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LOW-FREQUENCY TRANSCRANIAL MAGNETIC STIMULATION FOR ENHANCING COMMUNICATION IN CHILDREN WITH AUTISM AND SPECIFIC LANGUAGE IMPAIRMENT

Abstract: To evaluate whether low-frequency transcranial magnetic stimulation (TMS) is associated with improvement in speech-language function in children with autism spectrum disorder (ASD) and Specific Language Impairment (SLI), a treatment response difference by stimulation frequency and cortical target was assessed**.** This retrospective observational study analyzed clinical data from 131 children treated at Neurolab Neurorehabilitation Center (Almaty, Kazakhstan), between April 3, 2023, and July 30, 2024. The cohort included 58 children with ASD and 73 children with SLI. Speech-language function was rated before and after treatment using a structured 10-point clinical scale. TMS was delivered to the bilateral dorsolateral prefrontal cortex (DLPFC), with additional stimulation of Broca's and/or Wernicke's areas in selected participants. Frequencies of 0.3 Hz, 0.5 Hz, and 1.0 Hz were analyzed. Each course consisted of 10 daily sessions. Across the total cohort, mean speech-language rating improved from 3.46 to 3.96 points, with a mean improvement of 0.50 points. Improvement was greater in children with ASD than in children with SLI (0.83 vs. 0.25 points). The strongest response was observed in the ASD subgroup treated at 1.0 Hz, where mean improvement reached 2.13 points. In an adjusted linear regression model, the ASD x 1.0 Hz interaction remained significant (coefficient=1.55, p=0.004), while number of treatment courses was positively associated with improvement and motor delays were negatively associated with improvement. Low-frequency TMS was associated with improvement in clinician-rated speech-language function, but the effect was not uniform across stimulation protocols. The findings support the potential of TMS as a protocol-sensitive neuromodulation approach and indicate the need for prospective studies comparing stimulation parameters directly.

Keywords: transcranial magnetic stimulation, autism spectrum disorder, specific language impairment, low-frequency stimulation, speech development, neuromodulation.

Introduction

Human communication and socialization fundamentally rely on speech and language, which are guided by complex neural mechanisms regulated by functional networks in the central nervous system. Excitability and plasticity of cortical regions within these networks are considered to play a critical role in fostering the development of effective communication skills (Nasios et al., 2019). In cases of delayed speech development, such as in individuals with autism spectrum disorder (ASD) or Specific Language Impairment (SLI), they are disrupted, resulting in adverse effects on socialization, cognitive development, and quality of life. ASD is characterized by impairments in social interaction and communication, and by restricted or repetitive interests and behaviors. A major challenge for children with ASD is speech and language development delays, which can be displayed as delays in acquiring language skills or even a complete absence of speech (Mottron & Bzdok, 2020). In contrast, SLI is an isolated speech impairment with preserved cognitive and sensory functions.

Both conditions are the subjects of active research aimed at understanding their neurophysiological bases, developing effective support, and identifying potential treatments. Studies have reported altered brain oscillations, particularly in low-frequency and gamma ranges, in individuals with both ASD and SLI. These disruptions along with the atypical excitation/inhibition signaling and connectivity are theorized to impact the functional activity of cortical networks, reducing the efficiency of language processing (Arutiunian et al., 2024; Bruining et al., 2020; Kessler et

al., 2016; Larson et al., 2023). In SLI and developmental language disorder, current models emphasize procedural and sequence learning, auditory discrimination, and broader functional network differences (Doucet et al., 2025; Hsu & Bishop, 2014; Kujala & Leminen, 2017; Ullman et al., 2020). Considering the association of these disorders with altered cortical excitability and impaired neuroplasticity, neuromodulation methods such as transcranial magnetic stimulation (TMS), which aim to stabilize excitability and promote neuroplasticity, hold promise for improving communication-related symptoms in these patients.

