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ORIGINAL ARTICLE

Neurofeedback Recuperates Cognitive Functions in Children with Autism Spectrum Disorders (ASD)

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Abstract

Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by impaired social interaction, verbal and nonverbal communication, and behaviors or interests. Besides behavioral, psychopharmacological and biomedical interventions there is increasing evidence of non-invasive treatments like neurofeedback (NFB) that can improve brain activity. In this study, we have investigated whether NFB can improve cognitive functions in children with ASD. Thirty-five children with ASD (7–17 years) were selected by purposive sampling. The subjects underwent 30 sessions of NFB training for 20 min over 10 weeks' period. Psychometric tests i.e. Childhood Autism Rating Scale (CARS), IQ scoring and Reward sensitivity tests were administered at baseline. Pre and post NFB intervention assessment of executive functions, working memory and processing speed were done by NIH Toolbox Cognition Batteries. Friedman test revealed that children showed a statistically significant improvement in the NIH Tool Box cognitive assessments, including the Flankers Inhibitory Control and Attention Test (Pre-test = 3.63, Post-test = 5.22; $p = 0.00$), the Dimensional Change Card Sorting Test (Pre-test = 2.88, Post-test = 3.26; $p = 0.00$), the Pattern Comparison Processing Speed Test (Pre-test = 6.00, Post-test = 11:00; $p = 0.00$) and the List Sorting Working Memory Test (Pre-test = 4.00, Post-test = 6:00; $p = 0.00$), and displayed a trend of improvement at 2-month follow-up (Flankers Inhibitory Control and Attention Test (Post-test = 5.11 ± 2.79, Follow-Up = 5.31 ± 2.67; $p = 0.21$), the Dimensional Change Card Sorting Test (Post-test = 3.32 ± 2.37, Follow-Up = 3.67 ± 2.35; $p = 0.054$), the Pattern Comparison Processing Speed Test (Post-test = 13.69 ± 9.53, Follow-Up = 14.42 ± 10.23 $p = 0.079$) and the List Sorting Working Memory Test (Post-test = 6.17 ± 4.41, Follow-Up = 5.94 ± 4.03; $p = 0.334$). Our findings suggest NFB intervention for 10 weeks produce improvement in executive functions (Inhibitory Control and Attention and Cognitive Flexibility), Processing Speed and Working Memory in ASD Children.

Keywords Autism spectrum disorders · Neurofeedback · Cognitive functions · Executive functions

Introduction

Autism spectrum condition (ASD) is a neurodevelopmental disorder that influences physiological processes, cognition, functional behaviors, social-communication, and is frequently associated with co-morbidities (Lucido, 2012). The pathophysiology of ASD may be attributed to the combination of genetics, environmental exposures, epigenetics, immunology, metabolic and electrophysiological impairments, that result in atypical synchronization of brain activity affecting information processing (Compart, 2013; Holiga et al., 2019).

Coben et al. (2013) via variable resolution electromagnetic tomography (VARETA) images found consistent trends in neuroanatomical abnormalities and bilateral cortical dysfunction in ASD. Hyper-connectivity and complex connectivity patterns of neuronal pathways (Li et al., 2014; Wass, 2011), pre-frontal cortex, cerebellar and striatal dysfunction lead to motor and cognitive abnormalities leading to behavioral changes (Fuccillo, 2016). Studies have also shown the existence of an association between

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neural substrates and social cognition dysfunction as well as deficits in language (Just et al., 2004; Pelphrey et al., 2004). This lack of neural synchronization is responsible for language deficits in autism. Autism hampers language by influencing the left side of the brain and affects the social interactions and communication by effecting the right side of brain (Travers & Alexander, 2013). Catani et al (2008) in his research revealed that the short intracerebellar fibers had lower fractional anisotropy causing severe social impairment. Motor learning, development of motor skills and other non-motor processes may all be hampered by such deficiencies. These studies support the notion that connectivity alterations in autism leads to functional idiosyncrasy.

Neurofeedback does not only influence EEG power frequencies (Kouijzer et al., 2009a, 2009b; Scolnick, 2005) effectively, but it can also modify connectivity and coherence patterns across various brain areas (Coben & Padolsky, 2007). It helps a subject to learn to regulate his brain and cognitive functions (Arns et al., 2017). Infra low frequency (ILF) neurofeedback has recently been observed to significantly modify functional connectivity in various regions of brain and neural networks (Dobrushina et al., 2020; Rauter et al., 2022). Clinical studies suggest the beneficial effects of ILF-NFB in various illnesses (Othmer & Othmer, 2011) like depression (Grin-Yatsenko et al., 2018), ADHD (Schneider et al., 2021), Chronic Eating Disorder (Winkeler et al., 2022), Comorbid Post-Traumatic Stress Disorder (Winkeler et al., 2022), Chronic pain (Shapero & Prager, 2020) and for improving optimum performance, its use as a treatment strategy for ASD may therefore be beneficial.

