META-ANALYSIS

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Digital interventions for autism spectrum disorders: A systematic review and meta-analysis

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ABSTRACT

Importance: Digital technology is now widely available for the interventions of autism, but its validity and feasibility remain to be proved.

Objective: This study aimed to investigate the effectiveness of digital health interventions (DHIs) in improving core symptoms or intelligence quotient in patients with autism spectrum disorder (ASD).

Methods: Three databases including PubMed, Cochrane, and Scopus, were searched on November 15, 2022. Randomized clinical trials that enrolled patients with ASD who received DHIs and a control group without DHI treatment were included. Cochrane risk of bias tool (RoB 2) was applied to assess the risk of bias.

Results: A total of 33 studies, involving 1285 participants (658 [51.2%] in DHI groups and 627 [48.8%] in control groups), were analyzed to investigate the differences between DHI groups and control groups. Significantly greater improvements in the overall performance of ASD were observed in the DHI groups compared to the control groups (including active, waitlist, treatment-as-usual, and no treatment) with an effect size of 1.89 (Cohen's d 95% confidence interval [CI]: 1.26–2.52). Studies with treatment-as-usual, waitlist, and no treatment control demonstrated large effect sizes of Cohen's d 3.41 (95% CI: 0.84–5.97), Cohen's d 4.27 (95% CI: 1.95–6.59), and Cohen's d 4.52 (95% CI: 2.98–6.06) respectively. In contrast, studies with active control revealed insignificant effect sizes (Cohen's d 0.73, 95% CI: 0.12–1.33).

Interpretation: This meta-analysis found significantly greater improvements in core symptoms or intelligence quotient in ASD patients receiving DHIs compared to those in control conditions. ASD patients may benefit from the DHIs and reduce the economic burden.

KEYWORDS
Autism spectrum disorder, Digital interventions, Meta-analysis, Robotic interventions

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INTRODUCTION

Autism spectrum disorder (ASD) is a term used to describe a heterogeneous group of neurodevelopmental disorders involving early-appearing social communication deficits, and stereotyped and repetitive behaviors. According to the Diagnostic and Statistical Manual of Mental Disorders, 5th Edition, ASD is defined as persistent deficits in social communication and social interaction, along with restricted, repetitive patterns of behavior, interests, or activities.[1] The overall prevalence of ASD was 7.0–23.1 per 1000 children with 4.2 times more prevalent among boys compared with girls.[2,3] ASD is one of the heterogeneous etiology disorders with complex pathophysiology of genetic, environmental factors, and genetic-environment interactions.[4,5] Its symptoms can range broadly from mild to severe and usually need continuous long-term care and health interventions.

Health interventions for autism are commonly used to improve social deficits and alleviate repetitive and restricted patterns of behaviors.[6] Traditional behavior therapy was usually conducted by specialized therapists with face-to-face interventions, as there is currently no effective pharmacological treatment available to improve the core symptoms of autism.[7,8] However, the specialized therapist, specific settings, and fixed time of traditional therapies contribute to the heavy burden on individuals with ASD, their families, and society. Further, the coronavirus disease 2019 (COVID-19) pandemic challenged face-to-face therapies for ASD as epidemiological mitigation efforts (i.e., quarantine, isolation, and social distance) were promoted as the best strategy to cut off the channels of transmission.[9] Many patients experience therapy disruption and promote the use of therapy delivered via digital platforms.[10]

Digital health interventions (DHIs) deliver information, support, and therapy for health problems through technological or digital platforms. The last decade has seen a rapidly evolving of DHIs with an increasing variety (e.g., computer-assisted therapy, apps, wearable devices, robot-assisted therapy, and virtual reality technology).[11] Existing studies and meta-analysis suggest the mild to moderate efficacy of DHIs in chronic conditions,[12–14] and their efficacy in treating anxiety was reported to be as high as face-to-face programs.[15] Due to their affordability, efficiency, and convenience, DHIs could be a promising treatment for ASD.

Despite the significant efforts of individual studies to evaluate the DHIs in ASD, the effectiveness of DHIs remains unclear for the sample size was often small with inconsistent findings. Although a previous meta-analysis reported mild efficacy of DHIs in ASD,[16] given the evolution of DHIs caused by the COVID-19 pandemic, an update of the literature is necessary. Therefore, this study aimed to explore the effectiveness of DHIs in improving core symptoms or intelligence quotient in patients with ASD.

METHODS

Searching strategies

For this meta-analysis, we searched the PubMed, Cochrane, and Scopus databases for randomized clinical trials (RCTs) from inception to November 15, 2022. Published studies in the form of controlled trials with intervention and outcome assessment, as well as RCTs including pilot studies in patients with ASD, will be examined. There was no language restriction. The search algorithm for PubMed is available in File S1. The reference lists of previous meta-analyses were also searched.

Eligibility criteria

Eligible studies included (1) patients with confirmed ASD diagnosis; (2) study type of RCTs with intervention and outcome assessment, including pilot studies; (3) both intervention and control groups were ASD patients; (4) comparing DHIs group with a control group without DHIs treatment (treatment as usual, waitlist); (5) both intervention and control groups conducting pretest and posttest assessments of core features or intelligence quotient (IQ) with specific values. Studies were excluded if they (1) included only involved feasibility testing of an intervention, or (2) focused solely on assessing the acceptance or improvement of the caregiver's quality of life. If the same patient cohort was analyzed by more than one study, the study with the largest sample size or longest intervention period was included. Articles mainly reporting on the acceptance, feasibility, or follow-up effects of DHIs would be excluded.