TMS is a non-invasive brain stimulation technique that uses magnetic fields to modulate neural network activity. Repeated low-frequency application of magnetic impulses (LF-TMS; <1 Hz pulses) has been shown to suppress neuronal activity, reduce hyperconnectivity in specific cortical regions, and normalize brain signaling rhythms (Casanova et al., 2020; Gao et al., 2022). In adult patients with post-stroke aphasia, LF-TMS protocols have been shown to promote speech fluency, comprehension, and writing skills (Yao et al., 2020). Its application in pediatric populations opens new avenues for addressing speech and language impairments, considering the high plasticity of the developing brain (Bethlehem et al., 2022). The recent migration of the technique from academic to clinical practice has yielded abundant data useful for establishing specific stimulation protocols across various conditions (Scheper et al., 2022). Of particular interest is low-frequency TMS targeting the dorsolateral prefrontal cortex (DLPFC), involved in cognitive and executive functions related to language processes. LF-TMS reduces hyperactivity in gamma oscillations of children with ASD, improves cognitive performance, and decreases stereotypical behaviors (Casanova et al., 2020; Casanova et al., 2021). Improvements in nonverbal communication and language skills were also reported following LF-TMS to the prefrontal cortex in children with ASD (Tarhan et al., 2023). Several EEG markers of cognitive control in underage participants with ASD were normalized after six to twelve 1 Hz stimulation sessions, along with the improvements in oddball test performance (Sokhadze et al., 2018). One of the challenges in making inferences with this protocol is the wide array of conditions with described results, including improvements in healthy participants' performances in language tasks (Noda, 2021; Quet al., 2022).

Despite growing evidence for the application of TMS in neurological and neurodevelopmental conditions, its impact on speech development in ASD and SLI remains underexplored. Modeling neural circuits in children, whose brains exhibit heightened plasticity, offers unique opportunities to address speech impairments. However, precise parameters for optimizing therapeutic outcomes have yet to be determined. Given the complex relationship between cortical excitability and speech development, we hypothesize that LF-TMS (≤1 Hz) will significantly improve speech development in children with ASD compared to other neurodevelopmental disorders. This hypothesis is based on the unique neural characteristics of ASD, such as increased cortical excitability and altered neuroplasticity, which may facilitate a stronger response to neuromodulation interventions. Previous studies have shown that LF-TMS at 1 Hz targeting the DLPFC can normalize cortical excitability and reduce hyperconnectivity in prefrontal regions, improving cognitive and behavioral outcomes (Hamilton, 2026). Stimulation of the inferior frontal gyrus (IFG), commonly referred to as Broca's area, improved general accuracy in semantic and phonological, but not syntactic tasks or reaction times (Berent et al., 2015). In cases of SLI, additional stimulation of these areas may aid language acquisition. Studies on aphasia recovery suggest that targeting speech-related areas can improve language-related performance, which may be effective for children with speech disorders (Caulfield & Brown, 2022; Noda, 2021).

The primary objective of this study is to explore the therapeutic potential of LF-TMS in children with speech impairments, particularly those diagnosed with ASD and SLI. We aim to assess whether LF-TMS at 1 Hz yields greater improvements compared to other stimulation frequencies and to determine whether additional stimulation of speech-related areas (Broca's and Wernicke's regions) enhances communication. Additionally, the study investigates variables such as delays in gross motor skills development and the number of TMS sessions, which may significantly influence therapeutic outcomes. Preliminary data suggest that patients with ASD may benefit most from 1 Hz stimulation, and factors such as session frequency and motor delays are critical to speech and language development.

Materials and methods

Data was collected from children who underwent LF-TMS between April 3, 2023, and July 30, 2024. The analyzed cohort included 131 children with available pre- and post-treatment speech-language assessments, including 58 children with ASD and 73 children with SLI. A total of 131 children aged 3 to

12 years participated in the study, with a mean age of 7.2 years (SD = 2.3). Participants were required to have completed at least two courses of TMS therapy, and all underwent comprehensive pre- and post-treatment assessments of speech and language abilities. Children with significant neurological comorbidities unrelated to speech and language impairments were excluded, while motor delays, when present, were recorded for subgroup analysis. Baseline speech-language impairment differed between diagnostic groups. Children with ASD had lower baseline scores than children with SLI (mean 2.57 vs. 4.16), indicating greater initial severity in the ASD subgroup. Sex-based subgroup analysis was not performed because sex/gender was not included as a structured variable in the analysis dataset.

