriented macro-indicators to process-oriented micro-indicators could provide more valuable assessment information for current controversies. Second, there are variable confounding issues in the content of growth mindset interventions. Specifically, the premise of growth mindset interventions improving academic achievement involves simultaneously popularizing neuroplasticity knowledge and training on motivation and learning strategies [?, ?, ?, ?]. However, when motivation and learning strategy training are balanced between intervention and control groups, neuroplasticity knowledge alone does not produce academic achievement differences [?, ?]. Therefore, clarifying the content boundaries of growth mindset interventions has become a prerequisite for scientifically evaluating intervention effects and standardizing growth mindset cultivation practices.

2.3 Research Progress on the Neural Mechanisms of Growth Mindset

Brain plasticity is the core element of growth mindset interventions; however, research on the cognitive neural mechanisms of growth mindset is extremely scarce. Existing studies have primarily used ERP technology to examine differences in brain electrical signals between individuals with different mindsets during post-error feedback. Results show that individuals with a growth mindset exhibit higher P3 and Pe amplitudes when receiving error feedback, indicating greater attention allocation to error information during learning and consequently more error-correction behaviors [?, ?, ?]. fMRI studies have found that growth mindset partially overlaps with brain regions related to the intrinsic motivational system [?]. When facing learning error feedback, individuals with a growth mindset show higher activation in the anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (DLPFC), suggesting better error monitoring [?]. Additionally, growth mindset shows significant positive correlations with gray matter volume in the dorsal and ventral striatum and orbitofrontal cortex, which are responsible for reward processing [?, ?]. A recent study found that a 4-week growth mindset intervention for 7-10-year-old children could significantly enhance functional connectivity in the prefrontal cortex-striatum circuit [?]. However, this intervention still involved cognitive strategy training related to problem-solving, making it impossible to assess whether growth mindset training alone can induce neural plasticity changes and improve academic performance.

2.4 The Relationship Between Growth Mindset and Learning Process: A Self-Regulated Learning Theory Perspective

Since American psychologist Bandura first proposed self-regulated learning theory in the 1970s, researchers represented by Zimmerman, Schunk, Pintrich, Dweck, Winne, and Boekaerts have conducted extensive theoretical and practical research on the meaning, processes, dimensions, influencing factors, strategies, and models of self-regulated learning. Self-regulated learning refers to students' dynamic monitoring, regulation, and control of their learning processes [?]. Winne's [?] COPES model of self-regulated learning, based on an information-processing perspective, describes learning as a metacognition-driven self-regulated process encompassing four stages: task definition, goal setting and planning, implementation of learning strategies, and metacognitive adaptation for future learning [?]. The COPES model posits that learning is a process in which individuals, under the combined influence of internal characteristics and external contexts, accurately monitor and adjust strategy use and time allocation to achieve predetermined goals, involving motivational, cognitive, and metacognitive components.

Existing research on the relationship between mindsets and self-regulated learning has focused on examining the relationship between mindsets and motivational/cognitive content such as goal setting, challenge coping, effort persistence, feedback seeking, strategy use, academic engagement, causal attribution, and responses to failure [?, ?, ?, ?, ?, ?], while neglecting that metacognition is an important component of the learning process [?, ?]. Moreover, most studies rely on questionnaire-based correlational or multivariate research, with few experimental studies based on learning paradigms [?]. Therefore, guided by self-regulated learning theory and employing learning paradigms, we can more accurately reveal how growth mindset influences the learning process.

2.4.1 Growth Mindset and Metacognition in the Learning Process

Metacognition refers to "cognition about cognition," with metacognitive monitoring as its core component [?]. Metacognitive monitoring involves individuals' judgments and evaluations of ongoing cognitive activities, with judgment of learning (JOL) as its core measurement indicator [?]. Metacognitive control refers to the initiation and termination of cognitive activities, strategy adjustment, and time allocation, with allocation of study time as its core measurement indicator [?]. As metacognitive monitoring is crucial for triggering learners' self-regulated learning [?, ?, ?], researchers commonly use the monitoring-control model [?] and the executive function model [?] to explain the dynamic monitoring of metacognition during learning.

