

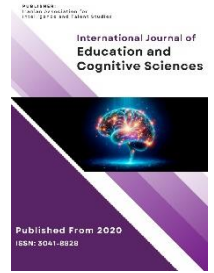


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## The Effectiveness of the Bigdeli Mind Simulation Technique on fMRI Activation in the Central/Precentral Gyrus and Temporal Gyrus of an Individual With Stuttering Following Therapeutic Interventions

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### ABSTRACT

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**Purpose:** The present study aimed to investigate the effectiveness of the Bigdeli mind simulation technique on functional magnetic resonance imaging (fMRI) activation in the central/precentral gyrus and temporal gyrus of a child with stuttering following therapeutic intervention.

**Methods and Materials:** The present research was conducted using an experimental single-case design with a pretest–posttest structure. The participant was a 9-year-old girl with developmental stuttering who was referred to a psychology services center in Tehran, Iran, in 2021 and was selected through convenience sampling. Functional magnetic resonance imaging was performed in two stages, including before treatment and two months after treatment. During imaging, the participant performed a task-based reading paradigm consisting of alternating text presentation and rest intervals. The fMRI data were acquired using a 3-Tesla Siemens Prisma MRI scanner and were analyzed using FSL software and the general linear model. The main regions of interest included the superior central gyrus, posterior central gyrus, and posterior superior temporal gyrus.

**Findings:** The findings demonstrated increased activation in all examined speech-related regions after treatment. In the posterior superior temporal gyrus, the number of active voxels increased from 403 before treatment to 454 after treatment, and the mean z-score increased from 5.38 to 5.67. In the superior central gyrus, active voxels increased from 1026 to 1232, while the mean z-score increased from 5.91 to 6.04. In the posterior central gyrus, active voxels increased from 1033 to 1127, and the mean z-score increased from 5.96 to 6.25. The reconstructed fMRI images also demonstrated greater post-treatment blood oxygenation activity in the central/precentral motor region and posterior superior temporal gyrus compared with the pre-treatment stage.

**Conclusion:** The findings suggest that the Bigdeli mind simulation technique was associated with increased neural activation in speech motor and language-processing regions related to speech fluency and auditory–verbal monitoring.

**Keywords:** Bigdeli mind simulation technique, stuttering, functional magnetic resonance imaging, fMRI, central gyrus, temporal gyrus, neuroimaging, neural activation

## 1. Introduction

Stuttering is one of the most complex fluency disorders affecting speech production, communication performance, emotional functioning, and social interaction in children and adolescents. The disorder is generally characterized by involuntary repetitions, prolongations, pauses, and disruptions in the normal rhythm and fluency of speech, and it can negatively influence educational, emotional, and interpersonal functioning across developmental stages (Afrooz, 1995; Ainsworth & Fraser, 1989). Researchers have emphasized that stuttering is not merely a peripheral speech disorder but rather a multidimensional neuropsychological phenomenon involving linguistic, cognitive, emotional, and motor mechanisms (Kakavand, 2009; Seif Naraghi & Naderi, 2004). Because fluent speech production requires highly coordinated interaction between auditory processing, motor planning, linguistic organization, and cognitive monitoring systems, disruptions in any component of this network may contribute to the emergence and persistence of stuttering (Kolb & Whishaw, 1947; Nazari et al., 2012).

Over the past decades, advances in neuroscience and neuroimaging have significantly transformed the understanding of speech disorders and their neural correlates. Functional magnetic resonance imaging (fMRI) has become one of the most important noninvasive techniques for investigating brain activity associated with cognitive, emotional, sensory, and linguistic functions (Mostafa, 2025; Shahbazi Gahrouei, 2006). Unlike conventional structural magnetic resonance imaging, which focuses on anatomical structures, fMRI evaluates changes in blood oxygenation level-dependent signals and provides indirect information regarding neural activation during specific tasks or cognitive states (Omidvarnia, 2024; Preibisch et al., 2003). The development of sophisticated preprocessing and statistical modeling techniques has enabled researchers to examine neural activation patterns with increasing precision and reliability across various clinical and behavioral domains (Ściślewska et al., 2025; Yan et al., 2025).

Recent neuroimaging studies have demonstrated that speech and language production involve distributed neural systems rather than isolated cortical regions. Speech fluency depends on the coordinated functioning of frontal motor regions, temporal auditory–language regions, sensorimotor integration pathways, limbic systems, and executive control networks (Kolb & Whishaw, 1947; Scheinost et al., 2021).

Among these structures, the precentral and central motor regions are especially important because they are responsible for motor planning and execution of speech-related movements. Similarly, the superior temporal gyrus, particularly its posterior division associated with Wernicke's area, plays a central role in auditory processing, language comprehension, semantic monitoring, and feedback regulation during speech production (Nazari et al., 2012; Van Borsel et al., 2002). Disruption in the coordination of these systems may impair the timing and sequencing necessary for fluent speech.