Magnetic pulses were delivered using the Neuro-MS/D transcranial magnetic stimulator manufactured by Neurosoft (Ivanovo, Russia). The equipment included a figure-of-eight coil for precise targeting of specific brain regions, including the dorsolateral prefrontal cortex (DLPFC), Broca's area, and Wernicke's area. Stimulation frequencies of 0.3 Hz, 0.5 Hz, and 1 Hz were utilized, with stimulation intensity calibrated individually at 80% of each participant's resting motor threshold (RMT). All 131 participants received DLPFC stimulation. In the structured dataset, 92 participants received additional Broca's area stimulation, 33 received Wernicke's area stimulation, and 19 received combined Broca's and Wernicke's area stimulation. Target combinations were distributed as follows: DLPFC only, n=25; DLPFC + Broca, n=73; DLPFC + Wernicke, n=14; DLPFC + Broca + Wernicke, n=19 Each treatment course consisted of 10 daily sessions. In the analyzed cohort, the number of completed courses ranged from 2 to 8.

To quantify severity and treatment progress, a structured impairment scale was adapted from validated models, mapping clinician-reported observations to a numerical scale ranging from 1 (severe impairment) to 10 (normal development). The scale mapped clinician-reported observations, such as response to name, use of simple words, and functional communication, onto predefined score ranges. This approach was used to standardize retrospective clinical descriptions into an analyzable ordinal outcome, consistent with previous work showing that clinician-rated global scales can be useful for tracking social-communication change in minimally verbal children with ASD (Toolan et al., 2021). Collected data was processed and analyzed using Pandas, Numpy, and Statsmodels Python libraries in the Google Colab environment. Linear regression models were applied to investigate relationships between TMS parameters and speech and language outcomes. Interaction effects were evaluated using linear regression models with interaction termsresults were visualized using Matplotlib and Seaborn libraries.

Ethical Considerations

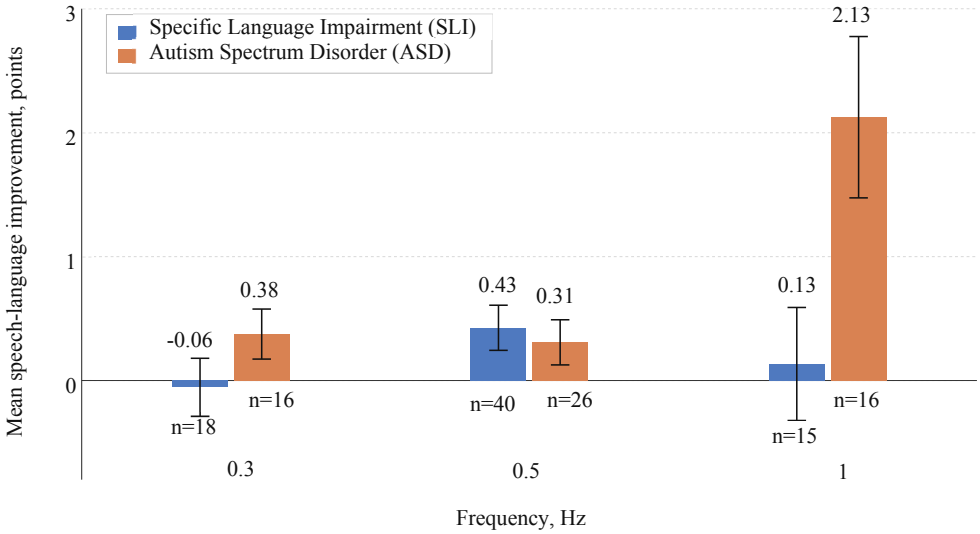
All procedures were approved by the Local Ethical Committee of Al-Farabi Kazakh National University (Protocol No. IRB-A843, IRB00010790, approval date: 23.02.2023), with written informed consent obtained from caregivers before enrollment.