Previous studies have found that growth mindset influences metacognitive performance [?, ?, ?]. For example, Ehrlinger [?] required participants to complete a 10-item antonym multiple-choice task and then assess their confidence in their performance. Regression analysis revealed that individuals with a fixed mindset showed overconfidence in self-performance evaluation, while those with a growth mindset made more accurate self-assessments, consistent with Pieschl et al.'s [?] findings and reflecting differences in metacognitive monitoring ability between the two mindset types. Based on PISA data from four Chinese provinces, research found that students' inefficient use of metacognitive strategies reduced the positive effect of growth mindset on academic literacy [?], while growth mindset in the creative domain could enhance individuals' accurate monitoring of the relationship between strategy type and idea novelty, and use this monitoring information to guide strategy selection and application, thereby promoting creative problem-solving [?]. Additionally, neuroscience research has found that individuals' metacognitive monitoring is highly correlated with the prefrontal cortex (PFC) and anterior cingulate cortex (ACC), and individuals with a growth mindset show increased ACC activation when facing error feedback [?]. However, these studies mostly examine the effect of growth mindset on a single component of metacognition and cannot fully characterize the relationship between growth mindset and metacognition. Based on the view that students' dynamic monitoring and regulation of learning processes need to be investigated in task contexts [?], this study aims to experimentally explore how growth mindset influences metacognitive monitoring performance during learning, including monitoring, control, and the monitoring-control relationship (e.g., how monitoring influences control) within a self-regulated learning context.

Nelson and Leonesio [?] developed a self-regulated learning paradigm under the metacognitive framework, namely "fixed-pace learning - judgment of learning - interference - test - self-paced restudy - retest," which has been recognized and used by many researchers with adaptations [?, ?, ?, ?, ?]. This learning paradigm includes core indicators of metacognitive monitoring and control, primarily reflected in: (1) Judgment of learning, which refers to individuals' estimation of the likelihood of correctly recalling currently learned material in an upcoming memory test. Individuals' JOL values for each material reflect their metacognitive monitoring level, while the difference between JOL values and test scores reflects metacognitive monitoring accuracy [?]. (2) Self-paced restudy. Study time allocation refers to individuals' management and control of their mental resources during learning, primarily involving item selection (priority selection or restudy choice) and self-paced study time, which can reflect metacognitive control level [?]. (3) Based on the monitoring-affect-control model [?], the correlation between judgment of learning and study time allocation can reflect the metacognitive monitoring-control relationship [?]. Conducting a series of empirical studies using this learning paradigm to fully characterize the relationship between growth mindset and metacognition will help further clarify the process mechanism through which growth mindset influences self-regulated learning and enrich theoretical models of self-regulated learning.

2.4.2 Growth Mindset, Feedback, and Metacognition in the Learning Process

Feedback is an indispensable factor in the learning process and a trigger for students' self-regulated learning behaviors [?, ?, ?]. As a form of data or information, feedback involves different types, sources, timing, forms, and valences [?]. Labuhn et al. [?] pointed out that how students perceive and understand feedback information significantly influences how they monitor and adjust their learning behaviors. Previous studies have found that individuals' mental representations of and responses to feedback information in learning contexts are influenced by mindsets [?, ?, ?], manifesting as growth mindset individuals effectively using corrective feedback information to guide subsequent effort, persistence, and strategy adjustment [?, ?, ?, ?], and showing higher P3 and Pe amplitudes when processing corrective feedback information [?] and stronger activation in the ACC and DLPFC [?], reflecting the involvement of the metacognitive monitoring system.