Neuroimaging findings in individuals with stuttering have revealed atypical activation patterns in several speech-related cortical regions. Functional imaging studies have frequently reported altered activation in frontal speech motor areas, temporal auditory regions, and supplementary motor networks during speech tasks (Preibisch et al., 2003; Van Borsel et al., 2002). Some investigations have shown reduced activity in left hemisphere language regions and compensatory activation in alternative neural pathways, suggesting inefficient speech monitoring and motor coordination processes in people who stutter (Kim et al., 2024; Nazari et al., 2012). Other studies have emphasized abnormalities in sensorimotor timing, auditory feedback integration, and cortical synchronization as possible neural mechanisms underlying persistent stuttering (Nicholson et al., 2024; Zhang et al., 2025). Consequently, contemporary approaches increasingly conceptualize stuttering as a disorder involving dysfunctional neural connectivity and impaired coordination between speech perception and speech production systems.

At the same time, psychological and emotional variables have also been recognized as important components in the development and maintenance of stuttering. Children and adolescents who stutter often experience increased anxiety, social withdrawal, communication apprehension, and lower psychological well-being compared with their fluent peers (Ahadi et al., 2012; Emami Meybodi et al., 2016). Emotional reactions to speech disruptions may further intensify anticipatory anxiety and cognitive self-monitoring during communication situations, thereby worsening speech fluency (Farahmandpour, 2009; Taylor & Schneider, 1989). Researchers have therefore emphasized the necessity of integrating cognitive, emotional, and neurophysiological perspectives when studying stuttering and designing therapeutic interventions (Gorosi et al., 2010; Jangi Qojabeyglou et al., 2014).

Various treatment approaches have been proposed for stuttering, including speech therapy, behavioral interventions, neurofeedback, cognitive interventions, auditory training, and family-centered approaches. Some studies have reported beneficial effects of neurofeedback and combined behavioral programs in reducing stuttering severity and improving communication performance (Najafi et al., 2010; Vahidi et al., 2016). Other investigations have highlighted the effectiveness of anxiety-reduction and emotion-focused interventions in improving speech fluency and communication attitudes among children who stutter (Ahadi et al., 2012; Jangi Qojabeyglou et al., 2014). Despite these advances, many interventions primarily focus on behavioral symptoms rather than directly targeting the underlying cognitive and neural mechanisms associated with speech production and monitoring.

In recent years, mind simulation techniques have attracted increasing attention as innovative therapeutic approaches in psychology, education, and rehabilitation sciences. Mental simulation generally refers to the cognitive process through which individuals mentally rehearse actions, events, or behavioral patterns before actual execution (Taylor & Schneider, 1989). The theoretical basis of simulation approaches suggests that repeated mental representation and rehearsal may facilitate cognitive organization, behavioral preparedness, neural adaptation, and emotional regulation (Casado-Aranda et al., 2022; Kim et al., 2024). Simulation-based interventions have been successfully used in educational settings, medical training, motor learning, and psychological rehabilitation to improve performance and reduce anxiety (Baradaran-Binazir et al., 2019; Mostafa, 2025).

Within the field of stuttering treatment, mind simulation approaches have recently emerged as promising interventions for improving speech fluency and communication attitudes. Bigdeli Shamloo introduced the concept of mind simulation as a structured cognitive-behavioral framework emphasizing mental programming, internal language organization, and cognitive rehearsal in speech production (Bigdeli Shamloo, 2017). Subsequent investigations reported favorable outcomes of mind simulation therapy in reducing stuttering severity and improving communication functioning among children and adolescents with stuttering (Akbari, 2020; Fallahi, 2021). Researchers have suggested that repeated mental simulation of fluent speech patterns may facilitate neural organization, enhance speech monitoring processes, and reduce maladaptive anticipatory responses associated with speech

production (Kamarzarin, Fallahi, et al., 2021; Kamarzarin, Golestani, et al., 2021).

The relationship between mental simulation and neural functioning has also gained attention within modern neuroimaging research. Contemporary fMRI studies have shown that cognitive rehearsal, emotional regulation, and neurofeedback-based interventions may produce measurable changes in neural activation and connectivity patterns (Nicholson et al., 2024; Scheinost et al., 2021). Real-time fMRI neurofeedback investigations have demonstrated that targeted modulation of neural systems can reduce anxiety symptoms and alter activation in limbic and cortical regions associated with emotional regulation and cognitive control (Kim et al., 2024; Zhang et al., 2025). These findings indicate that cognitive interventions may influence not only psychological functioning but also neural activation patterns measurable through functional imaging methods.

In addition, recent developments in neuroimaging analysis have improved the ability to evaluate functional activation during speech-related tasks. Event-related fMRI paradigms and advanced preprocessing strategies have reduced speech-associated imaging artifacts and increased the reliability of activation measurements in individuals with stuttering (Preibisch et al., 2003). Coordinate-based meta-analyses and resting-state investigations have further demonstrated the importance of examining distributed neural networks rather than isolated regions when evaluating speech and cognitive functioning (Omidvarnia, 2024; Yan et al., 2025). Such methodological advances provide an opportunity to investigate whether therapeutic interventions can produce measurable neural changes in speech-related brain regions following treatment.

