NEW RESEARCH

Neuroplasticity-Based Targeted Cognitive Training as Enhancement to Social Skills Program: A Randomized Controlled Trial Investigating a Novel Digital Application for Autistic Adolescents

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Objective: Few evidence-based social cognitive interventions are available to autistic youth as they navigate their complex, socially demanding teenage years. Building from pilot research using neuroplasticity-based targeted cognitive training, CICADAS (Care Improving Cognition for ADolescents on the Autism Spectrum), a digital application (app) designed to prime the brain for socio-affective learning, was developed. In a randomized active-controlled trial with 3 comparison arms, CICADAS was evaluated as a stand-alone program and as an augmentation to evidence-based PEERS (Program for the Education and Enrichment of Relationship Skills).

Method: Recruiting from clinics providing PEERS, 62 adolescents (11-18 years old) with confirmed autism were enrolled. Adolescents scheduled to start PEERS were assigned using block randomization to PEERS + CICADAS (n = 22) and PEERS + Active Control (n = 21) groups. A third comparison group (n = 19) comprised adolescents who used the app as a stand-alone intervention (CICADAS only). In addition to in-app performance metrics, data were collected from social, behavioral, and cognitive assessments (self-report/parent-report measures) at preintervention (baseline), postintervention (16 weeks), and follow-up (32 weeks) sessions.

Results: Significant effects of group, time, and group × time interaction were found on multiple measures collected longitudinally. For example, on the Pediatric Quality of Life Inventory, PEERS + CICADAS participants showed significant psychosocial health improvements ($F = 6.862$, $p = .002$) over the study timeline compared with trend level gains in the CICADAS only ($F = 2.150$, $p = .122$) and PEERS + Active Control ($F = 1.917$, $p = .153$) groups. Whereas all participants improved from baseline on the Social Responsiveness Scale, 2nd Edition ($F = 11.038$, $p < .001$), only the PEERS + CICADAS group gained significantly ($F = 3.786$, $p = .026$) on the social cognition subscale across all 3 time points.

Conclusion: Our data demonstrate the potential of CICADAS as a stand-alone intervention and suggest that engaging with the adaptive app (vs static active control) conferred an additional advantage to autistic teens participating in PEERS.

Key words: adolescent; autism; cognitive training; randomized controlled trial; social skills

JAACAP Open 2026;■(■):■-■.

Autism spectrum disorder (ASD) is a heterogeneous condition characterized by persistent challenges with social communication and interaction, restricted interests, repetitive behaviors, and atypical responses to sensory stimuli.[1] Although diagnosis may occur throughout the lifespan, symptoms tend to appear in the first 2 years of life. Accordingly, considerable effort has been directed toward improving early identification and interventions[2] such that fewer studies have investigated the particular experiences of older autistic[3] youth. Yet, it is during the teenage years that neural networks underpinning socioemotional processing undergo key adaptive changes alongside and in response to increasingly complex social networks and demands.[4,5] These processes begin to functionally mature in mid-adolescence,[6] a period of heightened experience-dependent learning identified as a second window of opportunity for neural plasticity.[7,8] For autistic teens who struggle with novel situations and interpersonal interactions, avoidance of distressing contexts and expectations may hinder development of essential experience-dependent social and cognitive skills.[4,9] These challenges are especially concerning for adolescents on the autism spectrum, given that high rates of comorbid depression and withdrawal, as well as heightened anxiety, may increase with social isolation.[10–12] (Note that in accordance with autistic community preference, we employ identity-first language, eg, autistic person, throughout our article.[3])

Although recent advances in telecommunication and telehealth[13] have facilitated the adaptation of more therapies to include efficacious remote-delivery and hybrid options,[14–16] the landscape of evidence-based, social cognitive interventions for autistic teens remains sparse.[17] As such, novel approaches designed to provide support during the critical period of adolescence are needed. Innovations in the development of computerized and neuroplasticity-based targeted cognitive training (NB-TCT) programs have shown promise in addressing general cognitive deficits in neuropsychiatry (eg, schizophrenia, attention-deficit/hyperactivity disorder [ADHD], depression) and aging.[18–20] Both proximal transfer (improvement of trained/near functions) and distal transfer (improvement of far/other functions) have been reported, even when compared with individuals in active control groups who perform a nonadaptive version of the training task or an unrelated computer exercise for an equal amount of time.[21–24] Neuroplasticity-based programs build on repetitive implicit learning mechanisms to promote more adaptive processing of experienced stimuli[25,26] by capitalizing on the dynamic capacity of the CNS to mature, change structurally and functionally via synaptic pruning and myelination in response to experience, and adapt after injury.[27] This synaptic plasticity–generated specialization of neuronal patterns enables and supports emergent behaviors and training-induced learning.[28] Additionally, experience-dependent plasticity in adolescent brain development has been shown to support compensatory mechanisms modulating symptom severity for neurodevelopmental disorders such as ADHD and Tourette's syndrome,[29,30] as well as depression.[31] Thus, optimal timing for efficacious delivery of neuroplasticity-based programs may occur during the sensitive neurodevelopmental phase of adolescence, potentially leading to long-term impacts.

Although studies with computerized cognitive training programs for autistic individuals have shown promise, findings have been inconsistent, in part due to widely varying methodologies (eg, small sample sizes, single-arm or nonrandomized controlled designs, nonvalidated measures, lack of follow-up assessments).[32,33] One randomized controlled trial tested the combination of computer-based neurocognitive training with group-based social cognition training in autistic adults and reported gains in cognitive abilities and functional outcomes.[34] To our knowledge, no studies have investigated whether adaptive cognitive training can enhance response to social skills interventions in autistic teens.

Recently, our team developed and implemented successfully an online NB-TCT program in an autistic adolescent sample.[35–37] Leveraging insights from this initial digital application (app)–based cognitive training study and informed by 2 prior trials of mobile apps conducted with psychotic and socially anxious youth,[36,37] we developed a remotely delivered intervention app named CICADAS (Care Improving Cognition for ADolescents on the Autism Spectrum) to tailor the delivery of adaptive, individualized NB-TCT through assessments of social cognitive processing and closed-loop mechanics.[38] Closed-loop technology incorporates rapid performance-based challenge adaptivity, psychophysics algorithms, and performance feedback to establish dynamic interactivity between the user and the app. By scaling the difficulty of the game based on real-time data of user performance, youth of widely varying baseline abilities can participate. Critically, this approach tailors to each user's experience, applying personalized levels of pressure on individual systems to harness inherent neuroplasticity processes and drive desired neural changes.[39,40] For example, a game designed to enhance speed of processing may direct closed-loop algorithms to accelerate stimulus presentation times and reduce response time windows as a user's performance improves. (Supplement 1, available online, provides additional details on app development.)

We hypothesized that engaging with CICADAS would prime the brain to acquire or improve cognitive skill sets, potentially serving as a stand-alone intervention and/or as an augmentation to empirically supported therapies such as the Program for the Education and Enrichment of Relational Skills (PEERS) for adolescents,[41] a group-based social skills intervention informed by a cognitive-behavioral therapy framework. As one of the few evidence-based interventions available to autistic teenagers,[41–43] the parent/caregiver-assisted, 16-week program works to teach participants how to solve real-life social dilemmas, appraise affective and social contexts, initiate and maintain conversations, and make friends, while receiving feedback from PEERS and clinicians. Randomized controlled trials have shown that adolescents who received the PEERS intervention demonstrated greater knowledge of how to make and keep friends, increased hosted gatherings, and improved quality of friendships and overall social skills with treatment gains maintained at 14-week follow-up and 1- to 5-year follow-up.[41,44,45] Notably, some adolescents benefit from PEERS more than others, highlighting the role of individual variability in response to treatment and indicating the potential for developing treatment enhancers.[46] Moreover, the required commitment of time and resources by a family combined with limitations in availability of such intensive programs severely hinder treatment accessibility.[17,47] Comparable efficacy of PEERS for adolescents via in-person and telehealth delivery has been reported recently, however, broadening potential reach beyond geographic restrictions.[14,15]

The overarching aims of our trial were to finalize development of the CICADAS app, ensuring that technical components were deployed as designed and data were collected as intended, and to examine the potential use of CICADAS as a stand-alone intervention and to enhance response to PEERS.[17] The present report describes the design, implementation, and outcomes from a validation trial to evaluate the acceptability, feasibility, and impact of the CICADAS app in autistic adolescents and preliminary efficacy data of CICADAS used as an adjunct to PEERS. Although the CICADAS app was designed to prime the brain to engage flexibly and learn adaptively, building on insight from combination studies in clinical populations[37,48] as well as clinician expertise, we posited that social cognitive gains from using CICADAS could be enhanced or reinforced in adolescents by the opportunity to practice interactive behavior with their PEERS cohorts during group sessions and through weekly in vivo socialization homework assignments. If NB-TCT can improve sensory and social processing, applying those skills with cohorts should support and augment gains from CICADAS alone and yield real-world transfer of skills.