Based on Hattie and Timperley's [?] feedback model, feedback can act on various sub-processes of self-regulated learning, including learning goal setting, progress assessment toward goals, and performance adjustment after feedback, to help individuals continuously monitor and modify their learning performance. In recent years, increasing research has found that feedback promotes students' self-regulated learning [?, ?, ?]. At the cognitive level, feedback can stimulate more cognitive engagement [?], deepen knowledge understanding and transfer [?, ?], and promote attitude and behavior development [?]. Furthermore, Narciss's [?] interactive tutoring feedback model and the model of conditions and factors for feedback processes and effects, as well as Nicol and Macfarlane-Dick's [?] metacognitive feedback theory, all emphasize that feedback influences metacognitive processes, manifested as feedback affecting metacognitive judgments, error monitoring, and strategy adjustment [?, ?, ?, ?, ?]. Neuroscience research has found that when students process corrective information, brain regions related to metacognitive monitoring such as the ACC, DLPFC, and parietal lobe show significantly enhanced activity [?]. However, some studies have found a dissociation between feedback's effects on metacognitive monitoring and control, showing that while students can use feedback information for internal self-monitoring, they cannot effectively regulate learning strategies [?, ?].

Previous research has primarily focused on how mindsets influence metacognitive monitoring of corrective feedback information. However, as an important means to enhance students' self-regulated learning in educational contexts [?], feedback involves different forms (task feedback and ability feedback) and valences (positive and negative) [?, ?]. Previous studies have found that growth mindset individuals focus on personal effort under mastery goals, while fixed mindset individuals focus on ability comparison under performance goals [?, ?], reflecting the influence of mindsets on task/ability feedback forms. Additionally, research has found that feedback valence affects individuals' emotional experiences, motivational responses, self-monitoring, strategy selection, and goal pursuit [?, ?, ?, ?, ?, ?]. For example, meta-analyses have found that compared to positive feedback, negative feedback reduces learners' intrinsic motivation [?], while mindsets can effectively mitigate the negative effects of negative feedback on self-efficacy, feedback seeking, and career success [?]. Notably, the effect of feedback valence depends on whether it appears alone or in combination with other feedback. If it appears alone as self-level feedback, it may not significantly affect learning, but when feedback concerns the task itself or involves individuals' self-regulation processes, its impact on learning is most significant [?, ?]. For example, Wang et al.'s [?] study found that task-level feedback (such as elaborated cognitive feedback) significantly promotes learning transfer, and this effect is moderated by learners' achievement goal orientation types, showing that elaborated cognitive feedback has a more positive impact on mastery-oriented learners but no effect on performance-oriented learners. Therefore, this study simultaneously examines feedback form and valence to deeply investigate differences in cognitive performance, metacognitive monitoring, and brain activity between individuals with different mindsets during feedback-based learning, revealing the metacognitive mechanisms through which growth mindset and feedback influence self-regulated learning. This has important implications for helping students achieve more effective self-regulated learning and for teachers to use feedback to guide more efficient learning.

Analysis of Current Research Status and Key Issues

Analyzing the current research status on the relationship between growth mindset and academic performance, several critical issues remain to be addressed. First, previous research has focused on whether growth mindset and interventions affect adolescents' academic achievement or outcomes, neglecting to investigate whether they influence adolescents' learning process performance. Since learning is a continuous process of self-regulation, evaluating the impact of growth mindset and interventions on academic performance should be reflected in process indicators of learning [?], rather than overemphasizing single-outcome indicators such as academic achievement. Therefore, it is necessary to shift the research perspective from "outcome evaluation" to "process evaluation" to investigate the influence of growth mindset and interventions on the learning process.

Second, motivational social-cognitive theory exhibits content bias and methodological limitations in revealing the relationship between growth mindset and learning processes, urgently requiring systematic empirical research guided by learning theoretical frameworks. In terms of research content, there is an overemphasis on motivational/cognitive components in the learning process while neglecting metacognitive components [?]. However, metacognition plays a crucial monitoring and regulating role in the learning process and is a key indicator reflecting the learning process [?]. Methodologically, research has mostly remained at the questionnaire level, with few experimental studies based on learning paradigms that can elucidate the process mechanisms of learning [?]. Therefore, it is necessary to employ learning process paradigms within a metacognitive framework to conduct systematic empirical studies to better reveal how growth mindset influences the learning process.