Evidence shows that early intensive training programs like Naturalistic Developmental Behavioral Interventions, applied behavior analysis (ABA) and pharmacological treatments improve the symptoms of ASD (Jensen & Sinclair, 2002; Landa, 2018). Recently NFB has emerged as a non-invasive therapy that modifies neuronal activity through visual and auditory feedback signals and can be used for neurodevelopmental disorders. Since, the neurofeedback training does not cause any adverse effects, therefore utilization of NFB for neurodevelopmental disorders has increased in the past few years (Arnold et al., 2013; Holtmann et al., 2011). Studies have exhibited improved executive functioning, communication and social interactions in ASD children after neurofeedback intervention (Friedrich et al., 2015; Kouijzer et al., 2009a, 2009b; Kouijzer et al., 2010). But mostly subjective tools are used for the assessment of Cognitive Functions such as Trail Making Test (TMT) and Stroop Test. Objective tools have not widely been used in the assessment of Cognitive functions for ASD. No NFB intervention has been assessed using these objective tools. We assessed the cognitive functions using objective cognitive tools after NFB Intervention.

Therefore, the main objective of our study was to assess the impact of Infra low frequency neurofeedback on the executive functions, processing speed and working memory of ASD children.

Methods

This was a single arm Pre and Post intervention study carried out from June 2021 to June 2022 at Shaheed Zulfiqar Ali Bhutto Medical University (SZABMU), Islamabad and Institute of Basic Medical Sciences (IBMS), Khyber Medical University (KMU), Peshawar, Pakistan. Purposive sampling technique was utilized.

Participants

Figure 1 shows the recruitment of participants (Fig. 1). Children and Adolescents age 7–17 years diagnosed with Autism by the psychiatrist using DSM (Diagnostic and Statistical Manual of Mental Disorders) V were included in the study. Mean age of the participants was 10.89 ± 3.66 years with 68.6% males and 31.4% females. Children with a brain trauma history or diagnosed with Tourette's syndrome, an uncontrolled seizure disorder, bipolar disorder or a history of any other psychiatric ailment were excluded from the study. Moreover, children on medications and any systemic disorders or enrolled in other trials were excluded from the study. Twenty five percent among the participants were diagnosed with ASD for the last 5 years. Most of the participants had co-morbid illnesses where gastrointestinal problems and sensory sensitivities were the most reported complaints (14.3%), 28.6% had history of medical illness, however 71.4% reported no medical history. History of family illness was only prevalent among 2.9% children with ASD.

Procedure

The ethical approval of study was obtained from Ethical Review Committee. Written informed consent was taken from all parents and assent from the eligible children. Data regarding age, socioeconomic status, educational status of

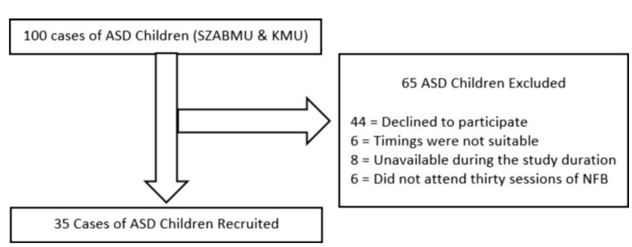

Fig. 1 Flow diagram showing recruitment of participants

participants, past medical history, history of genetic or any other chronic medical illness, was collected using a questionnaire. At the baseline, psychometric tests i.e. Childhood Autism Rating Scale (CARS), IQ scoring (Colored Progressive Matrices (CPM) and Reward sensitivity tests were performed. NIH Toolbox Cognition Batteries were used for the assessment of attention control, cognitive flexibility, working memory and processing speed. The tests in this battery are sensitive to cognitive dysfunction across a range of disease severities and across various age ranges. Participants received neurofeedback training thrice a week for 10 weeks (30 sessions in total). An Evaluation of the cognitive functions was done before and after NFB training and at follow-up (after 8 weeks).

Psychometric Testing

Childhood Autism Rating Scale (CARS)

Childhood Autism Rating Scale (CARS) is a behavioral rating scale consisting of 15 items developed to recognize children with ASD, and to differentiate them from developmentally handicapped children. CARS scores was determined by aggregating the fifteen individual ratings and the total CARS score can fall between 15 and 60. Children with scores between 30 and 36.5 are classified as mild to moderately autistic, while those with values between 37 and 60 are classified as severely autistic.

IQ Scoring [Colored Progressive Matrices (CPM)]

CPM can be utilized to evaluate the intellectual capacity of children and adults. It provides a raw score that, using the normative score as a base, can be converted to a percentile. Three sets (A, Ab, and B) of twelve items each make up Raven's CPM.

Reward Sensitivity Testing

Reward Responsiveness (RR) scale taps a one-dimensional construct. It has good internal consistency with Cronbach's alpha of 0.80. There are 8 items in this scale. By adding up all of the pertinent items, a final RR score is obtained.

Core Cognition Measures

Following cognition measures were assessed before and after Neurofeedback training and at follow-up of 8 weeks on the iPad Screen utilizing NIH Toolbox battery.

Inhibitory Control and Attention

It was evaluated by the NIH Toolbox Flanker Inhibitory Control and Attention Test (Flanker). In order to pass this test, the autistic child had to narrow his or her attention to the stimulus in front of them while sustaining their focus on it. There were twenty trials and took around three minutes. Accuracy and response time scores were combined to determine the final score. The computed score has a range of 0–10.

Cognitive Flexibility

It was checked by the NIH Toolbox Dimensional Change Card Sort Test (DCCS). A series of bivalent test photographs and target pictures were given to the kids to match. Additionally, "switch" trials were used, in which participants were asked to switch the dimension being matched. The administration of this test took four minutes. Accuracy and reaction time scores were used to determine scoring, with higher scores indicating greater cognitive flexibility. The computed score ranges between 0 and 10.