METHOD

This study was conducted with approval from the Western Institutional Review Board, an independent institutional review board that provides services for academic and nonacademic institutions. The Western Institutional Review Board is accredited by the Association for the Accreditation of Human Research Protection Programs (AAHRPP). All procedures were performed in accordance with the approved institutional review board protocol. The study was preregistered on ClinicalTrials.gov (NCT04562688) on September 18, 2020.

Participants

Potential participants (ages 11-18 years) and their parents/caregivers were recruited from partner clinics delivering PEERS and regional neurodevelopmental disorder registries, clinics, and communities. Clinical diagnosis of ASD and IQ $\geq$ 70 were confirmed by medical/clinical record review and/or standardized assessments/interviews (eg, ASD: Autism Diagnostic Observation Schedule, 2nd Edition [ADOS-2],[49] Autism Diagnostic Interview–Revised [ADI-R][50]; IQ: Wechsler Abbreviated Scale of Intelligence, 2nd Edition [WASI-II][51]). Participants were required to have reliable access to the internet and adequate sensorimotor capacity to perform the intervention and study activities (visual capacity adequate to read from a digital device at a normal viewing distance, auditory capacity adequate to understand normal speech, and motor capacity adequate to control and use a digital device) based on participant and/or parent/legal guardian self-report and as determined by the screening clinician and/or study team. Computer tablets and headphones were loaned to participants if needed.

Focus Groups and Individual Interviews

Before recruitment for the preliminary efficacy trial, we implemented a human-centered design process to help refine and finalize the CICADAS app. Three adolescents who met eligibility criteria and their parents/caregivers underwent informed consent/assent procedures; these participants were then asked to complete 1 session of intervention-embedded assessments using the digital app. Focus groups were then convened with stakeholders (participants, clinicians, study team) to discuss user experiences; this feedback was used to inform and improve the software design and ensure that assessment data populated the closed-loop algorithm correctly to guide the delivery of individualized NB-TCT. After participant feedback was reviewed and integrated into the app and dashboard design, pretrial participants were provided with access to the CICADAS app for a 2-week test run of the intervention. Participants were then queried about their experiences using the app (eg, enjoyment, ease of use, product quality, perceived usefulness) in a 1:1 user interview before convening again in a focus group to qualitatively evaluate manageability, clinical usefulness, and acceptability of the app; particular focus was directed to ensuring sufficient engagement with the interface to motivate sustained program use (Supplement 2, available online). Once decisions regarding app design were finalized, we moved to the preliminary efficacy phase of our study.

Study Procedures

We designed a randomized, active-controlled trial with 3 comparison arms to assess the feasibility and preliminary efficacy of the CICADAS app as a stand-alone intervention or as an enhancement to remotely delivered PEERS. We also aimed to evaluate its potential in improving social, cognitive, and real-world functioning.

Participants were recruited from 3 clinical sites that deliver PEERS whereby families who express an interest in

PEERS are placed on program wait-lists to accommodate limitations in group timing and space. Individuals who were slated to start a group soon and consented to join the research study were assigned using block randomization (REDCap randomization module[52]) to the PEERS + CICADAS group (n = 22; mean [SD] age = 13.77 [2.07] years; sex at birth = 14 male participants, 8 female participants) or the PEERS + Active Control group (n = 21; mean [SD] age = 14.19 [1.63] years; sex at birth = 16 male participants, 5 female participants) so they could start using the training app concurrently with PEERS. Individuals who would have to wait to join a later PEERS group were invited to join the study using the CICADAS app as a stand-alone intervention (CICADAS only group: n = 19; mean [SD] age = 14.05 [2.04] years; sex at birth = 12 male participants, 7 female participants). Table 1 summarizes participant characteristics, and Figure 1 presents the study design and CONSORT (Consolidated Standards of Reporting Trials) flow diagram.

Following eligibility screening and informed consent and assent with parents/caregivers and autistic adolescents, all participants completed baseline preintervention (T1) assessment measures (Table 2) with study personnel using secure, web-based videoconferencing and research data collection software (PsyToolkit,[66,67] REDCap[52]).

All participants, regardless of treatment group, also completed intervention-embedded assessments that consisted of 10 cognitive processing assessments (Figure 2A) before and after the 16-week intervention period. Participants assigned to the CICADAS only group were asked to engage with the CICADAS app for up to a total of 40 hours during the 16-week period. Participants randomized to the PEERS + CICADAS group completed the 16-week PEERS protocol[68,69] while engaging with the CICADAS app for a total of up to 40 hours over the intervention period. Participants who were assigned to the PEERS + Active Control group completed the 16-week PEERS protocol while engaging with the active control app for a

TABLE 1 Participant Characteristics (Baseline)[a]

	CICADAS only (n = 19)		PEERS + CICADAS (n = 22)		PEERS + Active Control (n = 21)	
	Mean	**(SD)**	**Mean**	**(SD)**	**Mean**	**(SD)**
Age, y	14.05	(2.04)	13.77	(2.07)	14.19	(1.63)
	n	(%)	n	(%)	n	(%)
Sex at birth						
Female	7	(36.84)	8	(36.36)	5	(23.81)
Male	12	(63.16)	14	(63.64)	16	(76.19)
Gender[b]						
Female	6	(31.58)	6	(27.27)	5	(23.81)
Male	11	(57.89)	14	(63.64)	16	(76.19)
Nonbinary	2	(10.53)	2	(9.09)	0	(0)
Race						
Asian	0	(0)	1	(4.55)	0	(0)
Black	0	(0)	0	(0)	1	(4.76)
Multiracial	3	(15.79)	0	(0)	2	(9.52)
White	16	(84.21)	21	(95.45)	18	(85.71)
Hispanic/Latino						
No	14	(73.68)	22	(100.00)	20	(95.24)
Yes	5	(26.32)	0	(0)	1	(4.76)
Additional diagnoses[c]						
Anxiety, yes	16	(84.21)	14	(63.64)	12	(57.14)
ADHD, yes	10	(52.63)	13	(59.09)	12	(57.14)
Depression, yes	5	(26.32)	5	(22.73)	7	(33.33)
OCD, yes	3	(15.79)	2	(9.09)	2	(9.52)