Results and discussion

The final analysis included 131 children, the ASD subgroup included 58 participants and the SLI subgroup included 73 participants (Table 1) Across the total cohort, mean speech-language rating improved from 3.46 before treatment to 3.96 after treatment, corresponding to a mean improvement of 0.50 points. The paired pre/post comparison showed a statistically significant overall improvement in speech-language rating (paired t-test, t=-3.82, p=0.00021). Children with ASD showed a larger mean improvement than children with SLI (0.83 vs. 0.25 points), although baseline severity also differed between groups. The ASD subgroup had lower baseline speech-language scores, suggesting greater initial impairment and a larger potential range for observable improvement. Among stimulation parameters, 1.0 Hz stimulation was associated with the largest speech-language improvement in children with ASD. In the adjusted linear regression model, the ASD x 1.0 Hz interaction remained significant (coefficient=1.55, p=0.004). Assessments of children with ASD were higher in vocabulary comprehension, speech fluency, and sentence construction after a 1 Hz stimulation course, regardless of additional stimulation sites. This aligns with prior literature suggesting that 1 Hz Repetitive Transcranial Magnetic Stimulation (rTMS) of DLPFC can normalize hyperactive cortical oscillations and improve neuroplasticity in individuals with ASD (Casanova et al., 2020; Casanova et al., 2021; Kessler et al., 2016; Sokhadze et al., 2018; Tarhan et al., 2023). Stimulation at lower impulse frequencies did not show comparable effects in this dataset. This may be explained by subgroup size and clinical heterogeneity, but it may also reflect the broader theoretical problem of rTMS parameter selection. Recent reviews emphasize that rTMS outcomes are shaped not only by frequency, but by a wider parameter space including intensity, pulse number, intersession inter-

val, target engagement, and endogenous brain activity (Caulfield & Brown, 2022). Therefore, the present results should not be read as proof that 1.0 Hz is universally optimal, but rather as evidence that the ASD subgroup in this sample was more responsive to this protocol (Figure 1).

Figure 1
Speech-language improvement by stimulation frequency in patients with SLI and ASD. Bars show mean change in the structured speech-language rating from first to last visit; error bars show standard error (SE). Sample sizes are shown on the figure. The largest mean improvement was observed in children with ASD treated at 1.0 Hz



This interpretation is also consistent with network-level models of rTMS. Stimulation of DLPFC may influence not only local cortical excitability, but also distributed networks connected with executive, salience, language, and sensorimotor functions. Systematic review evidence indicates that rTMS can alter resting-state connectivity beyond the stimulated node, and that the classical low-frequency/high-frequency excitability heuristic does not fully explain distal network effects (Beynel et al., 2020). In this context, the interaction between ASD diagnosis and 1.0 Hz stimulation may reflect a better fit between the protocol and the functional network state of this subgroup, rather than a simple frequency effect.

Table 1
Cohort characteristics and speech-language severity by diagnosis

Diagnosis	N	Age, mean	Age, SD	Baseline score, mean	Final score, mean	Improvement, mean	Improvement, SD
ASD	58	5.14	1.89	2.57	3.4	0.83	1.73
SLI	73	4.66	1.80	4.16	4.41	0.25	1.27

In the ASD subgroup, mean improvement was 0.38 points at 0.3 Hz, 0.31 points at 0.5 Hz, and 2.13 points at 1.0 Hz. In the SLI subgroup, mean improvement was -0.06 points at 0.3 Hz, 0.43 points at 0.5 Hz, and 0.13 points at 1.0 Hz (Table 2). Thus, 1.0 Hz appeared to be the most effective frequency for children with ASD in this sample, whereas the frequency-related pattern was less clear in SLI. The small negative mean at 0.3 Hz in the SLI subgroup should not be interpreted as proof of harm, but it is consistent with the broader observation that poorly matched or weakly justified stimulation parameters may produce little benefit and, in individual cases, even minor setbacks.