Working Memory

It was checked by NIH Toolbox List Sorting Working Memory Test (List Sorting) which is a measure of working memory which requires participants to immediately recall and arrange a variety of audibly and visually presented items. The test was administered for about seven minutes. List sorting test scores are calculated by adding the correctly recalled and ordered items on lists 1 and 2, with a range of 0–26. Higher normative values indicate greater working memory capacity.

Processing Speed

It was evaluated using the NIH Toolbox Pattern Comparison Processing Speed Test (Pattern Comparison). It was performed by asking the autistic child to quickly determine whether or not the two photos that were side by side were similar. Each child was given 85 s to answer. The images were shown one pair at a time (up to a maximum of 130). The administration of this test took around three minutes. The raw score of the test taker was equal to the correctly answered items, in a response time of 85 s, ranging between 0 and 130.

Neurofeedback

The neurofeedback intervention was conducted using neurofeedback system from BEE Medic Inc. (Germany), which consisted of software Cygnet® (BEE Medic Inc., Germany) and an EEG differential amplifier EEG NeuroAmp® II (Corscience Inc., Germany). The amplifier had two channels, a full bandwidth (DC to 100 Hz), a sampling rate of 500 sps, 32-bit resolution, and an integrated impedance meter. To ensure proper conductivity, the scalp at the electrode application site was first cleaned with a paste (Nuprep®; Weaver and Company, USA). Afterwards, the electrodes were applied utilizing a conductive paste (Ten20®; Weaver and Company, USA). The neurofeedback training was carried out during sessions 1–30 utilizing a high-resolution gaming laptop running Windows 10 and the Cygnet System combined with Somatic Vision Video feedback.

During neurofeedback training participants monitor their own brain waves via audio–video feedback to learn reinforcement and compensation. To enhance the cognitive functions of ASD children and adolescents, Infra-Low Frequency (ILF) neurofeedback was done as per the protocol developed by Othmer (2017). The goal of this ILF neurofeedback therapy was to control core neuro-regulatory networks including default mode, salience and central executive networks.

Appointment based sessions were conducted in the research lab, face to face in a noise-controlled setting, comfortable seating, no distractions via telephone calls or interruptions from staff, ensuring privacy and in the presence of parents/guardian. The standard method of placement of electrodes, as developed by Othmer and adopted in Othmer method was used (Othmer, 2017). Every session consisted of an EEG recording that was carried out using a bipolar electrode montage at T4–P4 site, with reference electrode (of both channels) at Cz and a grounding electrode at Fpz. Each participant received 30 separate 15–20 min Neurofeedback sessions over 10 weeks period. This procedure took a total of 35 min, divided into two 10-min training periods, a 5-min respite period in between, and a 10-min rest period at the end.

Statistical Analysis

For data analysis SPSS version 25 was used. Frequency analysis was done for demographic data. Data was tested for skewness and kurtosis and findings revealed that skewness and kurtosis were high. The findings suggested non-parametric testing of data. Friedman and Post Hoc Test were utilized for Comparison of Cognitive functions at Pre-Intervention, Post-Intervention and Follow up in children with ASD. For gender comparison of cognitive functions before and after neurofeedback training, Mann Whitney U Test was utilized. Spearman's Correlation was used to assess the relationship between CARS Score and cognitive functions.

Results

The mean CARS score for mild-moderate autism was 33.89 ± 2.04 while mean CARS score for severe autism was 47.31 ± 2.90. Frequency and percentage analysis computed to assess the levels of intelligence quotient depicts that 48.6% were intellectually average, 25.7% were intellectually defective, 22.9% were below average in intellectual capacity and 2.9% were above average in intellectual capacity.

There has been a significant improvement in all cognitive tests from pre-intervention to post-intervention, however, no significant changes are observed in the follow-up compared to post intervention (Table 1).

A statistically significant Improvement after neurofeedback training was observed in the Inhibitory Control & Attention ($\chi^2(2) = 51.60$, $p < 0.001$), Cognitive flexibility ($\chi^2(2) = 30.27$, $p < 0.001$), Processing speed ($\chi^2(2) = 32.96$, $p < 0.001$) and Working Memory ($\chi^2(2) = 26.87$, $p < 0.001$). Post hoc analysis with Wilcoxon signed-rank tests was done with a Bonferroni correction applied, and a significance level set at $p < 0.017$. Median (IQR), UQ and LQ values for pre-intervention, post-intervention and follow-up for inhibitory control & attention, cognitive flexibility, processing speed and working memory are shown in the graphs (Fig. 2).