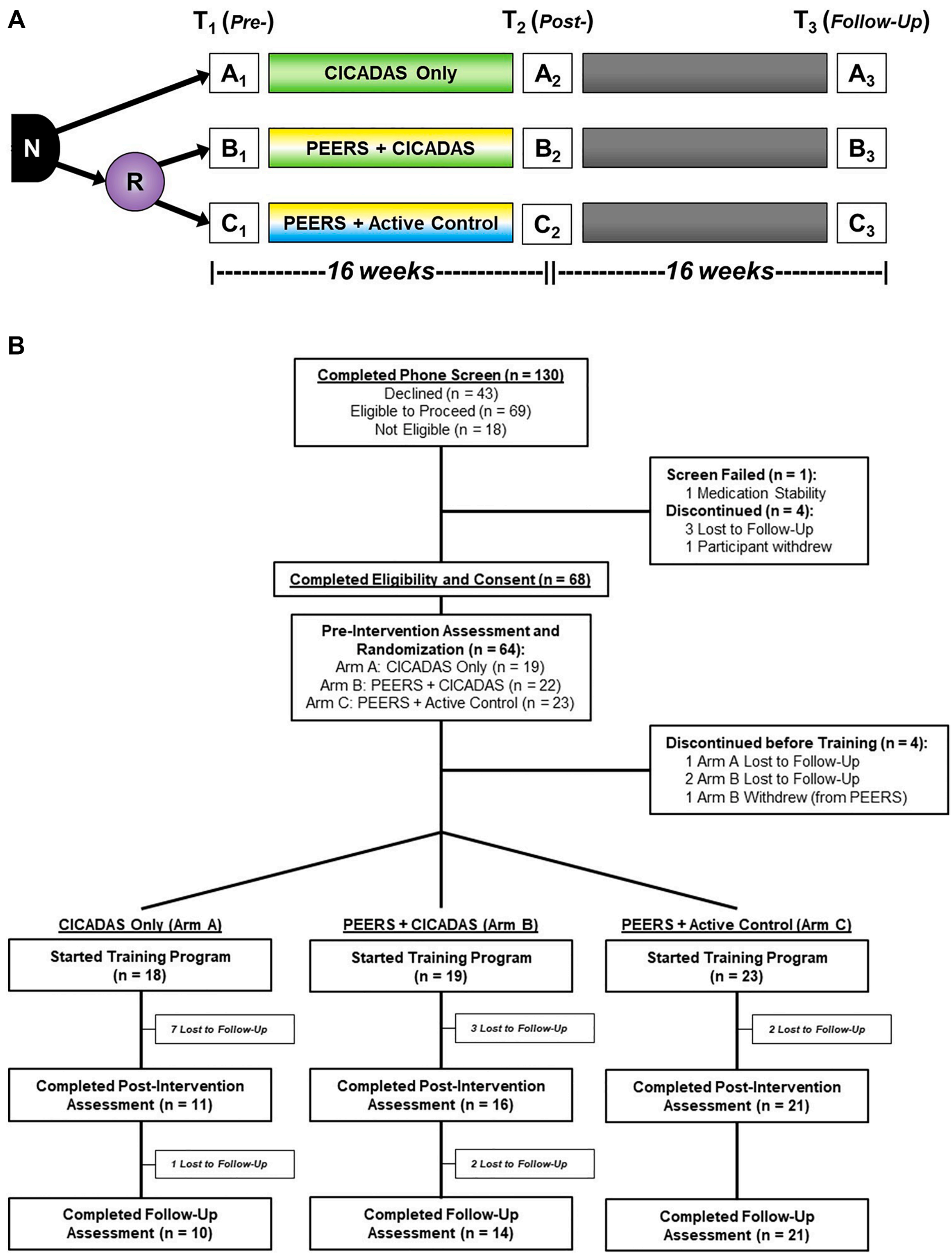
Note: *ADHD = attention-deficit/hyperactivity disorder; CICADAS = Care Improving Cognition for ADolescents on the Autism Spectrum; OCD = obsessive-compulsive disorder; PEERS = Program for the Education and Enrichment of Relational Skills.*

[a]*For comparisons of all variables across 3 groups, p values were nonsignificant (>.05).*

[b]*Self-identified gender.*

[c]*Parent/caregiver report.*

FIGURE 1 Study Design and CONSORT Flow Diagram



Note: *(A) Three-arm trial design with preintervention (T_1), postintervention (T_2), and 16-week (T_3) follow-up assessment sessions. (B) CONSORT Flow Diagram. CICADAS = Care Improving Cognition for ADolescents on the Autism Spectrum; N = sample; PEERS = Program for the Education and Enrichment of Relational Skills; R = randomization/allocation. Please note color figures are available online.*

TABLE 2 Outcome Measures Collected at PreIntervention (T1), PostIntervention (T2), and Follow-Up (T3) Assessments

Measure	Description	Domain
Parent/caregiver response		
Behavior Rating Inventory of Executive Function, Second Edition (BRIEF-2)[53]	Assesses impairments in executive function across global executive composite, behavior regulation, emotional recognition, and cognitive regulation indices	Cognitive
Brain Body Center Sensory Scales (BBCSS)[54]	Measures sensory vulnerabilities of auditory processing, visual processing, tactile processing, and eating and feeding behaviors	Sensory
Child Behavior Checklist (CBCL)[55]	Measures behavioral and emotional functioning; composite scales: internalizing problems scale sums anxious/depressed, withdrawn-depressed, and somatic complaints scores; externalizing problems scale combines rule-breaking and aggressive behavior; total problems scale sums scores of all problem items	Clinical
Pediatric Qualify of Life Inventory (PedsQL)[56]	Measures health-related quality of life	Health
Repetitive Behavior Scale—Revised (RBS-R)[57]	Measures breadth of repetitive behavior with subscales stereotyped behavior, self-injurious behavior, compulsive behavior, routine behavior, sameness behavior, and restricted behavior	Autism
Social Responsiveness Scale, Second Edition (SRS-2)[58]	Measures severity of autism spectrum symptoms as they occur in natural social settings	Autism
Social Skills Improvement System (SSIS)[59]	Assesses social skills, problem behaviors, and academic competence	Social
Adolescent response		
Flanker task[60,61]	Test of selective attention and inhibitory control, in which participants are asked to indicate the target letter while ignoring an array of "flanking" congruent/incongruent letters	Cognitive
SCAN-3:A Tests for Auditory Processing Disorders[62]	Screening for auditory processing difficulties; subtests: competing words (dichotic listening tasks) and filtered words (speech processing when the signal is distorted or compromised by a poor acoustic environment)	Sensory
Test of Adolescent Social Skills Knowledge (TASSK)[63]	Assesses treatment changes in adolescents' knowledge of social skills taught during PEERS	Social
Wisconsin Card Sorting Test (WCST)[64,65]	Neuropsychological test of set shifting, the capability to show flexibility when exposed to changes in reinforcement	Cognitive