Despite increasing interest in both mind simulation therapy and functional neuroimaging, relatively few studies have directly examined the neural effects of mind simulation interventions in individuals with stuttering. Existing investigations have primarily focused on behavioral outcomes such as speech fluency, communication attitudes, and anxiety reduction, while the neurofunctional correlates of treatment response remain insufficiently explored (Akbari, 2020; Fallahi, 2021). Moreover, limited evidence is available regarding changes in activation of the central/precentral motor regions and temporal language-processing regions following mind simulation interventions. Considering the critical role of these regions in speech movement coordination and language monitoring, examining post-treatment neural activation patterns may contribute to a more comprehensive understanding of the

mechanisms underlying therapeutic improvement in stuttering.

The present study is also important because it combines psychological intervention with neurofunctional assessment in a clinical case of childhood stuttering. Integrating therapeutic approaches with fMRI analysis may provide valuable information regarding how cognitive-behavioral interventions influence neural activation in speech-related systems. Such findings may contribute to the development of more targeted rehabilitation strategies and may improve understanding of the relationship between speech fluency, neural adaptation, and cognitive processing in children with stuttering (Casado-Aranda et al., 2022; Scheinost et al., 2021). Furthermore, studying neural activation before and after treatment may clarify whether improvements in speech performance are associated with measurable changes in cortical blood oxygenation and task-related neural recruitment.

Given the multidimensional nature of stuttering and the increasing importance of neuroscience-informed interventions, examining the effectiveness of Bigdeli mind simulation techniques through functional neuroimaging appears both theoretically and clinically necessary. Investigating activation changes in the central/precentral gyrus and temporal gyrus may provide insight into whether Bigdeli mind simulation therapy contributes to enhanced neural functioning in motor and language-processing systems associated with speech fluency. Therefore, the aim of the present study was to investigate the effectiveness of the Bigdeli mind simulation technique on fMRI activation in the central/precentral gyrus and temporal gyrus of an individual with stuttering following therapeutic interventions

## 2. Methods and Materials

### 2.1. Study Design and Participants

The present study was conducted using an experimental single-case design with a pretest-posttest framework. The research aimed to investigate the effectiveness of the mental simulation technique on functional brain activity in a child with stuttering, with particular emphasis on changes in the precentral gyrus and temporal gyrus as observed through functional magnetic resonance imaging (fMRI) following therapeutic interventions. A case-study methodology was selected because of the need for detailed neurofunctional assessment before and after treatment and the feasibility

limitations associated with repeated neuroimaging procedures in pediatric populations.

The participant in this study was a 9-year-old girl who was referred to the Mind and Psychology Services Center in Tehran, Iran, during 2021 due to persistent developmental stuttering. The participant was selected through convenience sampling based on accessibility and willingness to participate in the therapeutic and neuroimaging procedures. Prior to inclusion in the study, the participant underwent a comprehensive clinical evaluation to confirm the diagnosis of stuttering and to ensure eligibility for participation in the intervention process and imaging sessions. Organic neurological disorders, severe cognitive impairment, and other developmental conditions that could interfere with speech production or neuroimaging interpretation were carefully screened and controlled as exclusion criteria.

Ethical considerations were fully observed throughout the research process. Written informed consent for participation was obtained from the participant's parents prior to the commencement of the study. The child voluntarily participated in all treatment sessions and neuroimaging procedures after receiving age-appropriate explanations regarding the behavioral intervention process and the fMRI environment. In addition, efforts were made to reduce anxiety and stress associated with MRI scanning through psychological preparation and familiarization with the imaging environment before each scanning session.

Functional neuroimaging was performed in two separate stages. The first imaging session was conducted before the initiation of the therapeutic intervention in order to establish baseline neural activation patterns. The second imaging session was carried out approximately two months after completion of the intervention protocol to evaluate post-treatment neural changes associated with the mental simulation technique and speech-related improvements.

### 2.2. Measures

Data collection in the present study was conducted using a combination of clinical assessment procedures, demographic documentation, and functional neuroimaging techniques. The severity and characteristics of stuttering were initially evaluated through standardized stuttering assessment procedures and clinical interviews based on the diagnostic criteria presented in the Diagnostic and Statistical Manual of Mental Disorders (DSM). Clinical speech and language evaluations were performed by specialists in

speech-language pathology to determine the participant's fluency profile and speech disruption patterns.

A demographic information form was completed by the participant's parents and included variables such as age, gender, developmental history, and relevant medical information. Furthermore, an informed consent form outlining the objectives of the study, voluntary participation, confidentiality of information, behavioral treatment procedures, and fMRI conditions was completed by the participant's guardian prior to data collection.

One of the most important methodological considerations in designing an fMRI study is the preparation of a task paradigm that can be effectively implemented within the MRI environment while maintaining precise timing and participant compliance. In the present study, a speech-reading task was specifically designed for functional imaging purposes. A speech-language specialist prepared a linguistically balanced and phonologically controlled text appropriate for the participant's stuttering severity level. The text was developed according to phonetic and phonological principles of the Persian language, including appropriate distribution of vowels, consonants, and graphemes.

The prepared text was subsequently divided into 45 segments with relatively equal levels of linguistic difficulty. Each segment consisted of approximately two to three words presented sequentially during the imaging session. The task paradigm was programmed and implemented by the image processing laboratory in a block-design format. During scanning, each text segment was displayed for 10 seconds, followed by a 10-second rest interval. This alternating sequence of task and rest periods was repeated continuously throughout the imaging procedure.