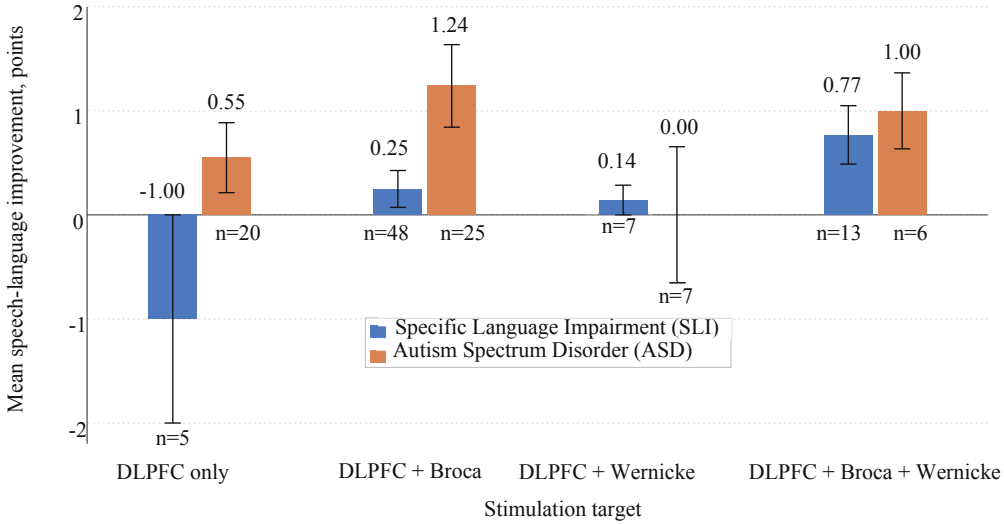
Table 2
Speech-language improvement by frequency and diagnosis

Frequency, Hz	Diagnosis	N	Mean	SD	SE
0.3	ASD	16	0.375	0.806	0.202
0.3	SLI	18	-0.056	0.998	0.235
0.5	ASD	26	0.308	0.928	0.182
0.5	SLI	40	0.425	1.152	0.182
1	ASD	16	2.125	2.604	0.651
1	SLI	15	0.133	1.767	0.456

Preexisting delays in motor abilities were associated with slower speech-language development (β = -1.2028, p = 0.014), consistent with the interconnected nature of motor and language development (Hamilton, 2026). Integrating motor rehabilitation alongside TMS may enhance outcomes for this subgroup. Additionally, the number of TMS sessions was positively correlated with improvements in speech and language abilities scores (β = 0.4748, p < 0.001), which may support the theoretical cumulative effect of intervention, or benefit from sustained rhythmicity of the TMS course (Bethlehem et al., 2022). The model accounted for the time passed between sessions and measures.

Subset of patients with SLI that received LF-TMS on Broca and Wernicke areas expressed better language comprehension and production, with the in-group effects (β = 1.5176, p = 0.004 and β = 1.1497, p = 0.019), respectively. In the overall cohort, the largest mean improvement was observed in children who received DLPFC + Broca + Wernicke stimulation (0.84 points), followed by DLPFC + Broca stimulation (0.59 points), DLPFC-only stimulation (0.24 points), and DLPFC + Wernicke stimulation (0.07 points). These results are consistent with findings in aphasia patients, in whom stimulation of these regions facilitated recovery in language processing (Hamilton, 2026; Nasios et al., 2019; Yao et al., 2020). However, this difference has not shown to be statistically significant in between-group analysis, as well as in the results of participants from the ASD group (Figure 2).

Figure 2
Speech-language improvement by TMS stimulation target in SLI and ASD patients.
Bars show mean change in the structured speech-language rating from first to last visit; error bars show standard error (SE). Sample sizes (n) are shown on the figure. Target-specific findings should be interpreted cautiously because several subgroups were small.