***Note**: PEERS = Program for the Education and Enrichment of Relational Skills.*

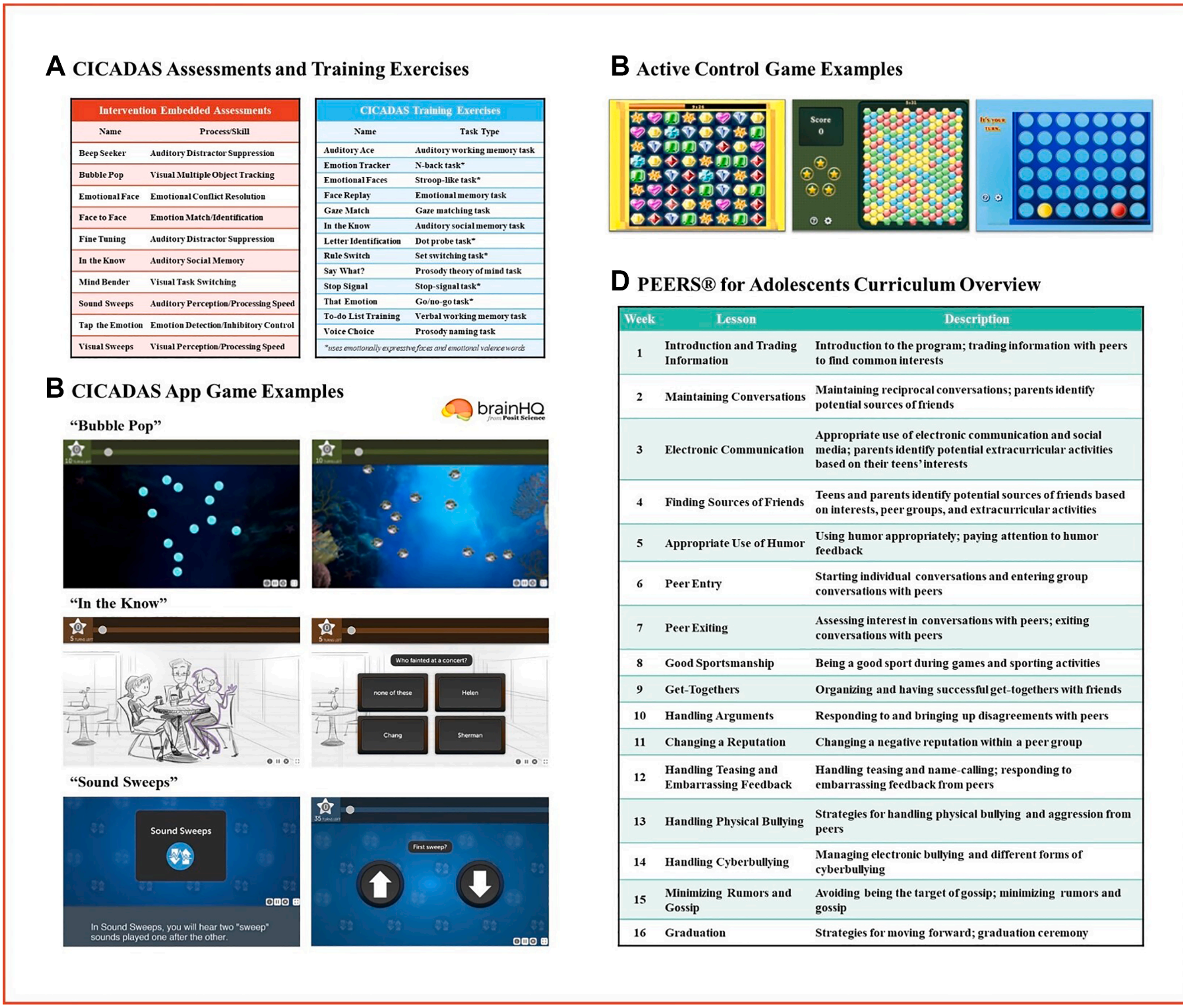
total of up to 40 hours over the intervention period. Study personnel reviewed procedures with PEERS clinicians, who were asked to refrain from mentioning the trial during group sessions to preserve study blinding. After completing their assigned training program, participants completed postintervention (T2) assessment measures identical to the T1 session. To assess whether changes observed after training were maintained or changed over time, a follow-up (T3) assessment session was conducted 16 weeks after the T2 assessment.

Interventions

CICADAS app. Participants completed baseline assessments and NB-TCT exercises on a digital device for up to 40 hours through BrainHQ (www.brainhq.com; Posit Science Corporation). The CICADAS app captures user-specific sensory and cognitive processing metrics through 10 brief computerized assessments; these data are used to guide and personalize the delivery of 13 NB-TCT exercises that are adaptive, ie, the task difficulty adjusted on a trial-to-trial and session-by-session basis to the abilities of each individual (Figure 2A, B). A second set of computerized assessments was administered following the intervention period. Participants had to log in to access these assessments and exercises using a study-provided username that contained no personally identifiable information.

Active Control app. Participants played previously vetted and popular casual video games for an overall duration time matched to the CICADAS program. These comparison, nonadaptive active control games (Figure 2C) were not designed with a targeted purpose, but the

FIGURE 2 Intervention-Embedded Assessments, Training Exercises, Examples of CICADAS/Active Control Games, and Overview of PEERS for Adolescents Curriculum



Intervention Embedded Assessments	
Name	Process/Skill
Beep Seeker	Auditory Distractor Suppression
Bubble Pop	Visual Multiple Object Tracking
Emotional Face	Emotional Conflict Resolution
Face to Face	Emotion Match/Identification
Fine Tuning	Auditory Distractor Suppression
In the Know	Auditory Social Memory
Mind Bender	Visual Task Switching
Sound Sweeps	Auditory Perception/Processing Speed
Tap the Emotion	Emotion Detection/Inhibitory Control
Visual Sweeps	Visual Perception/Processing Speed

CICADAS Training Exercises	
Name	Task Type
Auditory Ace	Auditory working memory task
Emotion Tracker	N-back task*
Emotional Faces	Stroop-like task*
Face Replay	Emotional memory task
Gaze Match	Gaze matching task
In the Know	Auditory social memory task
Letter Identification	Dot probe task*
Rule Switch	Set switching task*
Say What?	Prosody theory of mind task
Stop Signal	Stop-signal task*
That Emotion	Go/no-go task*
To-do List Training	Verbal working memory task
Voice Choice	Prosody naming task

*uses emotionally expressive faces and emotional valence words

Week	Lesson	Description
1	Introduction and Trading Information	Introduction to the program; trading information with peers to find common interests
2	Maintaining Conversations	Maintaining reciprocal conversations; parents identify potential sources of friends
3	Electronic Communication	Appropriate use of electronic communication and social media; parents identify potential extracurricular activities based on their teens' interests
4	Finding Sources of Friends	Teens and parents identify potential sources of friends based on interests, peer groups, and extracurricular activities
5	Appropriate Use of Humor	Using humor appropriately; paying attention to humor feedback
6	Peer Entry	Starting individual conversations and entering group conversations with peers
7	Peer Exiting	Assessing interest in conversations with peers; exiting conversations with peers
8	Good Sportsmanship	Being a good sport during games and sporting activities
9	Get-Togethers	Organizing and having successful get-togethers with friends
10	Handling Arguments	Responding to and bringing up disagreements with peers
11	Changing a Reputation	Changing a negative reputation within a peer group
12	Handling Teasing and Embarrassing Feedback	Handling teasing and name-calling; responding to embarrassing feedback from peers
13	Handling Physical Bullying	Strategies for handling physical bullying and aggression from peers
14	Handling Cyberbullying	Managing electronic bullying and different forms of cyberbullying
15	Minimizing Rumors and Gossip	Avoiding being the target of gossip; minimizing rumors and gossip
16	Graduation	Strategies for moving forward; graduation ceremony

(A) Digital application (app) embedded assessments and CICADAS (Care Improving Cognition for ADolescents on the Autism Spectrum) exercises. Screenshots of (B) CICADAS app games and (C) active control games. (D) Overview of the 16-week PEERS (Program for the Education and Enrichment of Relational Skills) for Adolescents Curriculum.

CICADAS and active control programs were matched carefully for levels of intensity, modality, reward delivery, and overall engagement. Active control participants were also administered the computerized assessments completed by the CICADAS group before and after the intervention period.

PEERS for Adolescents. Participants were recruited from individuals interested in enrolling in PEERS for Adolescents,[41] a 16-week, evidence-based social skills program designed to help autistic adolescents and other youth with social challenges learn to make and keep friends while effectively handling conflict and rejection. Behavioral rehearsal of skills and structured practice interactions during socialization activities (eg, playing sports, games) with direct feedback from clinicians are integrated into the curricula. Using a parent-assisted group-based model and a neurodiversity-affirming approach, the program provides 90-minute weekly sessions that incorporate didactic instruction, role-play demonstrations, behavioral rehearsal exercises, and homework assignments with weekly review to reinforce learning (Figure 2D).

Data Analysis

To evaluate the feasibility, acceptability, and usability of the CICADAS app, we conducted an analysis of program adherence and overall program completion rate in all intent-to-treat (ITT) participants who completed at least 1 training session. To test the efficacy of the CICADAS app as a stand-alone social cognitive intervention and as an augmentation to PEERS, we assessed changes in sensory processing, cognition, symptom reduction, social skills and behaviors, as well as health-related quality of life. First, we examined any differences in baseline demographic characteristics and outcomes variables; any such factors that showed trend level significant differences ($p < .1$) were noted and used as covariates in our statistical model. Data from each outcome measure were analyzed using a linear mixed model with group and time as fixed factors and age and gender as covariates. Missing data were handled with an iterative maximum likelihood procedure to estimate model parameters optimally.[70] Significant ($p < .05$) findings for main effects and group × time interaction factors were of key interest; interaction effects were evaluated with a Bonferroni correction ($\alpha/3 = 0.017$) to account for multiple comparisons.