Third, the neural basis underlying growth mindset interventions remains unclear, and there is a lack of objective neural indicators to reflect the true effectiveness of growth mindset and interventions on academic performance. Although growth mindset interventions are based on brain plasticity, research on their neural mechanisms is scarce, leaving the neural foundation of these interventions unclear [?]. Moreover, previous growth mindset intervention content has involved not only neuroplasticity knowledge popularization but also training on motivational and learning strategy knowledge such as effort investment, optimal strategies, and help-seeking. The interaction and confounding of these variables have obscured the true effects of growth mindset interventions, which has become a focal point of questioning and controversy among researchers [?, ?, ?]. Furthermore, the lack of neural plasticity indicators has limited precise evaluation of this issue to some extent. Therefore, it is necessary to utilize ERP and fMRI techniques to explore the neural activity and brain plasticity mechanisms through which growth mindset and interventions influence learning processes, using neural activity and brain plasticity indicators to reflect the impact of growth mindset and interventions on academic performance.

4 Research Framework

Based on the COPES theory of self-regulated learning, this study addresses the core question of "Does growth mindset influence the learning process?" by investigating this issue from three levels: behavioral performance, neural activity, and brain plasticity. Grounded in COPES theory, which proposes that learning is influenced by the interaction between individual characteristics and external contexts, and that mindsets affect the psychological representation of feedback information in learning contexts [?, ?, ?], this study incorporates feedback as an external learning context factor throughout the entire research. We introduce two feedback contexts—task feedback and ability feedback [?, ?]—to respectively emphasize the mastery-performance goal tendencies of growth-fixed mindset individuals [?, ?, ?], aiming to better observe the behavioral performance and neural basis of growth mindset's influence on the learning process. The overall research framework is shown in Figure 1 [Figure 1: see original paper]. Study 1 uses a self-regulated learning paradigm to investigate whether mindsets influence behavioral performance in the learning process across different feedback contexts, reflecting the impact of growth mindset and feedback on the learning process through behavioral indicators. Study 2 employs ERP technology to examine whether mindsets influence neural signals during the learning process in different feedback contexts, providing objective neural activity evidence for the influence of growth mindset and feedback on the learning process. Study 3 conducts short-term growth mindset implicit priming for fixed mindset individuals in a laboratory context and examines whether their behavioral performance and neural activity during feedback-based learning converge with those of growth mindset individuals. Using fMRI technology, Study 3 also investigates whether long-term growth mindset intervention can significantly alter gray matter volume in key brain regions and the strength of connectivity between large-scale networks, and whether these changes mediate the relationship between growth mindset intervention and academic performance, revealing the brain plasticity mechanisms through which growth mindset intervention influences feedback-based learning processes and performance.

4.1 Study 1: Behavioral Performance of Growth Mindset and Feedback Influencing the Learning Process

Mindset is the core of individuals' meaning systems [?], influencing their interpretation of and response patterns to learning contexts [?]. As an important cue in learning contexts, feedback has been found to be mentally represented differently by individuals with different mindsets [?], with growth mindset individuals focusing on personal effort under mastery goals and fixed mindset individuals focusing on ability comparison under performance goals [?, ?]. Based on this, Study 1 introduces task feedback (Experiment 1) and ability feedback (Experiment 2) contexts to respectively emphasize the mastery-performance goal tendencies of growth-fixed mindset individuals, with each feedback context including both positive and negative valences, to better observe the behavioral performance of individuals with different mindsets during self-regulated learning.

Both Experiment 1 and Experiment 2 adopt a 2 (mindset: growth, fixed) × 2 (feedback valence: positive, negative) between-subjects design. The Growth Mindset Scale [?] is used to differentiate individuals with different mindset types. The self-regulated learning task procedure is: fixed-pace learning and JOL—interference—test—feedback—self-paced restudy and JOL—retest. The key behavioral indicators examined are metacognitive monitoring level and accuracy (JOL values and the discrepancy between JOL and recall performance), metacognitive control performance (restudy selection for initially correct/incorrect items, self-paced study time), metacognitive monitoring-control relationship (correlation between JOL and study time allocation), and test gains. We hypothesize that growth mindset individuals can accurately monitor and flexibly adjust their restudy selection and time allocation based on feedback valence information, resulting in higher test gains.