A *Mann–Whitney U test* was conducted to determine differences in cognitive functions across genders before and after neurofeedback. Figure 3 shows that no significant differences were observed in inhibitory control and attention (Pretest: Z = − 1.51, U = 89.50, $p > 0.05$), cognitive flexibility (Pretest: Z = − 0.08, U = 129.50, $p > 0.05$) and working memory (Pretest: Z = − 1.56, U = 89.50, $p > 0.05$) before neurofeedback. Also, no significant differences were observed in inhibitory control and attention (Posttest: Z = − 1.36, U = 93.50, $p > 0.05$), cognitive flexibility (Posttest: Z = − 1.12, U = 100.50, $p > 0.05$) and working

Table 1 Comparison of cognitive functions through NIH toolbox at pre-intervention, post-intervention and follow up in ASD children

Cognitive functions	Pre-intervention (Pre) (median)	Post-intervention (post) (median)	Follow up (FU) (median)	*P* value		
				Pre versus post	Pre versus FU	Post versus FU
Inhibitory control and attention	3.63	5.22	5.57	0.000	0.000	0.21
Cognitive flexibility	2.88	3.26	3.63	0.000	0.000	0.054
Processing speed	6.00	11.00	12.00	0.000	0.000	0.079
Working memory	4.00	6.00	6.00	0.000	0.000	0.334

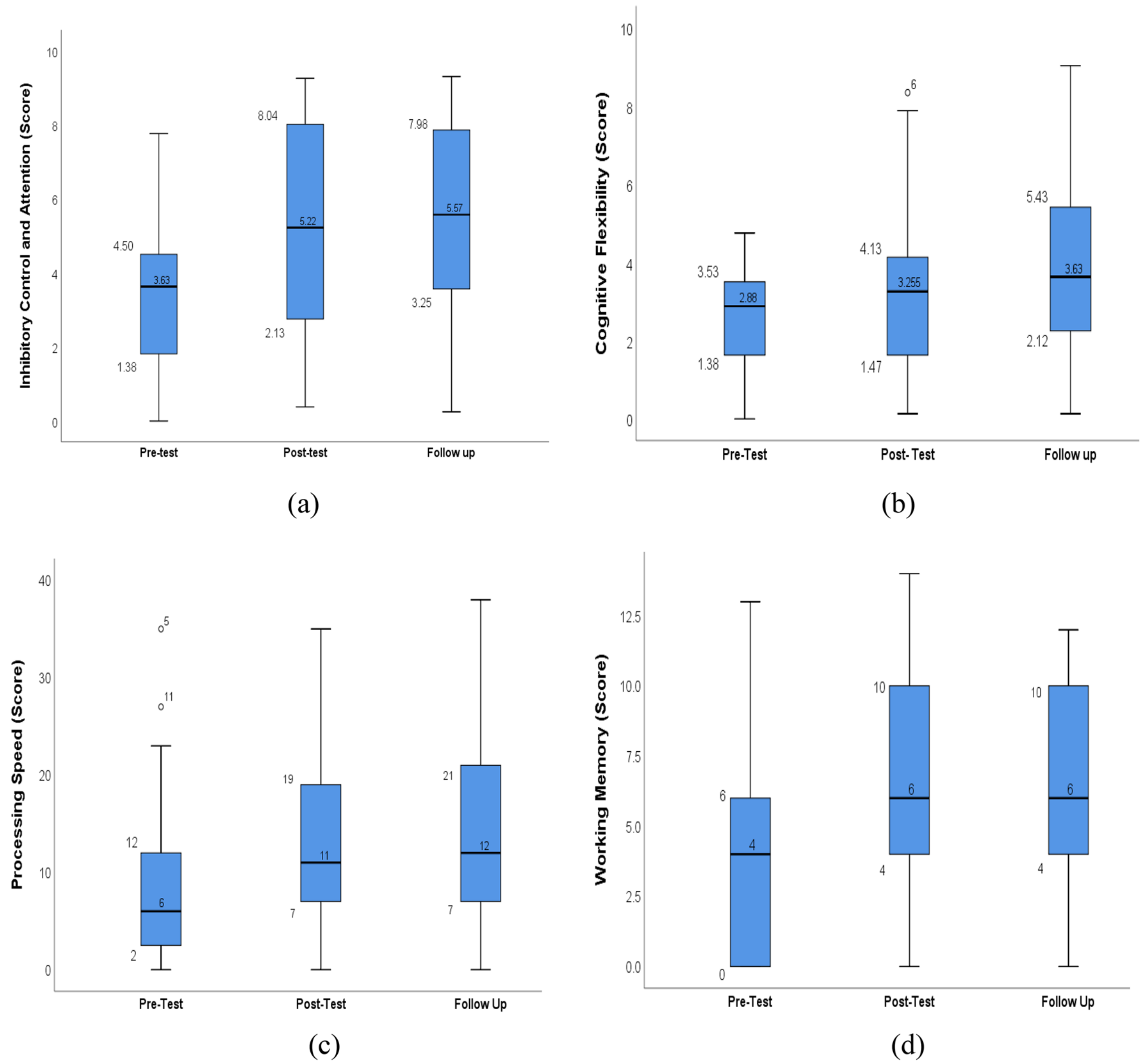

Fig. 2 Comparison of cognitive functions (Median (IQR), UQ, LQ) through NIH toolbox at pre-intervention, post-intervention and follow up in children with ASD

memory (Posttest: $Z = -1.80$, $U = 82.00$, $p > 0.05$) after neurofeedback. In contrast, male and female ASD children showed significant differences with regards to pre (Pre-test: $Z = -2.10$, $U = 73.00$, $p < 0.05$) and post (Posttest: $Z = -2.261$, $U = 68.50$, $p < 0.05$) intervention processing speed (Fig. 3).

Correlation was computed to assess the relationship between Cognitive Functions and CARS Score before Neurofeedback training among the children with autism spectrum disorder. Figure 4 shows a negative relationship of CARS Score with inhibitory control and attention ($r_s = -0.37$, $p = 0.026$), Cognitive Flexibility ($r_s = -0.47$, $p = 0.004$), processing speed ($r_s = -0.48$, $p = 0.003$) and working memory ($r_s = -0.66$, $p = 0.000$) indicating improved cognitive functions with decreased severity of autism (Fig. 4).