RESULTS

A total of 68 potential participants completed eligibility screening and informed consent/assent; 62 participants completed preintervention (T1) assessments and were allocated into 1 of 3 groups (19 in CICADAS only group, 22 in PEERS + CICADAS group, 21 in PEERS + Active Control group). Four participants discontinued the study before completing the first training session. Thus, 60 participants formed our predefined ITT (all participants who completed at least 1 training session) population (18 CICADAS only, 21 PEERS + CICADAS, 21 PEERS + Active Control). We found no group differences in demographic variables at baseline.

Completion Rate

Of ITT participants, 80.0% completed immediate post-training assessments (48 of 60), and 73.3% completed the 16-week follow-up assessment (44 of 60).

Changes in Intervention Embedded Assessments. We found a significant group × time interaction for an auditory longer-term memory and comprehension (“In the Know”) task favoring the NB-TCT groups (CICADAS only and PEERS + CICADAS) over the PEERS + Active Control group ($F = 6.04$, $p = .016$). Participants who trained with the CICADAS app (as a stand-alone intervention or with PEERS) showed changes in performance on the intervention embedded assessments; after 16 weeks of training, participants in the NB-TCT groups showed significant improvements on “In the Know” ($t = 3.59$, $p < .01$) and “Sound Sweeps” (auditory processing speed and accuracy training; $t = 2.53$, $p = .018$) tasks; trend level gains were found for the “Bubble Pop!” (visual attention and tracking; $t = 1.99$, $p = .058$) task.

Changes in Outcome Measures

Significant effects of group, time, and group × time interactions were found on a number of measures (Table 3) collected over the 3 time points, T1, T2, and T3.

ASD Measures. On the Repetitive Behavior Scale–Revised (RBS-R) total score,[57] we found a significant effect of time ($F = 10.539$, $p < .001$) showing improvement across all participants from pre- to post-intervention that was maintained at follow-up. Although group × time interaction ($F = 0.0976$, $p = .425$) was not significant, trend level effects of group ($F = 2.750$, $p = 0.072$) indicated that participants in the CICADAS only group started the program with slightly more severe RBS-R symptoms than participants who received the PEERS intervention.

Repeated measures of the Social Responsiveness Scale, Second Edition (SRS-2)[58] also showed significant effects of time ($F = 11.038$, $p < .001$) for total score driven by significant improvements from T1 to T2 for all 3 groups ($t = 2.087$, $p = .039$). Given that PEERS is a well-supported evidence-based social skills intervention, we were not surprised by findings of pre-post intervention benefits for the PEERS groups that were maintained at follow-up. However, our finding that the CICADAS only group showed significant improvement over time without PEERS suggests benefits from using the CICADAS app as a stand-alone intervention. Similar effects of time were also found for SRS-2 subscales of social awareness ($F = 3.094$, $p = .050$), social cognition ($F = 7.571$, $p = .001$), social communication ($F = 10.835$, $p < .001$), social motivation ($F = 3.685$, $p = .029$), and restricted interests and repetitive behaviors ($F = 10.142$, $p < .001$). Of interest, the PEERS + CICADAS group demonstrated significant improvement across all 3 time points ($F = 3.894$, $p = .024$) on the social cognition subscale, suggesting that engaging with CICADAS (vs PEERS + Active Control group) conferred an additional advantage to the PEERS intervention in the social cognitive domain.

TABLE 3 Group × Time Interactions for Each Assessment Measure

		CICADAS only			PEERS + CICADAS			PEERS + Aactive Control			Group		Time		Group × time interaction[a]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	*F*	*p*	*F*	*p*	*F*	*p*
Autism measures																
Repetitive Behaviors Scale—Revised (RBS-R)																
Total score	Mean	21.17	20.19	17.62	16.93	12.98	11.97	16.09	13.81	10.65	2.750	.072†	10.539	.000***	0.976	.425
	SE	2.17	2.35	2.57	1.97	2.06	2.16	2.02	2.04	2.06						
Social Responsiveness Scale, 2nd Edition (SRS-2)																
Total score	Mean	84.88	71.60	78.65	83.60	72.22	71.16	88.59	76.54	67.26	0.106	.900	11.038	.000***	1.297	.277
	SE	4.97	5.95	6.49	4.52	5.00	5.51	4.63	4.70	4.88						
Social awareness	Mean	13.39	11.13	11.77	12.78	13.29	12.25	13.45	12.08	10.41	0.230	.795	3.094	.050*	1.605	.180
	SE	1.07	1.26	1.37	0.98	1.07	1.17	1.00	1.01	1.05						
Social cognition	Mean	14.78	11.94	12.76	14.88	12.13	11.76	14.53	13.38	11.52	0.021	.980	7.571	.001***	0.902	.466
	SE	1.13	1.35	1.48	1.02	1.14	1.25	1.05	1.06	1.11						
Social communication	Mean	29.55	24.87	27.89	28.77	24.49	25.12	31.04	26.28	23.28	0.146	.865	10.835	.000***	1.458	.222
	SE	1.96	2.30	2.51	1.78	1.95	2.14	1.83	1.85	1.91						
Social motivation	Mean	13.15	11.81	12.83	12.59	10.11	10.02	13.82	12.84	11.95	1.157	.321	3.685	.029*	0.671	.614
	SE	1.18	1.39	1.52	1.08	1.18	1.29	1.10	1.12	1.16						
Restricted and repetitive behaviors	Mean	14.00	11.78	13.55	14.59	12.23	11.85	15.76	12.08	10.21	0.062	.940	10.142	.000***	1.768	.143
	SE	1.05	1.30	1.40	0.95	1.07	1.19	0.98	0.99	1.04						
Clinical measures																
Child Behavior Checklist (CBCL)																
Total problems	Mean	29.74	30.15	26.04	27.96	17.21	18.82	24.59	19.70	16.28	2.616	.081†	9.318	.000***	3.218	.016*
	SE	3.06	3.46	3.77	2.78	2.96	3.11	2.91	2.90	2.96						
Internalizing problems	Mean	17.64	17.66	15.70	15.73	9.49	10.60	14.30	11.92	10.73	2.929	.061†	6.661	.002**	2.432	.053†
	SE	1.80	2.07	2.26	1.63	1.76	1.85	1.71	1.69	1.75						
Externalizing problems	Mean	12.11	12.50	10.21	12.23	7.73	8.23	10.25	8.03	5.48	1.013	.369	6.633	.002**	2.396	.056†
	SE	1.98	2.17	2.34	1.80	1.88	1.96	1.87	1.86	1.90						
Cognitive measures																
Behavior Rating Inventory of Executive Function, 2nd Edition (BRIEF-2)																
Global executive composite	Mean	132.58	127.69	125.35	131.75	118.27	118.19	133.18	126.27	119.70	0.706	.498	10.253	.000***	1.071	.375
	SE	4.04	4.78	5.41	3.67	4.01	4.31	3.85	3.85	3.90						
Behavioral regulation index	Mean	25.39	24.83	24.12	26.39	22.59	22.99	25.47	24.09	22.29	0.281	.756	9.764	.000***	2.548	.045*
	SE	0.97	1.14	1.29	0.89	0.96	1.03	0.93	0.93	0.94						
Cognitive regulation index	Mean	71.52	68.55	67.72	70.06	64.17	62.45	74.54	71.06	67.50	1.199	.308	7.243	.001***	0.444	.777
	SE	2.97	3.36	3.76	2.71	2.88	3.07	2.84	2.84	2.86						
Emotional regulation index	Mean	35.67	34.03	33.41	35.30	31.23	32.28	33.19	31.14	29.86	1.352	.266	7.954	.001***	1.018	.403
	SE	1.43	1.65	1.86	1.30	1.40	1.50	1.36	1.36	1.38						

(continued)