4.2 Study 2: Neural Activity of Growth Mindset and Feedback Influencing the Learning Process

Feedback contains both valence and information value aspects. Research on feedback indicates that the FRN component shows differences in feedback valence, reflecting individuals' monitoring of behavior [?]. The P300 component can reflect different processing of feedback information value [?, ?]. Based on this, Study 2 uses ERP technology to examine the neural activity through which mindsets influence the self-regulated learning process in real-time task feedback (Experiment 3) and real-time ability feedback (Experiment 4) contexts, with a focus on FRN and P300 components.

Experiments 3 and 4 respectively set up real-time task feedback and real-time ability feedback contexts, each involving positive and negative feedback valences. Both experiments adopt a 2 (mindset: growth, fixed) × 2 (feedback valence: positive, negative) mixed design, with mindset as a between-subjects variable. The Growth Mindset Scale [?] is used to differentiate individuals with different mindset types. The self-regulated learning task procedure is: fixed-pace learning and JOL—interference—test and feedback—self-paced restudy and JOL—retest. The key behavioral indicators examined are the same as in Study 1. The key ERP indicators are the mean amplitudes of P3 and FRN in frontal, central, occipital, parietal, and temporal regions. We hypothesize that behavioral performance will be consistent with Study 1. For ERP indicators, we hypothesize interactions among mindset, feedback valence, and different brain regions in evoking P3 and FRN amplitudes.

4.3 Study 3: Neural Basis of Growth Mindset Implicit Priming and Long-Term Intervention Influencing Feedback-Based Learning Process and Academic Performance

Researchers have used mindset induction materials (text stories stating "the brain is plastic, you can become smarter") for laboratory-based growth mindset implicit priming [?, ?, ?], or employed "neuroplasticity" knowledge [?] and "saying is believing" practices [?] for educational context growth mindset interventions [?, ?]. However, whether growth mindset interventions can change brain neural activity signals, structural morphological indicators, and functional connectivity patterns, and whether these brain plasticity indicators mediate the relationship between growth mindset intervention and academic performance, remains unsupported by evidence. Based on this, this study uses ERP (Experiment 5) and fMRI (Experiment 6) to examine the effects and neural plasticity mechanisms of growth mindset implicit priming and long-term intervention on feedback-based learning processes and academic performance.

Experiment 5 uses ERP technology to examine the effects of growth mindset implicit priming on feedback-based learning process performance and neural activity. The experiment adopts a 2 (group: intervention, control) × 2 (feedback: correct, incorrect) mixed design, with group as a between-subjects variable. First, the Growth Mindset Scale is used to screen fixed mindset individuals, who are randomly assigned to intervention and control groups. Second, mindset induction materials are used for growth mindset implicit priming in the intervention group, while control group participants read materials introducing research progress on quantum satellite communication. Third, all participants complete a self-regulated learning task (fixed-pace learning and JOL—interference—test and correctness feedback—self-paced restudy and JOL—retest) while EEG data are collected. The behavioral and ERP indicators examined are the same as in Study 2.

Experiment 6 uses fMRI technology to examine the neural plasticity mechanisms through which growth mindset intervention influences academic performance. The experiment adopts a 4 (group: growth mindset intervention, growth mindset+motivation and learning strategies intervention, control, vs no intervention) × 2 (measurement: pre-test, post-test) mixed design, with group as a between-subjects variable and measurement as a within-subjects variable. To examine the true effectiveness of growth mindset on academic performance, we controlled for the controversial variable of motivation and learning strategies training across groups. The intervention content for each group is: Growth mindset intervention group: "neuroplasticity knowledge and experience" and "saying is believing practice and application"; Growth mindset+motivation and learning strategies intervention group: "neuroplasticity knowledge and experience," "motivation and learning strategies knowledge and techniques," and "saying is believing practice and application"; Control group: "science knowledge and experiments," "motivation and learning strategies knowledge and techniques," and "self-experience sharing and application"; No intervention group: receives no intervention. The entire intervention lasts 6 weeks, with 6 sessions. Data collected include self-regulated learning task behavioral indicators (same as Experiment 5), academic engagement scores and metacognitive scores (process indicators), academic achievement (Chinese and mathematics), MRI scans (including structural and resting-state images), and growth mindset scores at pre-test and post-test. To explore the delayed effects of growth mindset intervention on academic achievement, academic engagement scores, metacognitive scores (process indicators), academic achievement (Chinese and mathematics), and growth mindset scores are collected again at 3 months and 1 year post-intervention.