Functional MRI data were acquired while the participant read the presented text aloud during activation periods and remained at rest during rest intervals. The total duration of the fMRI acquisition protocol was approximately 15 minutes and 10 seconds. This task-based imaging paradigm enabled the researchers to evaluate changes in neural activation associated with speech production and language processing before and after the therapeutic intervention.

### 2.3. Data Analysis

The acquired neuroimaging data were analyzed at the National Brain Mapping Laboratory using the FMRIB Software Library (FSL), which is a widely used software package for processing and analyzing functional magnetic resonance imaging data. The preprocessing stages included

motion correction, spatial normalization, temporal filtering, and artifact reduction to improve the quality and reliability of the functional data.

Following preprocessing, statistical analyses were performed to identify activation changes in speech-related brain regions, particularly the precentral gyrus and temporal gyrus, during the language task. Functional activation maps obtained from the pre-intervention and post-intervention stages were compared to determine alterations in neural activity patterns associated with the mental simulation intervention.

The processed neuroimaging outputs were subsequently interpreted and reviewed by specialists in image processing and neurofunctional analysis. The final interpretation focused on identifying treatment-related changes in cortical activation patterns and evaluating the relationship between therapeutic intervention and neural functioning associated with speech fluency and language processing.

### 3. Findings and Results

The present study examined whether the mental simulation technique produced observable changes in fMRI activation in a child with stuttering after therapeutic intervention, with specific focus on the central/precentral motor region and the temporal gyrus. Functional magnetic resonance imaging was used to evaluate blood oxygenation level-dependent signal changes during a speech-related reading task. The participant was assessed in two stages: before treatment and two months after treatment. The main contrast used for interpretation was the rest-reading contrast, through which task-related neural activation was identified during speech production and language processing.

Before analyzing the main findings, the fMRI data were preprocessed and processed to reduce possible sources of error and to increase the reliability of the activation maps. Since fMRI data are sensitive to physiological and technical artifacts, including head movement, respiration, cardiac activity, temporal differences in slice acquisition, spatial distortion, and low-frequency noise, the preprocessing procedure included quality control, slice timing correction, motion correction, distortion correction, spatial normalization, spatial smoothing, temporal filtering, visualization of activation results, statistical modeling, and statistical inference. These stages allowed the comparison of pre-treatment and post-treatment activation patterns in the target regions of interest.

The fMRI data were analyzed using the general linear model. In this model, the observed fMRI signal was modeled as  $Y = XB + e$ , where  $Y$  represents the voxel-wise time series obtained from the brain scan,  $X$  represents the experimental design matrix based on the reading and rest conditions,  $B$  represents the estimated beta coefficients related to task-induced activation, and  $e$  represents the residual error. This model made it possible to estimate the relationship between the reading task and the observed blood oxygenation response in each voxel. The analysis was conducted using FSL software, and the regions of interest were extracted according to the Harvard–Oxford cortical atlas.

The imaging procedure was performed using a 3-Tesla Siemens Prisma MRI scanner. The functional task consisted of alternating text-reading and rest blocks. Each reading block lasted 10 seconds and was followed by a 10-second rest interval. Overall, the paradigm included 45 text

presentations and 45 rest intervals, with a total duration of approximately 15 minutes. During the activation periods, the participant read the displayed text, and during the rest periods, she remained at rest. This task design enabled the comparison of speech-related activation before and after the therapeutic intervention.

The main regions analyzed in relation to the article title were the central/precentral motor region and the posterior superior temporal gyrus. The central/precentral motor region is involved in the motor planning and execution of speech movements, while the posterior superior temporal gyrus is closely related to Wernicke’s area and plays an important role in auditory–verbal processing, word comprehension, and language monitoring. The number of active voxels and the mean z-score were used as the main quantitative indicators of neural activation.