TABLE 3 Continued

		CICADAS only			PEERS + CICADAS			PEERS + Aactive Control			Group		Time		Group × time interaction[a]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	*F*	*p*	*F*	*p*	*F*	*p*
Wisconsin Card Sorting Test (WCST)																
Mean reaction times	Mean	2,366.35	1,917.23	1,861.01	2,227.68	1,646.10	1,745.03	2,187.40	2,053.26	1,822.15	0.860	.428	22.803	.000***	3.417	.012**
	SE	120.71	144.30	144.95	109.76	119.51	125.88	112.45	114.99	116.06						
Total errors, %	Mean	0.28	0.27	0.21	0.29	0.24	0.24	0.26	0.24	0.18	0.477	.623	5.044	.008**	0.517	.723
	SE	0.03	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03						
Perseverative errors, %	Mean	0.17	0.16	0.14	0.18	0.14	0.14	0.16	0.16	0.12	0.276	.759	5.382	.006**	1.244	.297
	SE	0.01	0.02	0.02	0.01	0.01	0.02	0.01	0.01	0.01						
Nonperseverative errors, %	Mean	0.12	0.11	0.07	0.11	0.10	0.10	0.12	0.08	0.07	0.182	.834	3.205	.045*	0.558	.693
	SE	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02						
Flanker task																
Congruent correct, %	Mean	80.81	87.16	83.16	80.78	81.33	84.55	86.85	85.66	87.23	0.586	.560	0.848	.432	1.539	.198
	SE	3.48	3.83	4.12	3.13	3.32	3.57	3.21	3.26	3.29						
Incongruent correct, %	Mean	76.91	76.00	80.03	79.35	77.84	79.93	84.69	82.28	84.73	1.299	.281	1.032	.361	0.072	.990
	SE	3.60	4.13	4.45	3.22	3.50	3.82	3.30	3.39	3.42						
Accuracy interference	Mean	−3.90	−8.57	−2.96	−1.43	−2.86	−2.64	−2.19	−3.48	−2.31	1.132	.329	0.960	.386	0.304	.875
	SE	2.35	2.77	2.88	2.08	2.36	2.50	2.13	2.23	2.23						
Reaction time interference	Mean	18.21	−18.92	30.79	8.20	25.12	8.47	5.52	38.00	37.13	0.574	.567	0.460	.633	1.213	.311
	SE	19.10	22.43	23.39	16.91	19.12	20.27	17.30	18.12	18.12						
Health measures																
Pediatric Quality of Life Inventory (PedsQL)																
Total scale	Mean	59.44	60.95	65.76	59.74	67.46	70.60	63.85	63.99	69.30	0.526	.594	6.461	.003**	1.073	.375
	SE	3.26	4.01	4.19	2.96	3.20	3.37	3.08	3.40	3.13						
Psychosocial health	Mean	56.59	59.90	65.64	56.06	66.06	66.47	61.19	62.16	66.99	0.251	.779	7.517	.001***	1.616	.177
	SE	3.23	3.83	4.18	2.94	3.21	3.38	3.05	3.05	3.11						
Physical health	Mean	65.28	69.39	72.07	67.04	69.47	77.79	69.04	68.81	73.62	0.111	.895	2.517	.086[†]	0.273	.895
	SE	4.44	5.43	6.14	4.04	4.50	4.84	4.20	4.21	4.30						
Sensory measures																
Brain-Body Center Sensory Scales (BBCSS)																
Affiliative touch aversion	Mean	1.49	1.59	1.41	1.53	1.24	1.18	1.71	1.49	1.56	1.147	.324	1.749	.180	0.927	.452
	SE	0.16	0.20	0.21	0.15	0.16	0.17	0.15	0.15	0.16						
Auditory hypersensitivity	Mean	1.97	1.66	1.91	1.69	1.59	1.44	1.88	1.85	1.69	2.129	.127	1.834	.165	0.979	.423
	SE	0.13	0.17	0.17	0.12	0.13	0.14	0.12	0.12	0.13						

(*continued*)

TABLE 3 Continued

		CICADAS only			PEERS + CICADAS			PEERS + Aactive Control			Group		Time		Group × time interaction[a]	
		T1	T2	T3	T1	T2	T3	T1	T2	T3	*F*	*p*	*F*	*p*	*F*	*p*
Auditory hyposensitivity to voices	Mean	1.88	1.88	1.89	1.87	1.67	1.71	1.77	1.72	1.63	0.640	.531	0.714	.492	0.460	.765
	SE	0.13	0.17	0.17	0.12	0.13	0.14	0.12	0.12	0.13						
Digestive problems	Mean	1.38	1.05	1.43	1.23	1.11	1.26	1.21	1.20	1.21	0.339	.714	5.401	.006**	1.749	.146
	SE	0.10	0.13	0.13	0.09	0.10	0.11	0.09	0.09	0.10						
Ingestive problems	Mean	1.09	1.02	1.04	0.95	0.98	0.96	1.12	1.10	1.13	2.275	.112	0.164	.849	0.238	.916
	SE	0.07	0.09	0.09	0.06	0.07	0.08	0.06	0.06	0.07						
Selective eating	Mean	2.01	1.77	1.76	1.66	1.56	1.37	1.80	1.70	1.58	1.398	.255	5.627	.005**	0.495	.739
	SE	0.15	0.17	0.18	0.13	0.14	0.15	0.14	0.14	0.14						
Tactile hypersensitivity	Mean	1.81	1.43	1.54	1.68	1.61	1.41	1.62	1.43	1.46	0.247	.782	8.871	.000***	2.113	.086†
	SE	0.11	0.13	0.14	0.10	0.11	0.12	0.10	0.10	0.11						
Visual hypersensitivity	Mean	1.41	1.43	1.46	1.09	1.16	1.31	1.46	1.38	1.42	3.262	.045*	0.683	.508	0.669	.615
	SE	0.10	0.13	0.13	0.09	0.10	0.11	0.09	0.09	0.10						
SCAN-3:A Tests for Auditory Processing Disorders																
Competing total	Mean	37.01	34.82	35.72	34.20	32.74	36.14	29.12	38.40	37.10	0.078	.925	0.709	.495	1.875	.121
	SE	3.36	3.96	4.23	2.97	3.28	3.51	3.04	3.10	3.17						
Filtered total	Mean	27.76	28.37	30.06	28.47	29.54	30.77	30.12	30.67	35.17	1.992	.146	3.262	.042*	0.467	.760
	SE	1.67	2.01	2.13	1.48	1.65	1.76	1.52	1.55	1.58						
Social skills measures																
Social Skills Improvement System (SSIS)																
Social skills scale	Mean	79.78	80.05	82.62	80.48	86.31	88.06	76.10	82.23	87.69	0.614	.544	7.498	.001***	1.105	.360
	SE	3.12	3.82	4.02	2.76	2.96	3.11	2.93	3.14	2.96						
Autism spectrum subscale	Mean	19.10	18.13	15.69	17.87	15.24	14.94	20.25	17.41	15.41	1.434	.246	11.941	.000***	0.726	.577
	SE	1.03	1.39	1.40	0.91	1.02	1.07	0.98	1.12	0.99						
Problem behavior subscale	Mean	41.13	39.24	33.90	35.49	30.64	29.22	35.16	35.35	29.19	2.329	.106	9.570	.000***	1.359	.256
	SE	2.39	2.92	3.05	2.11	2.28	2.39	2.25	2.42	2.27						
Test of Adolescent Social Skills Knowledge (TASSK)																
Total score	Mean	16.74	16.60	16.98	15.12	20.53	21.02	17.66	22.73	23.11	9.114	.000***	30.560	.000***	7.114	.000***
	SE	0.86	0.98	1.11	0.80	0.85	0.93	0.82	0.81	0.83						

Note: *CICADAS = Care Improving Cognition for ADolescents on the Autism Spectrum; PEERS = Program for the Education and Enrichment of Relational Skills; T1 = preintervention; T2 = postintervention; T3 = follow-up.*

[a]*Bonferroni correction was applied to adjust for multiple comparisons.*

**p ≤ .05; **p ≤ .01; ***p ≤. 001; †trend level effect (p ≤ .1).*

Clinical Measures. Total problems scores on the Child Behavior Checklist (CBCL)[55] revealed a significant effect for time ($F = 9.318$, $p < .001$) indicating a reduction of problem behaviors for all groups and a significant group × time interaction ($F = 3.218$, $p = .016$) reflecting significant changes for the PEERS + CICADAS group ($F = 12.398$, $p < .001$) and the PEERS + Active Control group ($F = 4.625$, $p = .012$). The CBCL internalizing problems subscale (including withdrawn/depressed, anxiety/depressed, and somatic complaints) showed a significant effect of time ($F = 6.661$, $p = .002$) and a trend level group × time interaction ($F = 2.432$, $p = .053$) and effect of group ($F = 2.929$, $p = .061$). The externalizing problems subscale (including delinquent and aggressive behaviors) showed a trend level group × time interaction ($F = 2.396$, $p = .056$) and significant effect of time ($F = 6.633$, $p = .002$).