Correlation was also computed to assess the relationship between Cognitive Functions and CARS Score among the children with autism spectrum disorder after Neurofeedback training. Figure 5 reveals a negative relationship of CARS Score with inhibitory control and attention ($r_s = -0.43$, $p = 0.010$), Cognitive Flexibility ($r_s = -0.43$, $p = 0.008$), processing speed ($r_s = -0.52$, $p > 0.001$) and working memory ($r_s = -0.68$, $p = 0.000$) indicating improved cognitive functions with decreased severity of autism (Fig. 5).

Discussion

We aimed to check the effectiveness of Neurofeedback. Our findings reveal that 10 weeks of NFB improved the executive functioning (Inhibitory control, attention and cognitive

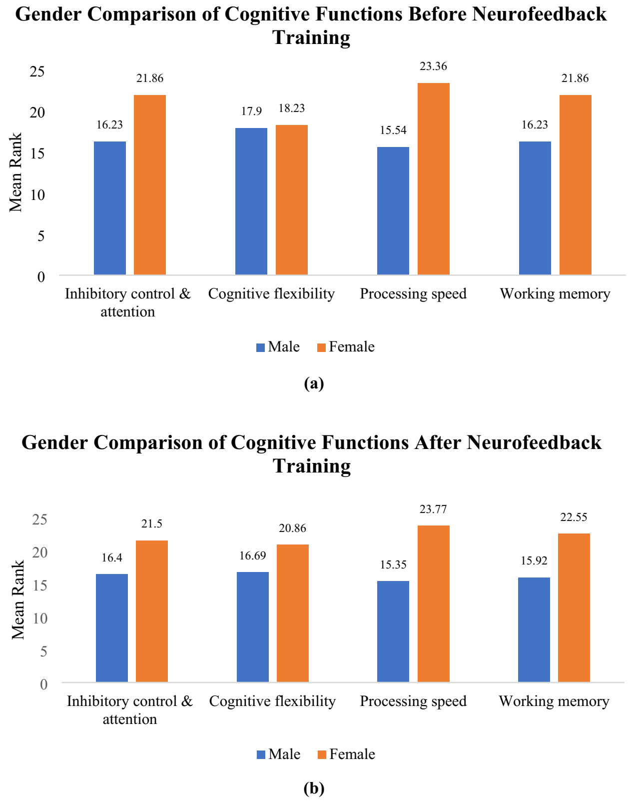

Fig. 3 Gender comparison of cognitive functions before (**a**) and after (**b**) neurofeedback training

flexibility), processing speed, and working memory in ASD. There has been a significant improvement from pre- to post-intervention, however, improvement was maintained at follow up. Several studies (Jarusiewicz, 2002; Kouijzer et al., 2009a, 2009b; Rauter et al., 2022) have been carried out to explore the effectiveness of NFB in ASD. But mostly subjective tools are used for the assessment of cognitive functions such as Trail Making Test (TMT) and Stroop Test. Objective tools have not widely been used in the assessment of Cognitive functions for ASD. No NFB intervention has been assessed using these tools.

Our study showed an improvement in executive functions (Inhibitory control and attention and cognitive flexibility) after NFB. Similar to the findings of our study Kouijzer et al. (2009a, 2009b) found that executive capacities (Attentional control and cognitive flexibility) of ASD children were significantly improved after 20 weeks of NFB therapy. Since cognitive flexibility allows the dynamic activation and modulation of cognitive activities in response to varying requirements of task (Varanda & Fernandes, 2017), NFB training will help them to adjust to different demands and task contexts, change attentional focus, improve social interaction, creative thinking, spatial navigation and planning. Improvements were also observed in communication and behavior. We found that after 8 weeks of cessation of NFB, improvements were maintained. Similarly, Kouijzer et al. (2009a, 2009b) showed that improvements in executive control were maintained or augmented 12 months after the cessation of training sessions. It suggests that NFB training results in long lasting improvement in executive functions and social behavior. They proposed that NFB induces changes in EEG-power resulting in augmented activation of the anterior cingulate cortex (ACC), which brings long lasting improvement in cognitive functions. Both the studies observed an improvement in executive functions but they utilized Continuous Performance Test (CPT), Test of Sustained Selected Attention (TOSSA), Stroop test, Response inhibition score, Verbal Memory Test (VBM), Visual Memory Test (VIM), Trail Making Test (TMT), Milwaukee Card Sorting Test (MCST) and Tower of London (TOL) whereas we used NIH tool box for assessing executive functions. Likewise, Pineda and colleagues (2014) and Vosooghifard et al (2013) also showed improved social communication and cognition after NFB.