Based on structural and resting-state brain data, we compare changes in cortical thickness, gray matter volume in key brain regions (orbitofrontal cortex, anterior cingulate cortex, and dorsal prefrontal cortex), and functional connectivity of large-scale brain networks (frontoparietal network, salience network, and default mode network) before and after growth mindset intervention. Mediation models are used to examine whether brain structural and functional plasticity changes mediate the relationship between growth mindset intervention and academic performance. We hypothesize that after growth mindset priming, fixed mindset individuals' behavioral performance and neural activity during feedback-based learning will converge with those of growth mindset individuals in Studies 1 and 2. Growth mindset intervention will significantly increase gray matter volume in the medial prefrontal cortex and alter functional connectivity patterns within and between executive control networks, dorsal attention networks, and default mode networks, and these plasticity indicators will mediate the relationship between growth mindset intervention and academic performance.

5 Theoretical Construction

In recent years, cultivating adolescents' growth mindset has flourished in educational circles both domestically and internationally. However, controversy continues over whether growth mindset and its interventions can promote adolescents' academic performance. As more researchers call for examining the heterogeneity of growth mindset and its interventions [**?**, **?**], evaluating the true effectiveness of growth mindset and interventions in promoting adolescents' academic performance and breaking through the current controversial state of "yes or no" has become a key issue in the field. A critical breakthrough point lies in shifting the evaluation of adolescents' academic performance from macro-indicators to micro-indicators, revealing the influence of growth mindset on the learning process, which can provide new research perspectives, experimental paradigms, and assessment indicators for current controversies. In view of this, this study starts from the process-oriented nature of learning, employs a self-regulated learning paradigm under the metacognitive framework, combines multiple research methods and techniques, constructs a COPES theoretical framework of growth mindset influencing the learning process, and systematically reveals the internal mechanisms through which growth mindset affects the learning process from three levels: behavioral performance, neural activity, and brain plasticity.

First, based on the COPES theory of self-regulated learning, this study attempts to construct a theoretical framework of growth mindset influencing the learning process (as shown in Figure 2 [Figure 2: see original paper]) to reveal the internal mechanisms. Although most research based on motivational social-cognitive theory emphasizes that growth mindset is an explanatory element of the motivational system of learning [?], it does not touch upon the process-oriented nature of self-regulated learning, neglecting the metacognitive components of the learning process, making it difficult to provide theoretical explanations that comprehensively reflect the relationship between growth mindset and learning. As metacognition is key to students' self-regulated learning [?], existing research has found that mindsets influence metacognitive monitoring levels [?, ?], and metacognitive monitoring is closely related to individuals' motivational system components such as goal orientation, task value, and interest [?, ?]. However, how growth mindset, motivation, and metacognition interact during self-regulated learning remains unclear. This theoretical framework of learning includes all core components of learning and can reveal from a micro-level how growth mindset activates the goal-motivation and metacognitive systems to monitor and regulate the learning process in a top-down manner, involving how to make learning judgments, allocate study time, select restudy strategies, form metacognitive monitoring-control relationships, and achieve restudy gains. This can fully characterize the interactive patterns among growth mindset, motivation, metacognition, and self-regulated learning behaviors, representing an important theoretical expansion for evaluating the relationship between growth mindset and learning.