Cognitive Measures. On the Behavior Rating Inventory of Executive Function, Second Edition (BRIEF-2),[53] we found significant effects of time on the global executive composite score ($F = 10.253$, $p < .001$) and the behavioral regulation ($F = 9.764$, $p < .001$), emotional regulation ($F = 7.954$, $p = .001$), and cognitive regulation indices ($F = 7.243$, $p = .001$). We also found a significant group × time interaction for the behavioral regulation index ($F = 2.548$, $p = .045$). A higher global executive composite score indicates difficulty in 1 or more areas of executive function. Although all participants demonstrated a reduction of executive functioning challenges over time, the PEERS + CICADAS group showed a significant ($F = 7.849$, $p = .001$) improvement with patterns suggesting pre-to post-intervention changes that were maintained at follow-up.

Participant performance on the Wisconsin Card Sorting Test (WCST)[64,65] revealed significant reduction in errors over time for total errors ($F = 5.044$, $p = .008$), perseverative errors ($F = 5.382$, $p = .006$), and non-perseverative errors ($F = 3.205$, $p = .045$). For mean reaction times, we also found significant effects for time ($F = 22.803$, $p < .001$) and a significant group × time interaction ($F = 3.417$, $p = .012$) indicating a reduction in processing speed across the 3 sessions. Pairwise comparisons from T1 to T2 showed significant improvement for the PEERS + CICADAS group ($p = .001$) and the CICADAS only group ($p = .002$); the PEERS + Active Control group did not show a significant T1 to T2 change ($p = .483$).

We calculated 2 interference scores for the Flanker task[60,61]: subtracting the mean reaction time for the correct congruent items from the mean reaction time for the correct incongruent items and subtracting the mean accuracy for the congruent items from the mean accuracy for the incongruent items. Although performance on the Flanker task did not differ significantly across groups and time, trend level improvements in accuracy were demonstrated by the CICADAS only group for congruent items across all time points ($F = 2.532$, $p = .085$). Engaging with the CICADAS app may potentially confer some advantage on performance when completing a computerized test of selective attention.

Health Measures. On the Pediatric Quality of Life Inventory (PedsQL),[56] we found significant effects of time for total scale ($F = 6.461$, $p = .003$) and psychosocial health summary ($F = 7.517$, $p = .001$) scores with a trend effect on the physical health summary ($F = 2.517$, $p = .086$) score. In particular, the PEERS + CICADAS group showed significant improvements on the composite measure of psychosocial health ($F = 6.862$, $p = .002$) over the entire study timeline. The CICADAS only ($F = 2.150$, $p = .122$) and PEERS + Active Control ($F = 1.917$, $p = .153$) groups trended toward improvement over time.

Sensory Measures. Significant effects of time were found on the Brain Body Center Sensory Scales (BBCSS)[54] for digestive problems ($F = 5.401$, $p = .006$), selective eating ($F = 5.627$, $p = .005$), and tactile hypersensitivity ($F = 8.871$, $p < .001$) indicating an overall reduction of symptoms. A significant group effect was found for visual hypersensitivity ($F = 3.262$, $p = .045$). We also found a trend level group × time interaction for tactile hypersensitivity ($F = 2.113$, $p = .086$). Of note, the CICADAS only group showed the most symptom reduction for tactile hypersensitivity over time ($F = 5.987$, $p = .004$), followed by the PEERS + CICADAS group ($F = 3.099$, $p = .050$). The PEERS + Active Control group showed a trend level effect in the same direction ($F = 2.881$, $p = .062$).

Results from the SCAN-3A Tests for Auditory Processing Disorders[62] showed a significant effect of time on the filtered words subtest ($F = 3.262$, $p = .042$) indicating better performance over time for all groups. Performance on the competing words subtest did not change significantly across the 3 time points.

Social Skills Measures. Participant scores on the social skills scale of the Social Skills Improvement System (SSIS)[59] rating scale increased significantly over time ($F = 7.498$, $p = .001$) with significant differences between T1 and T2 ($t = -2.523$, $p = .013$) in particular. Notably, participants in the CICADAS only group did not show significant change ($F = 0.340$, $p = .713$) between the preand post-intervention period. A similar pattern was found for the autism spectrum subscale ($F = 11.941$, $p < .001$) driven by significant decreases in autism-related symptoms between T1 and T2 ($t = 2.370$, $p = .019$). The PEERS + CICADAS and the PEERS + Active Control groups showed significant improvements ($p = .022$ and $p = .001$, respectively) and the CICADAS only group showed a trend-level change ($p = .098$) over time. It should be noted that the SSIS social skills scale evaluates skills that are addressed in the PEERS curriculum, and gains from the evidence-based intervention are not surprising. Further, we found significant reductions on the problem behaviors scale (externalizing problems, internalizing problems, hyperactivity/inattention, autism spectrum, bullying) over the course of the study ($F = 9.570$, $p < .001$) wherein the PEERS + CICADAS and the PEERS + Active Control groups showed significant improvement ($p = .015$ and $p = .010$, respectively) and the CICADAS only group showed a trend level change ($p = .059$) over time. These data suggest that whereas all groups acquired some gains from intervention over the course of the study, the use of the CICADAS app may confer therapeutic gains as a stand-alone intervention and as an adjunct to PEERS.

On the Test of Adolescent Social Skills Knowledge (TASSK),[63] we found significant effects of group ($F = 9.114$, $p < .001$), time ($F = 30.560$, $p < .001$), and group × time interaction ($F = 7.114$, $p < .001$). These findings may be attributed mainly to T1 to T2 improvements in both the PEERS + Active Control and PEERS + CICADAS groups ($p = .000$) that were maintained at the 16-week follow-up (T3); the CICADAS only group showed no significant change over time. However, because the TASSK was designed to assess learning from participation in the PEERS program, improvements on the TASSK may be curriculum specific. Nevertheless, these data provide further evidence for the efficacy of the PEERS intervention for autistic teens.

DISCUSSION

Our evaluation of the neuroplasticity-based CICADAS app for autistic adolescents yielded some promising findings. Incorporating CICADAS with PEERS, one of the few evidence-based social cognitive therapies available to teens, allowed us to evaluate whether CICADAS enhanced or interfered with expected efficacy from the established social skills program. Concurrently, we also assessed the impact of using CICADAS as a stand-alone intervention. Because our battery of assessment measures spanned several domains, some of which were not directly targeted or assessed in the intervention programs, we were able to observe broader-reaching effects over time. For example, we found that the PEERS + CICADAS group showed significant improvements on the composite measure of psychosocial health (PedsQL) over the study timeline. Although the CICADAS only and PEERS + Active Control groups also demonstrated an upward trajectory (near trend) on the PedsQL, the addition of CICADAS to PEERS enhanced outcomes for the participants significantly. Including the PEERS + Active Control randomization group addressed the question of whether engaging weekly with static (ie, nonadaptive) computer games affected participant outcomes relative to the PEERS + CICADAS group. Indeed, we found significant advantages for the PEERS + CICADAS group over the PEERS + Active Control group on measures of executive function (BRIEF-2, WCST) that may be attributed to the added benefits of engaging in an adaptive social cognitive training app.