A case control study regarding neurofeedback therapy in ASD by Coben and Padolsky (2007) also supports our findings. Unlike the utilization of NIH tool box for cognitive assessment in our study they used a broad range of assessments including neuropsychological tests, QEEG analyses, parental judgment of outcome, infrared imaging and behavior rating scales. An 89% success rate of NFB and approximately 40% decrease in core ASD symptoms were reported based on parental judgment. The positive clinical outcomes in these subjects were associated with reduction in cerebral hyper-connectivity. Moreover, no follow up data of the participants was reported by them. Secondly the assessments were mostly subjective in contrast to our NIH Tool Box. They provided 20 sessions of NFB while we provided 30 sessions which might be the reason for a more significant improvement in executive functions in our study. Furthermore, the mean age was higher in our study which might suggest their better performance in carrying out the cognitive function tests themselves. Also, they used the conventional theta/beta protocol that targets spectral power of EEG in 0.5–50 Hz frequency band while we used ILF-NFB which targets slow cortical potentials (SCP), with the EEG power below 0.1 Hz. ILF-NFB is a cutting-edge technique which directly regulates cortical excitability and improves the performance of cognitive tasks. It is recommended as an evidence-based treatment for various mental disorders (Grin-Yatsenko et al., 2020) especially the autistic brains (Rauter et al., 2022). ILF neurofeedback has the advantage of recording full-band EEG, as well as surface potential in the ILF range and supra threshold frequencies of nine distinct power bands in the spectral range of 0.5–40 Hz, and processing the data to produce audio-visual feedback signals for the participant (Rauter et al., 2022). Deficits in executive

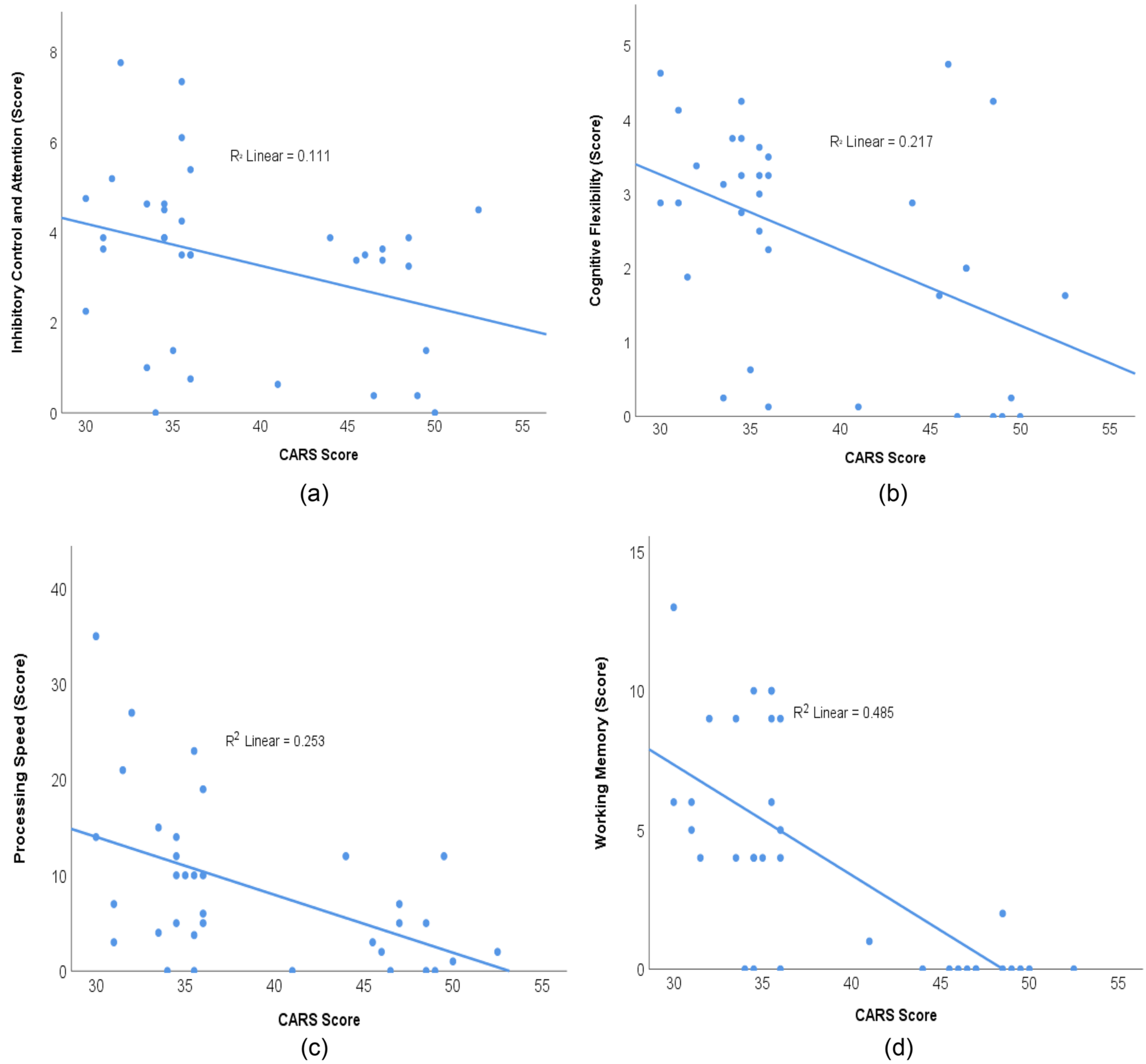

Fig. 4 Correlation between inhibitory control and attention (**a**), cognitive flexibility (**b**), processing speed (**c**), working memory (**d**) and CARS score before neurofeedback intervention

function linked with autism have been ascribed to dysfunction of frontal lobe leading to the inability to shift attention and perseveration (Coben & Padolsky, 2007).