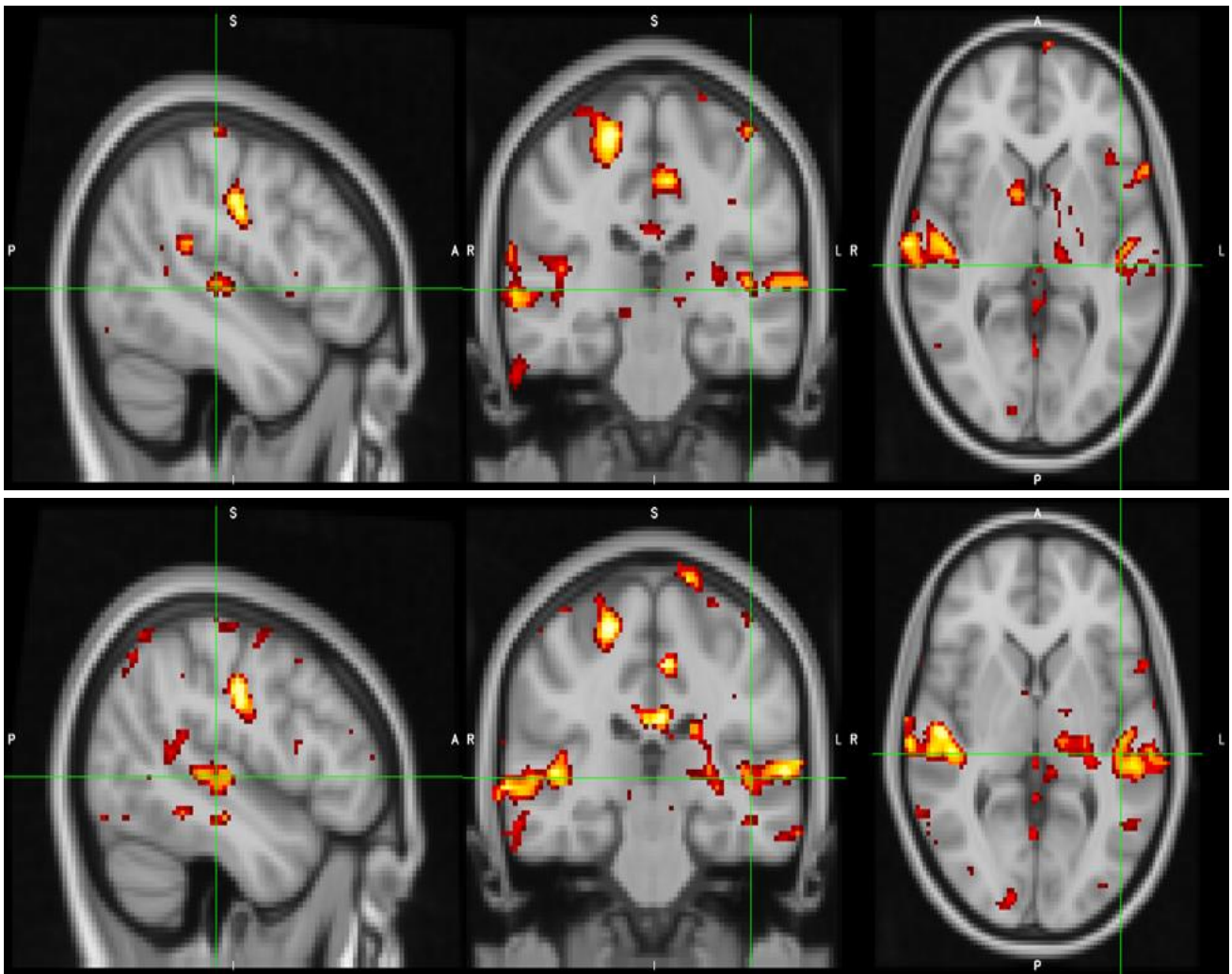
**Table 1**

*Number of Active Voxels and Mean z-Score in the Main Regions of Interest*

Region of Interest	Active Voxels Before Treatment	Active Voxels After Treatment	Mean z-Score Before Treatment	Mean z-Score After Treatment
Superior temporal gyrus, posterior division	403	454	5.38	5.67
Superior central gyrus	1026	1232	5.91	6.04
Posterior central gyrus	1033	1127	5.96	6.25

The regions of interest were extracted based on the Harvard–Oxford cortical atlas. The mean z-score values were calculated for active voxels above the z-score threshold of 3.8 in each region. As shown in Table 1, activation increased after treatment in all title-related regions. In the posterior superior temporal gyrus, the number of active voxels increased from 403 before treatment to 454 after treatment, and the mean z-score increased from 5.38 to 5.67. This indicates increased post-treatment activation in a temporal language-processing region associated with speech comprehension and monitoring. In the superior central gyrus, the number of active voxels increased from 1026 to 1232, and the mean z-score increased from 5.91 to 6.04. In the posterior central gyrus, the number of active voxels increased from 1033 to 1127, and the mean z-score increased from 5.96 to 6.25. These findings indicate stronger post-treatment activation in motor and sensorimotor areas involved in speech-related movement.

The first research question examined whether the mental simulation technique affected fMRI activation in the central/precentral gyrus after therapeutic intervention. The reconstructed fMRI images were presented using axial, sagittal, and coronal views. In these images, active regions were shown in red and yellow based on blood oxygenation activity, and the intersection of the green lines indicated the region of interest. Comparison of the pre-treatment and post-treatment images showed increased activation in the central/precentral motor region after treatment. This finding was consistent with the quantitative data, which showed increases in both active voxel counts and mean z-scores in the superior central and posterior central regions. Therefore, the post-treatment fMRI pattern suggests increased blood oxygenation and stronger neural activity in motor regions involved in speech production.