CICADAS is self-paced and designed to be engaging for the user; these gamified exercises are adaptive such that they maintain difficulty levels at a user's upper performance threshold by both incrementally adjusting exercise properties (eg, exposure duration, stimulus similarity, span length) and providing trial-by-trial performance feedback. This training works to strengthen early auditory and visual perceptual processes, as well as more complex social cognitive operations, to improve cortical representations and downstream functional outcomes. Executive functioning may impact social competence by facilitating higher-order strategies (eg, behavioral, emotional, cognitive regulation) that are necessary for interacting with others.[71,72] Of particular interest, we posit that baseline differences in clinical features may predict app engagement and impact. For example, a large number of participants reported comorbid ADHD (Table 1); potentially with a large sample size in a confirmatory efficacy trial, we would be able to detect if the executive function demands of adhering to a training schedule might hinder social cognitive gains from the app.

Although PEERS teaches teens to consciously alter their attention and behavior through instruction and practice, the program does not systematically target processing of basic sensory information that support real-world interactions.[73] We thus propose that a bottom-up approach to training will strengthen the basic perceptual and processing abilities needed to understand and navigate the more complex inputs encountered via social skills training and beyond. In essence, the acquisition of fundamental skills is vital when establishing a strong foundation in any discipline; these competencies may then lead to improved confidence and the capacity to tackle more varied and complex challenges.[74]

Although the results from the present study examining NP-TCT programs in conjunction with social skills interventions show promise and warrant further development and investigation, some limitations should be considered when interpreting the findings. First, male participants accounted for more than two-thirds of our study sample; although this gender imbalance is less than that reported in the broader autism population, the discrepancy may affect our ability to generalize across all autistic individuals. Further, we note that approximately 7% of our sample self-identified as nonbinary (Table 1). Future larger sample sizes potentially will enable us to substratify by gender identities and expressions to examine the role of gender diversity. Second, participants in our sample were predominantly White. Although this aligns with population data for our recruitment sites in the Upper Midwest region of the United States, we are limited in our ability to generalize across more diverse populations. Future work will need to recruit from a broader geographic and demographic range. Third, to evaluate the use of CICADAS vs active control as an adjunct or augmentation to PEERS, we had to recruit from families who were on clinic wait-lists and had the resources and time to enroll in a longitudinal trial. Although we were able to loan digital devices to participants who needed them to train with our TCT app, we were unable to provide internet services. Although the telehealth modality confers accessibility to more remote communities and affords more flexibility of scheduling, the need for reliable internet and technology can be a limiting factor for many families. Fourth, although our ITT analysis was implemented to offset some of the interindividual variability in engagement, and exposure requirements were met for data inclusion, it would not have been feasible to control for the myriad potentially confounding factors (eg, schoolwork, illness, vacation) that may have skewed our final analyses.

Finally, our preliminary efficacy trial was designed with 3 arms with data collection spanning 32 weeks; as anticipated, our sample sizes were modest. In fact, because our data collection took place in the midst of the COVID-19 pandemic, we increased our recruitment efforts to meet sample size targets because many families who had been interested in enrolling in PEERS and/or the research study experienced changes in priorities, resources, or timing that affected their interest or ability to participate. Although we planned to recruit participants for the CICADAS only group from families interested in and waiting for space in PEERS, COVID-19 restrictions impacted the ability and/or interest of families to continue with their treatment plans. We attribute higher rates of attrition in the CICADAS only group in part to these circumstantial challenges and fatigue with online programming (eg, virtual schooling). We also posit that families who were able to invest the time and resources to participate in PEERS may have been better equipped to sustain participation in the research study. The added support afforded by weekly group sessions with clinicians, parents/caregivers, and peers may have increased participant engagement. Future app-based protocols may recommend the commitment of a study partner (eg, parent, caregiver, sibling) to provide consistent support and encouragement throughout the training program.

Of interest, despite main effects of improvements over time, the CICADAS only group showed the highest restrictive repetitive behaviors (RBS-R) and more clinical problems (CBCL) broadly. These differences may reflect baseline as well as overall differences in time spent with peer groups and in social settings wherein PEERS participants follow a prescribed schedule of social skills training and practice. As such, clinical recommendations for NB-TCT may benefit from parent/caregiver-facilitated or organized opportunities to practice social communication and interactions with other individuals in various contexts. Future trials will also need to measure quality and quantity of outside (in-person or virtual) social interactions relative to alone time and nonsocial activities to gauge whether cognitive/sensory processing gains transfer to social skill improvement.

Given the strength of pairing observed in this initial investigation, our future studies will investigate CICADAS + PEERS outcomes in larger and more diverse samples. We will further refine our adaptive TCT program by selecting for training exercises that were most efficacious and constructive for participants. In this protocol, our research coordinators worked closely with families to monitor and check in with participants during the trial, providing organizational support as needed. Variability of outcome range may be related to differences between engaging with the app at a steady rate vs irregular bursts of training that sum to equivalent hours of exposure. Follow-up research could also evaluate if CICADAS would be beneficial as a self-paced, stand-alone program in participants who do not have executive functioning or organizational challenges. In contrast, the NB-TCT program may be especially helpful for autistic participants with co-occurring attentional or learning challenges that decrease their ability to absorb, use, or practice what they learn during social skills training.

NB-TCT has emerged as a promising approach to improve outcomes in multiple clinical and cognitive domains. The appeal of evidence-based TCT programs is their broad accessibility (remote delivery), cost-effectiveness, and potential for individual tailoring of treatment targets. Our findings demonstrated not only the potential efficacy of CICADAS as a stand-alone program, but also that training with the adaptive CICADAS app (vs the static active control app) conferred an additional advantage to autistic teens who participated in the established PEERS intervention. CICADAS shows promise as a feasible, deliverable, and beneficial intervention, and our investigation has elucidated measurement and targeting goals to pursue in larger-scale efficacy trials.

CRediT authorship contribution statement

Angela Tseng: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Amy Yang:** Writing – review & editing, Investigation, Data curation. **Amy Vaughan Van Hecke:** Writing – review & editing, Resources, Methodology. **Rebekah L. Hudock:** Writing – review & editing, Resources, Methodology. **Elizabeth A. Laugeson:** Writing – review & editing, Resources. **Hyun Kyu Lee:** Writing – review & editing, Validation, Software, Resources, Project administration, Formal analysis. **Bruno Biagianti:** Writing – review & editing, Software, Resources, Funding acquisition, Conceptualization. **Suma Jacob:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Accepted November 13, 2025.

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This research was funded by NIH SBIR R43MH124542 inspired by independent data through Suma Jacob and Angela Tseng (Minnesota Partnership Funds).

This study was conducted with approval from the Western Institutional Review Board (WIRB), an independent IRB that provides services for academic and nonacademic institutions. WIRB is accredited by the Association for the Accreditation of Human Research Protection Programs (AAHRPP). All procedures were performed in accordance with the approved IRB protocol. The study was preregistered on ClinicalTrials.gov (NCT04562688).

Preliminary findings from this study were presented at the annual meeting of the American College of Neuropsychopharmacology (ACNP); Dec 3-6, 2023; Tampa, FL, USA.

Data Sharing: Data are not publicly available due to privacy restrictions.

We are most grateful to all participant families and clinician teams involved. We also appreciate assistance with recruitment from Chris Emery, MSW, LICSW, and Pat Pulice, MA, LP, Sr VP (Fraser, Minnesota), the Fraser, Marquette University, and University of Minnesota Autism Project teams, and research coordination by Kathy Wannaviroj (Posit Science Inc.).

Disclosure: Elizabeth A. Laugeson has received royalties for the sales of books and manuals from Taylor & Francis and Wiley & Sons. Angela Tseng, Amy Yang, Amy Vaughan Van Hecke, Rebekah L. Hudock, Hyun Kyu Lee, Bruno Biagianti, and Suma Jacob have reported no biomedical financial interests or potential conflicts of interest.

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https://doi.org/10.1016/j.jaacop.2025.11.003

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