Second, this study examines the interactive influence of growth mindset and feedback information on self-regulated learning, taking feedback contexts as an entry point, which further enriches and extends the COPES theory. Students' implicit beliefs (such as mindsets) influence the processing of external feedback information [?], while feedback, as a trigger for students' self-regulated learning, stimulates their metacognitive monitoring and regulation behaviors, helping us better observe transformations in students' learning, learning processes, behaviors, and motivations [?]. Some self-regulated learning models emphasize the profound impact of feedback on how students engage in and implement learning processes [?, ?, ?], and further detailed characterization of differences in cognitive performance, metacognitive monitoring, and brain activity between individuals with different mindsets during feedback-based learning based on the COPES framework is also crucial. This can not only broaden and 完善 the content of the COPES model but also provide references for feedback intervention methods in current growth mindset cultivation practices.

Moreover, this study attempts to clarify the neural basis underlying growth mindset interventions. Currently, a wave of growth mindset interventions based on brain plasticity has swept the globe. However, whether growth mindset interventions can induce neural plasticity changes remains unclear, leading to increasing questioning about the effectiveness of growth mindset intervention programs [?]. Previous growth mindset intervention programs have involved training on variables such as achievement goals and attributions [?, ?]. Considering that growth mindset overlaps with intrinsic motivational systems in brain regions such as the anterior cingulate cortex, dorsolateral prefrontal cortex, and striatum [?, ?, ?], the question of to what extent neural plasticity changes in research results originate from growth mindset intervention itself needs to be addressed by optimizing current growth mindset intervention programs. This study investigates related neural activity and brain plasticity changes through growth mindset implicit priming and long-term intervention while controlling for various motivational confounding variables across groups, providing empirical support for the neural plasticity of growth mindset interventions. The exploration of neural mechanisms can not only deepen the understanding of how growth mindset acts on self-regulated learning processes, verify and enrich the COPES theoretical framework, but also help precisely evaluate the true effects of growth mindset interventions on neural plasticity changes and provide a basis for optimizing growth mindset educational intervention programs.

Regarding the cultivation practice of adolescents' growth mindset, most researchers focus on popularizing neuroplasticity knowledge and motivation and learning strategy techniques [?, ?, ?]. However, based on the mindset-context interaction theory's proposal that effective growth mindset interventions need to be implemented in supportive contexts [?], it is necessary in the future to break through student-centered interventions and consider the classroom environment where students are situated. Some recent studies have found positive effects of teachers in shaping students' growth mindset in classroom contexts [?, ?]. How to guide teachers to implement classroom practices conducive to cultivating students' growth mindset, this study provides a potential leverage point: the construction of teachers' classroom feedback messages. As an important carrier of teacher-student interaction in classroom contexts and an operational method for training students to become self-regulated learners [?], if teachers can grasp differences in cognitive performance, metacognitive monitoring, and brain activity between students with different mindsets during feedback-based learning, and on this basis weigh issues such as whether to feedback students' effort or ability, students' learning outcomes or process performance, to construct growth mindset classroom feedback patterns, they can provide a psychologically supportive classroom environment for cultivating students' growth mindset [?]. That is, future growth mindset cultivation can consider not only the student level but also incorporating the construction of teachers' growth mindset classroom feedback into educational practice.

This study systematically explores the behavioral performance and neural response patterns of growth mindset affecting the learning process, attempts to construct a theoretical framework of growth mindset influencing the learning process, not only promotes the development of this research theme from continuous controversy toward gradual clarification, but also responds to the requirement of "strengthening process evaluation" in the new era of educational evaluation reform. Meanwhile, as growth mindset cultivation based on brain plasticity is widely applied in educational practice, clarifying the neural activity and brain plasticity through which growth mindset and interventions influence the learning process can provide a basis for precisely formulating cultivation programs and effectiveness evaluation for adolescents' growth mindset, promoting the scientific and standardized implementation of growth mindset cultivation. Additionally, integrating students' growth mindset cultivation into supportive classroom feedback contexts is also a direction for future educational practice to consider.

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