Consistent with our findings of improved executive functions Sokhadze et al (2014) also exhibited that neurofeedback improves executive functions like attention to targets, reduced over-reactivity to non-targets, radically decreased motor response errors to target stimuli in subjects with ASD. In contrast to our ILF-NFB they used integrated transcranial magnetic stimulation (TMS) neurofeedback (TMS-NFB, N = 20) to assess the impact of 18 sessions on behavioral responses, event-related potential (ERP) recording, and other functional and clinical outcomes. They suggested that by exaggerating inhibitory tone and enhancing lateral inhibition, low frequency TMS improves executive functions. Self-regulation training method that may further improve executive functions is prefrontal neurofeedback.

Study by Scolnick (2005) on children with Asperger's disorder also showed improvements in behavior after NFB but the results were not significant. The exact cause of these insignificant results remains unclear but it might be due to the high drop-out (5 out of 10). Ramot el al (2017) utilized real-time fMRI neurofeedback and observed changes in resting state connectivity patterns and behavior, proposing that

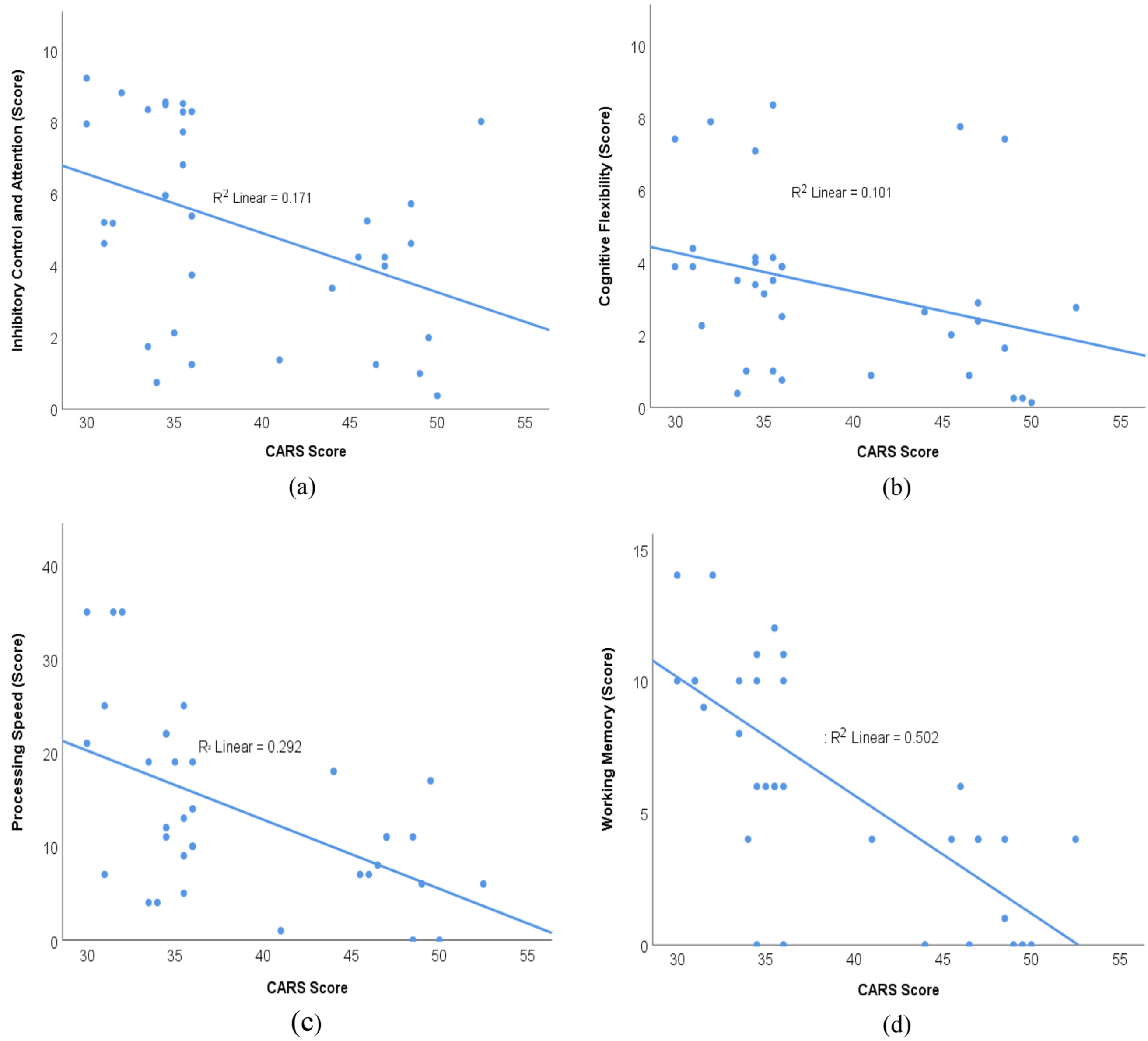

Fig. 5 Correlation between inhibitory control and attention (**a**), cognitive flexibility (**b**), processing speed (**c**), working memory (**d**) and CARS score after neurofeedback intervention

NFB can be utilized to directly modify complex, network connectivity patterns. It suggests that fMRI neurofeedback may also play a role in enhancing cognitive functions. This method enables implicit training of networks, such as those that were discovered to be under-connected in ASD, by allowing for the real-time monitoring of network states and the reinforcement of desired ones through positive feedback.