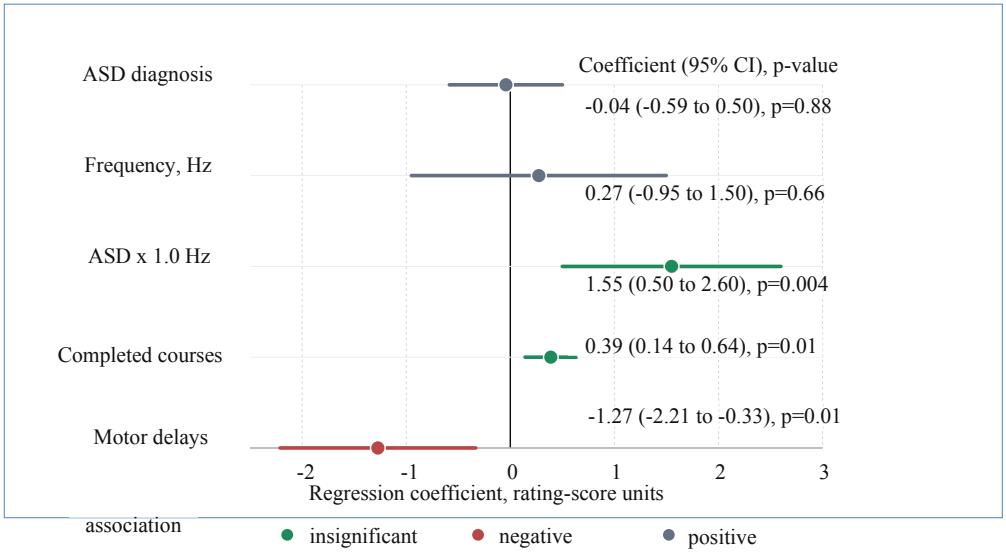
Patterns differed by diagnosis. In children with ASD, DLPFC + Broca stimulation was associated with the largest mean improvement (1.24 points), followed by DLPFC + Broca + Wernicke stimulation (1.00 point), DLPFC-only stimulation (0.55 points), and DLPFC + Wernicke stimulation (0.00 points). In children with SLI, the largest mean improvement was observed in the DLPFC + Broca + Wernicke group (0.77 points), followed by DLPFC + Broca (0.25 points), DLPFC + Wernicke (0.14 points), and DLPFC-only stimulation (-1.00 point) (Table 3). Due to the inequal distribution throughout target-by-diagnosis subgroups, these target-specific results should be interpreted cautiously.

Table 3
Speech-language improvement by stimulation target and diagnosis

Stimulation target	Diagnosis	N	Mean	SD	SE
DLPFC + Broca	ASD	25	1.24	1.99	0.40
DLPFC + Broca	SLI	48	0.25	1.23	0.18
DLPFC + Broca + Wernicke	ASD	6	1.00	0.89	0.37
DLPFC + Broca + Wernicke	SLI	13	0.77	1.01	0.28
DLPFC + Wernicke	ASD	7	0.00	1.72	0.66
DLPFC + Wernicke	SLI	7	0.14	0.38	0.14
DLPFC only	ASD	20	0.55	1.50	0.34
DLPFC only	SLI	5	-1.00	2.24	1.00

The overall pre/post change was statistically significant, but the magnitude and direction of improvements varied across diagnostic, frequency, and target subgroups. The adjusted linear model is summarized visually in Figure 3. The strongest positive association was observed for the ASD x 1.0 Hz interaction, while motor delays were associated with lower improvement. The relatively large variability observed in several subgroups should therefore be considered part of the result rather than only a statistical limitation. Brain stimulation effects are increasingly understood as state-dependent: the same external stimulation can have different consequences depending on ongoing oscillatory activity, connectivity, prior neural activity, and individual neurodevelopmental profile (Bergmann, 2018; Jannati et al., 2022). This framework is compatible with our observation that diagnosis, stimulation frequency, number of courses, and motor delays jointly influenced speech-language change.