**Figure 1***Activated Regions of the Central/Precentral Gyrus Before (Above) and After (Below) Treatment*

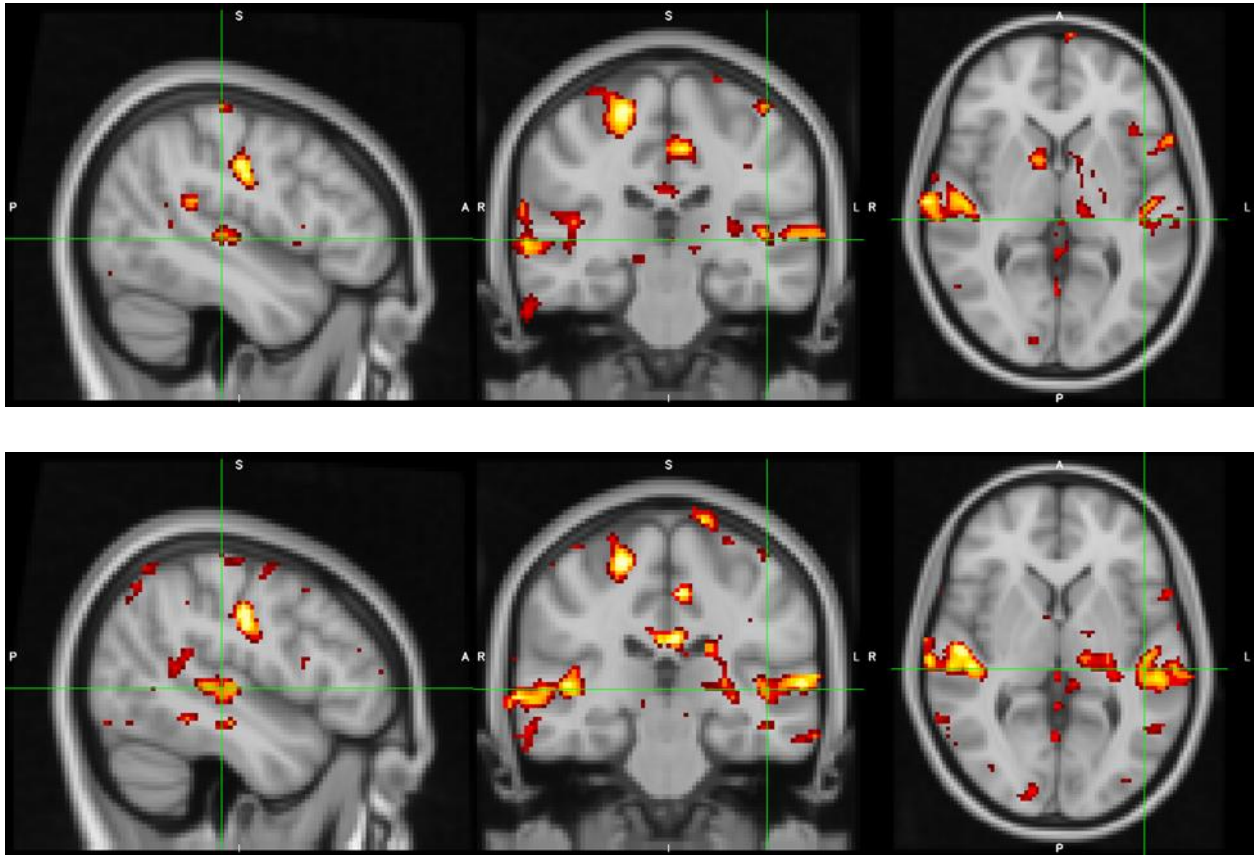
In Figure 1, Image 1 represents the activation pattern before treatment, and Image 2 represents the activation pattern after treatment. The figure shows activity in the motor region located around the central/precentral gyrus. After treatment, the activation pattern became more extensive than before treatment, indicating increased functional engagement of the speech-related motor area. This increase may reflect improved recruitment of neural systems involved in the motor control of speech following the mental simulation intervention.

The second research question examined whether the mental simulation technique affected fMRI activation in the

temporal gyrus after therapeutic intervention. The posterior superior temporal gyrus was considered the main temporal region of interest because of its relationship with Wernicke's area and its role in language comprehension, auditory-verbal processing, and the storage and processing of word meaning. The comparison of the pre-treatment and post-treatment fMRI images showed increased activation in this region after treatment. This visual finding was supported by the quantitative results, which showed that active voxels in the posterior superior temporal gyrus increased from 403 to 454, and the mean z-score increased from 5.38 to 5.67.

**Figure 2**

*Activated Regions of the Superior Temporal Gyrus, Posterior Division, Before (Above) and After (Below) Treatment*



In Figure 2, Image 1 represents the activation pattern in the posterior superior temporal gyrus before treatment, and Image 2 represents the activation pattern after treatment. The post-treatment image shows stronger activation compared with the pre-treatment image. This increase indicates greater blood oxygenation and functional activity in the temporal language-processing region after the therapeutic intervention. Since this region is involved in word comprehension and speech monitoring, the observed increase may suggest improved neural engagement during the speech-related reading task.

Overall, the findings showed that after therapeutic intervention using the mental simulation technique, blood oxygenation level-dependent activation increased in both main regions aligned with the article title: the central/precentral gyrus and the posterior superior temporal gyrus. The increase in the central/precentral region indicates stronger activity in motor and sensorimotor areas involved in speech movement, while the increase in the posterior superior temporal gyrus indicates stronger activity in a language-processing region related to comprehension and speech monitoring. These findings suggest that the mental

simulation technique was associated with measurable post-treatment changes in fMRI activation in brain regions relevant to stuttering and speech-language processing. However, because the study was conducted as a single-case design, the findings should be interpreted cautiously and require confirmation through future studies with larger samples, control conditions, and simultaneous behavioral measures of speech fluency.