Moreover, we observed an improvement in processing speed of ASD children after NFB. The rate at which simple perceptual and cognitive activities can be carried out is called cognitive processing speed. Typically, this is assessed under time pressure, which requires focused attention (Yumba, 2017). Our study shows that deficits of processing speed in autism may be improved by NFB and can result in a decreased reaction time leading to improved decision making, basic mathematical calculations and manipulating numbers. Similar to our findings Kouijzer et al. (2009a, 2009b) in his study found improvement in speed and efficiency after NFB. No significant decline in speed and efficiency was found between post-intervention and follow-up data. This is similar to our findings where processing speed was improved after NFB intervention and also at Follow up. We targeted the parietal regions for NFB training in our study. In contrast to our study, Lucido et al. (2012) found that neurofeedback had no discernible effects on processing speed, which may have been due to the training's site selection. The training excluded the parietal and occipital lobe regions, which studies have related to processing speed (Peers et al., 2005). Nonetheless, the chart did demonstrate a trend towards progress over the course of the 20 sessions, which implies additional training might have produced a noticeable improvement.

We found an improvement in working memory as well after NFB training. Similar to our results Martínez-Briones et al. (2021) found that NFB training improved the speed of working memory retrieval in children with learning disorders. Improved Working memory has a positive impact on academic achievements, and an improved response time in a task involving memorizing numbers is a significant finding. Since working memory is a cognitive process responsible for processing and storing information during challenging cognitive activities like learning, reasoning and comprehension so NFB training may help the children in improving comprehension and understanding by storing relevant information (Yumba, 2017). There is paucity of data regarding the effects of NFB on working memory in ASD children. However positive effects of NFB on working memory have been observed in children with ADHD (Ensafi et al., 2014; Hasslinger et al., 2022).

Recent studies on ASD adolescents have also revealed that ASD-symptoms (social cognition and motivation) (Konicar et al., 2021) executive functions (Prillinger et al., 2022) and psychopathological symptoms (Werneck-Rohrer et al., 2022) are improved substantially after NFB. Moreover, consistent with our outcomes Mekkawy et al. (2021) also proposed that cognitive function impairment in ASD can be decreased through NFB training but unlike our objective tools of cognitive assessment they utilized the traditional questionnaire-based tests.

Several research studies explicitly reported improvements in cognition and social behavior after neurofeedback therapy among ASD children (Friedrich et al., 2015; Kouijzer et al., 2010; Zivoder et al., 2015). Nevertheless, results of these studies must be construed cautiously, as these studies had quite small sample sizes (n = 10 to n = 28). Studies (Kouijzer et al., 2009a, 2009b; Kouijzer et al., 2010) observed noteworthy maintenance and improvements in executive function and social behavior at 1-year follow-up. Another research work exhibited that, though neurofeedback therapy did not considerably decrease symptoms of ASD, it did bring an improvement in cognitive flexibility, which was maintained at 6 months follow-up (Kouijzer et al., 2013). These studies further support our results that neurofeedback has a long-term impact on the improvement in cognitive capacities.

Our results also show that male and female children with ASD have no significant differences with respect to improvements in executive functioning and working memory but the processing speed was found to be significantly improved in female participants in comparison with the male participants. Regarding gender differences, Kothari et al. (2013) support our findings that emotional processing is impaired in boys on spectrum in comparison with the girls on spectrum, assuming that perhaps ASD girls compensate their underlying deficits. Hull et al. (2017) assessed gender variations in performance of cognitive flexibility tasks and found that no differences on the Wisconsin card sorting test, whereas performance on the Trail Making Test was better in females. In addition, Werneck-Rohrer et al. (2022) also looked at gender variations regarding improvements in cognitive flexibility, emotion recognition abilities and psychopathological symptoms in autistic teenagers but found no statistically significant gender-related variances.

Moreover, we observed a significant negative correlation between CARS score (Severity of Autism) and cognitive functions including Inhibitory control, attention, cognitive flexibility, processing speed and working memory. A negative correlation has been observed between CARS Score and Inhibitory Self Control, Flexibility, Inhibition and Working Memory (Mahdavi et al., 2017; Miller, 2018). It elucidates that greater the severity of autism, the higher the CARS Score and the lower are the executive functions (Inhibitory Control and attention, cognitive flexibility, processing speed and working memory). However, we didn't assess the CARS score at the end of the intervention. The limitations of our study consist of the inclusion of the population from one center and limited generalizability due to small sample size. Nevertheless, our research exhibited that children with ASD can benefit from Neurofeedback intervention. It is suggested to conduct Randomized Control Trials for comparison of NFB and other adjunct therapies. Furthermore, shorter and longer duration with variable sessions of NFB and bigger population may yield robust results. Assessment of biochemical parameters assessment and comparison with FMRI may be beneficial.

Conclusion

Our findings suggest that in children and adolescents with ASD, Infra-low frequency NFB has significant positive effects on cognitive functions which means NFB has a potential effect on neurofunctional substrates of cognitive functions.

Author Contributions SS made substantial contributions to the conception and design of the work, acquisition, analysis and interpretation of data. She drafted the work and revised it critically for important intellectual content. She approved the version to be published. She agree to be accountable for all aspects of the work in ensuring that questions

related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. SHH made substantial contributions to the conception and design of the work as well as interpretation of data. He revised the content critically for important intellectual content. He approved the version to be published. He agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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