Figure 3
Adjusted linear regression model of speech-language improvement.
Markers show regression coefficients in structured speech-language rating-score units, and horizontal bars show 95% confidence intervals. Positive coefficients indicate greater improvement in the structured speech-language rating. The model included diagnosis, stimulation frequency, ASD x 1.0 Hz interaction, number of completed courses, and motor delays



Conclusion

This study provides another argument for the therapeutic potential of LF-TMS for improving speech and language abilities in children with developmental delays. The analysis of the clinical data demonstrates that children with both ASD and SLI diagnoses may benefit from LF-TMS, but the outcomes varied significantly between the two populations. Practitioners are encouraged to rely on diagnostic and neurophysiological profiles of their patients to imply optimal individualized approaches to support and treatment.

A significant improvement in speech and language acquisition was observed in the ASD subset of our sample after 1 Hz TMS on bilateral DLPFC. This observation is consistent with both the literature and clinical practice, as 1 Hz is the most common lf-TMS frequency, as well as the one yielding results more consistently than sub-1 Hz protocols (Casanova et al., 2020; Casanova et al., 2021; Qu et al., 2022). Although the theoretical mechanism is hypothesised to be the same across lf-TMS protocols, our results suggest that a more intrinsic difference may take place instead of a capability to deliver more impulses. On the other hand, improvements in various measures, including speech and language metrics across different disorders and in healthy subjects, may be due to a mechanism non-specific to the condition (Kessler et al., 2016; Qu et al., 2022). More research involving the registry of occilatory and cortical connectivity biomarkers across various stimulation paradigms is highly encouraged. The additional stimulation of the language network nodes yielded conservative, yet noticeable enhancements of the treatment, especially within the subset of patients with SLI. In contrast, lf-TMS, which focused only on the DLPFC, has shown no observable effect in this subset of patients, underscoring the importance of considering the disorder's pathophysiology in the choice of protocol. Despite minimal improvements, the differences in observations across TMS parameters may deem implementation of the method to support the treatment of isolated language impairments a promising direction for future research (Hamilton, 2016).

Network-level models of rTMS suggest that stimulation effects may spread across connected regions and interact with distributed language, executive, and sensorimotor systems (Beynel et al., 2020). This framework may explain why a protocol that is useful in one diagnostic subgroup can be weak or unstable in another. Delays in motor development, on the other hand, were identified as a limiting factor influencing observed improvements in both groups. This finding is consistent with developmental and network-based accounts of language acquisition, in which motor development contributes to communicative experience, gesture, interaction with objects and people, and later speech-language development (Iverson, 2010; Leonard & Hill, 2014; Skipper et al., 2017). It is also consistent with evidence that speech perception and language functions recruit distributed motor-language networks rather than isolated classical language areas (Berent et al., 2015). From this perspective, motor delay may reduce the readiness of the broader motor-language system to benefit from stimulation, and integrating motor rehabilitation strategies with TMS may enhance therapeutic outcomes.

This study takes advantage of the increased use of TMS in clinical settings to explore possible improvements in current practices by analyzing existing data. Apart from the confirmation of the establishing protocol for support in ASD efficacy, the analysis revealed apparent under-performance of the sub-1 Hz protocols as well as added to the scarce data on application of TMS in SLI. We encourage clinical practitioners to consider recent studies and diagnostic profiles of patients in choice of the treatment and stimulation parameters. Measuring and collecting data would also be beneficial to establish standardized supporting approaches to various conditions. More controlled studies are needed to refine protocols and establish magnetic stimulation as an efficient tool for neurorehabilitation.

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Conflict of interest

The authors declare that they have no conflicts of interest.

Author contributions

Amir Baikatov: Conceptualization, Methodology, Formal Analysis, Visualization, Writing – Original draft, Writing – Review and Editing.

Dauren Zhumakhanov: Investigation, Data Curation, Resources, Project Administration, Writing – Review and Editing.

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