#### 4. Discussion and Conclusion

The present study investigated the effectiveness of the Bigdeli mind simulation technique on functional magnetic resonance imaging activation in the central/precentral gyrus and temporal gyrus of a child with stuttering following therapeutic intervention. The findings demonstrated that after treatment, increased activation was observed in both the central/precentral motor region and the posterior superior temporal gyrus. Specifically, the number of active voxels and mean z-score values increased in the superior central gyrus, posterior central gyrus, and posterior superior temporal gyrus after intervention. These findings suggest that the Bigdeli mind simulation technique was associated

with increased blood oxygenation level-dependent activity in neural regions involved in speech motor control, auditory processing, and language monitoring.

One of the major findings of the present study was the increased activation in the central/precentral motor regions after treatment. The superior central gyrus and posterior central gyrus demonstrated higher active voxel counts and greater mean z-score values in the post-treatment stage compared with the pre-treatment stage. These findings may indicate improved neural recruitment and more effective engagement of motor speech systems following the intervention. Speech production requires precise coordination between cortical motor planning regions and articulatory execution systems, and disruptions in this coordination are believed to play an important role in stuttering (Kolb & Whishaw, 1947; Nazari et al., 2012). Therefore, the increased activation observed in the central/precentral region may reflect improved functional organization of speech-related motor processes after the Bigdeli mind simulation intervention.

The present findings are consistent with neuroimaging studies suggesting that stuttering is associated with atypical activation patterns in frontal and motor regions involved in speech control (Preibisch et al., 2003; Van Borsel et al., 2002). Previous investigations have reported abnormalities in timing, coordination, and sensorimotor integration among individuals who stutter, particularly in left hemisphere speech networks and supplementary motor systems (Kim et al., 2024; Nazari et al., 2012). The observed increase in activation after treatment in the current study may therefore represent a compensatory or restorative neural response associated with improved speech motor coordination. In this regard, the findings support theoretical perspectives suggesting that behavioral and cognitive interventions may influence not only overt speech performance but also the neural systems underlying speech production (Nicholson et al., 2024; Scheinost et al., 2021).

Another important finding of the present study was the increased activation in the posterior superior temporal gyrus following treatment. The posterior superior temporal region is closely associated with Wernicke's area and is involved in auditory processing, word comprehension, semantic integration, and speech monitoring. In the current study, the increase in active voxels and mean z-score values in this region after treatment may indicate improved auditory-verbal monitoring and language processing during speech production. Efficient speech fluency depends not only on motor execution but also on continuous auditory feedback

and monitoring systems that evaluate the accuracy and fluency of verbal output (Kolb & Whishaw, 1947; Van Borsel et al., 2002). Therefore, enhanced activation in the superior temporal gyrus may suggest improved integration between auditory processing and motor speech systems after intervention.

These findings align with earlier studies indicating that individuals with stuttering frequently exhibit altered activation in temporal language regions associated with speech perception and monitoring (Nazari et al., 2012; Preibisch et al., 2003). Reduced or inefficient activity in auditory-language systems may impair the monitoring of speech output and contribute to disruptions in fluency. Consequently, increased activation in the temporal gyrus after treatment may reflect improved neural processing of auditory and linguistic information. Such an interpretation is also compatible with studies emphasizing the importance of neural connectivity and distributed speech networks in fluent speech production (Omidvarnia, 2024; Yan et al., 2025).

The findings of the present study may also be interpreted in light of cognitive and psychological theories related to mental simulation. Mental simulation involves the internal rehearsal of actions, behaviors, and anticipated events, allowing individuals to mentally organize behavioral sequences before actual performance (Taylor & Schneider, 1989). From this perspective, repeated mental simulation of fluent speech patterns may facilitate the reorganization of cognitive and neural processes involved in speech production. Researchers have proposed that mental rehearsal and simulation can activate neural systems similar to those engaged during actual performance, thereby strengthening neural pathways and improving behavioral execution (Casado-Aranda et al., 2022; Kim et al., 2024). The increased activation observed in the central/precentral and temporal regions in the current study may therefore reflect neurofunctional changes associated with repeated mental rehearsal during treatment.

The present findings are also consistent with previous investigations examining the effectiveness of mind simulation therapy in reducing stuttering severity and improving communication attitudes. Akbari reported that the desired behavior modeling technique based on mind simulation reduced stuttering severity among individuals with moderate to severe stuttering (Akbari, 2020). Similarly, Fallahi demonstrated that mind simulation therapy contributed to reductions in stuttering severity and improvements in communication attitudes among children and adolescents who stutter (Fallahi, 2021). Kamarzarin and

colleagues further emphasized the usefulness of mind simulation interventions for individuals with stuttering and psychological difficulties (Kamarzarin, Fallahi, et al., 2021; Kamarzarin, Golestani, et al., 2021). The current study extends these earlier findings by demonstrating that such improvements may also be associated with measurable changes in neural activation patterns observed through fMRI.

Another important aspect of the findings concerns the relationship between emotional regulation, anxiety reduction, and speech fluency. Previous research has shown that individuals with stuttering frequently experience anxiety, communication apprehension, social discomfort, and lower psychological well-being (Ahadi et al., 2012; Emami Meybodi et al., 2016). Increased anxiety may intensify self-monitoring and anticipatory stress during communication, thereby worsening speech disruptions (Ainsworth & Fraser, 1989; Farahmandpour, 2009). Mind simulation techniques may reduce these maladaptive responses by creating greater cognitive preparedness and reducing uncertainty during speech performance. Studies involving real-time fMRI neurofeedback have shown that cognitive interventions can alter activation patterns in emotional and regulatory neural systems associated with anxiety reduction (Nicholson et al., 2024; Scheinost et al., 2021). Although the current study primarily focused on speech-related regions, it is possible that the observed neural changes were partially influenced by reduced emotional stress and improved cognitive regulation during speech tasks.

The findings may also be interpreted from the perspective of neuroplasticity. Neuroplasticity refers to the capacity of the nervous system to reorganize functional connections and neural activity patterns in response to learning and experience. Cognitive rehearsal and repeated behavioral training may strengthen synaptic pathways associated with speech production and monitoring, particularly during childhood when neural systems remain highly adaptable (Kolb & Whishaw, 1947; Taylor & Schneider, 1989). In this context, the increased activation observed after treatment may indicate adaptive neural reorganization associated with repeated mental simulation exercises. Similar patterns of neural modulation have been reported in neurofeedback and fMRI-based intervention studies involving emotional regulation and cognitive training (Kim et al., 2024; Zhang et al., 2025).

The use of fMRI in the present study also highlights the growing importance of neuroimaging methods in speech

pathology and rehabilitation sciences. Functional imaging allows researchers to move beyond purely behavioral observations and examine the neural correlates of treatment response directly. Previous studies have emphasized the value of event-related fMRI paradigms for reducing speech-associated artifacts and improving the reliability of activation measurements in stuttering research (Preibisch et al., 2003). Advances in neuroimaging preprocessing and statistical modeling have further increased the ability to detect subtle treatment-related neural changes (Mostafa, 2025; Ściślewska et al., 2025). Consequently, combining therapeutic interventions with neurofunctional assessment may provide a more comprehensive understanding of how treatment influences speech-related neural systems.

At the same time, the findings should be interpreted cautiously because neural activation increases do not necessarily indicate complete normalization of speech function. Increased activation may reflect improved efficiency, compensatory recruitment, or greater effort during task performance. Therefore, while the observed post-treatment changes suggest positive neurofunctional adaptation, they should be interpreted alongside behavioral speech outcomes and communication performance. The current findings nevertheless support the view that Bigdeli mind simulation interventions may contribute to measurable changes in neural systems associated with speech motor control and language processing.

The present study also contributes to the broader literature on interdisciplinary approaches to rehabilitation. Integrating cognitive intervention methods with neuroimaging technologies may help clinicians better understand individual differences in treatment response and may support the development of more personalized therapeutic strategies. Since stuttering involves complex interactions among neural, cognitive, emotional, and behavioral systems, multidimensional interventions may provide more effective outcomes than approaches focused solely on overt speech symptoms (Gorosi et al., 2010; Jangi Qojabeyglou et al., 2014). The findings of the current study therefore emphasize the importance of considering both neurofunctional and psychological processes in the treatment of childhood stuttering.

One limitation of the present study was the use of a single-case experimental design involving only one participant. Although the design allowed detailed examination of neural activation before and after treatment, the findings cannot be generalized to all individuals with stuttering. In addition, the study did not include a control

group or long-term follow-up assessment to evaluate the stability of neural changes over time. Another limitation was that behavioral speech outcomes were not quantitatively analyzed alongside the neuroimaging findings. Furthermore, factors such as emotional state, task familiarity, and individual neural variability may have influenced the observed activation patterns.

Future research should investigate the effectiveness of Bigdeli mind simulation therapy using larger samples and controlled experimental designs. Longitudinal studies examining the long-term stability of neural activation changes after treatment would also be valuable. Future investigations may additionally compare mind simulation interventions with other therapeutic approaches such as neurofeedback, cognitive behavioral therapy, or speech restructuring programs. Simultaneous evaluation of behavioral speech fluency, emotional functioning, and neural activation may provide a more comprehensive understanding of treatment mechanisms. Moreover, future studies may examine functional connectivity between speech-related neural networks rather than focusing only on regional activation.

From a practical perspective, the findings suggest that Bigdeli mind simulation techniques may be useful as complementary interventions in the rehabilitation of children with stuttering. Incorporating cognitive rehearsal and mental simulation exercises into speech therapy programs may help improve speech motor coordination and language monitoring processes. Clinicians working in speech pathology and child rehabilitation settings may also benefit from integrating neuroscience-informed approaches into therapeutic planning. In addition, the use of functional neuroimaging may help evaluate treatment effectiveness more objectively and may contribute to the development of individualized intervention programs tailored to each patient's neural activation profile.

### Authors' Contributions

All authors significantly contributed to this study.

### Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

### Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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### Declaration of Interest

The authors report no conflict of interest.

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### Ethical Considerations

In this study, to observe ethical considerations, participants were informed about the goals and importance of the research before the start of the interview and participated in the research with informed consent.

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