Data extraction and processing

The title and abstract screening were independently conducted by two reviewers, Tianqi Wang and Yu Ma. Articles were excluded if they were repetitive, reviews, case reports, non-controlled studies, or if the control group were not ASD patients. Articles that pre-post test or control type were not mentioned in the abstract, would not be excluded at this step. Tianqi Wang and Yu Ma read the full text of the remaining studies. Conflicts regarding inclusion were resolved through discussion and adjudication by the third reviewer, Hao Zhou. Data were primarily extracted by Tianqi Wang and checked by Hao Zhou. We extracted demographic data of participants, including age and sex, as well as inclusion and exclusion criteria, group size, intervention type and duration, control group condition, and mean scores with standard deviation (SD) pre-test and post-test of core features or IQ. If studies did not provide mean scores, the mean scores and SD were estimated from the median with the maximum and minimum values or the median with the interquartile range.[17] The conducting time and publication time of studies were also extracted. For studies that assessed outcomes by several scales, the outcome most relevant to ASD core symptoms or IQ would be chosen. The outcome reported by parents will be chosen if both parents and teachers participate in the evaluation.

Risk of bias assessment

The Cochrane risk of bias tool (RoB 2) was applied to evaluate the risk of bias in the included studies.[18] The following five domains, including (1) randomization process, (2) deviations from intended interventions, (3) missing outcome data, (4) measurement of the outcome, and (5) selection of the reported results, were assessed. Each domain ranged from low to high risk of bias. The overall low, moderate, and high risk of bias were categorized referred to the combination of each domain. Two independent researchers (Tianqi Wang and Yu Ma) assessed the risk of bias independently, and any disagreements were resolved through discussion.

Statistical analysis

Stata 14.0 (StataCorp) was used to calculate the pooled effect sizes and 95% confidence intervals (CIs). Given the various assessments in evaluating the outcomes of different DHIs in patients with ASD, Cohen's d as an index of SD, was applied as a measure of effect size to synthesize the different outcome measures. Cohen's d was considered as small (0.2), moderate (0.5), and large (0.8), conventionally. We used a pretest and posttest with a control method to correct the preexisting differences between the intervention and control groups.[19] Given the anticipated significant heterogeneity, a random-effects pooling model was utilized to accommodate the true effect size. Heterogeneity was assessed by forest plotting and calculating I^2. Heterogeneity was categorized as low (25%), moderate (50%), and high (75%) according to I^2.[20] Publication bias was assessed by funnel plot, the Egger test, and the Duval and Tweedie trim-and-fill method.[21] If the conclusion of the meta-analysis did not change after the adjustment of the trim-and-fill method, the results were considered robust, indicating insignificant publication bias. The statistical significance level was set at a two-tailed P-value < 0.05.

RESULTS

A total of 1994 reports were identified through database searching, with a further 17 articles identified from reference lists of previous meta-analyses. Of the 2011 reports, 571 were removed due to duplication, and 1257 were excluded after screening titles and abstracts for not meeting the inclusion criteria. A further 149 articles were excluded based on full-text reading. The remaining 34 articles met the inclusion criteria and two of them including a duplicated cohort of samples were excluded. One of these articles reported two separate intervention groups, adding one more study to the meta-analysis (Figure 1). In total, 32 articles comprising 33 studies were included in the meta-analysis (Table 1). Studies were conducted in America (n = 12),[22–33] China (n = 4),[34–37] Australia (n = 3),[38–40] United Kingdom (n = 3),[41–43] Japan (n = 2),[44,45] Greece (n = 1),[46] Israel (n = 1),[47] Ireland (n = 1),[48] Netherland (n = 1),[49] Macedonia (n = 1),[50] Italy (n = 1),[51] Korea (n = 1),[52] Singapore (n = 1),[53] and Sweden (n = 1).[47]

Overall, 1285 participants were involved in the meta-analysis, with 658 (51.2%) participants in DHI groups and 627 (48.8%) participants in control groups. Per-study sample sizes ranged from 14 to 154 with a median of 36, mean of 39.2, and SD of 24.9. The ages of the participants ranged from 1 year to 52 years. Twenty-seven studies enrolled only pediatric participants, three enrolled only adults, and four studies enrolled both pediatric and adult participants, respectively. Most studies (12, 36.4%) used an active control, 11 (33.3%) used a waitlist control, seven (21.2%) used a treatment-as-usual control, and three (9.1%) used no intervention control. In total, 12 (36.4%) studies enrolled participants with an IQ ≥ 70 or high function as well as high language levels. Other 21 (63.6%) studies enrolled participants without limitation of IQ ≥ 70. Sixteen studies (47.1%) used scales to assess the performance of patients with two of them using Social Responsiveness Scales. The remaining studies assessed the domains reflecting core symptoms (i.e., social support intensity, role-play performance, and eye contact rate) using specific assessments and values. Referring to the outcome assessment, 12 (36.4%) studies assessed overall performance, 11 (33.3%) assessed social interaction, 6 (18.2%) assessed communication, and 4 (12.1%) assessed repetitive and restricted behaviors.

The intervention group consisted of DHIs only (27, 81.8%) and DHIs combined with other therapies (6, 18.2%). Computer programs and mobile applications (15, 45.5%) were the most commonly used DHIs, followed by robotic interventions (11, 33.3%), and virtual reality (2, 6.1%). The remaining DHIs included wearable devices, telehealth, iPod touch, electroencephalogram brain-computer interface, and DVD guide were each studied once, respectively. The intervention duration ranged from 15 min to 5520 min (median 800 min), with a mean duration of 968.5 min (SD: 978.4 min).

We compare the overall effects of DHIs with the control group. Among participants who received DHIs, significantly higher improvements were found compared with

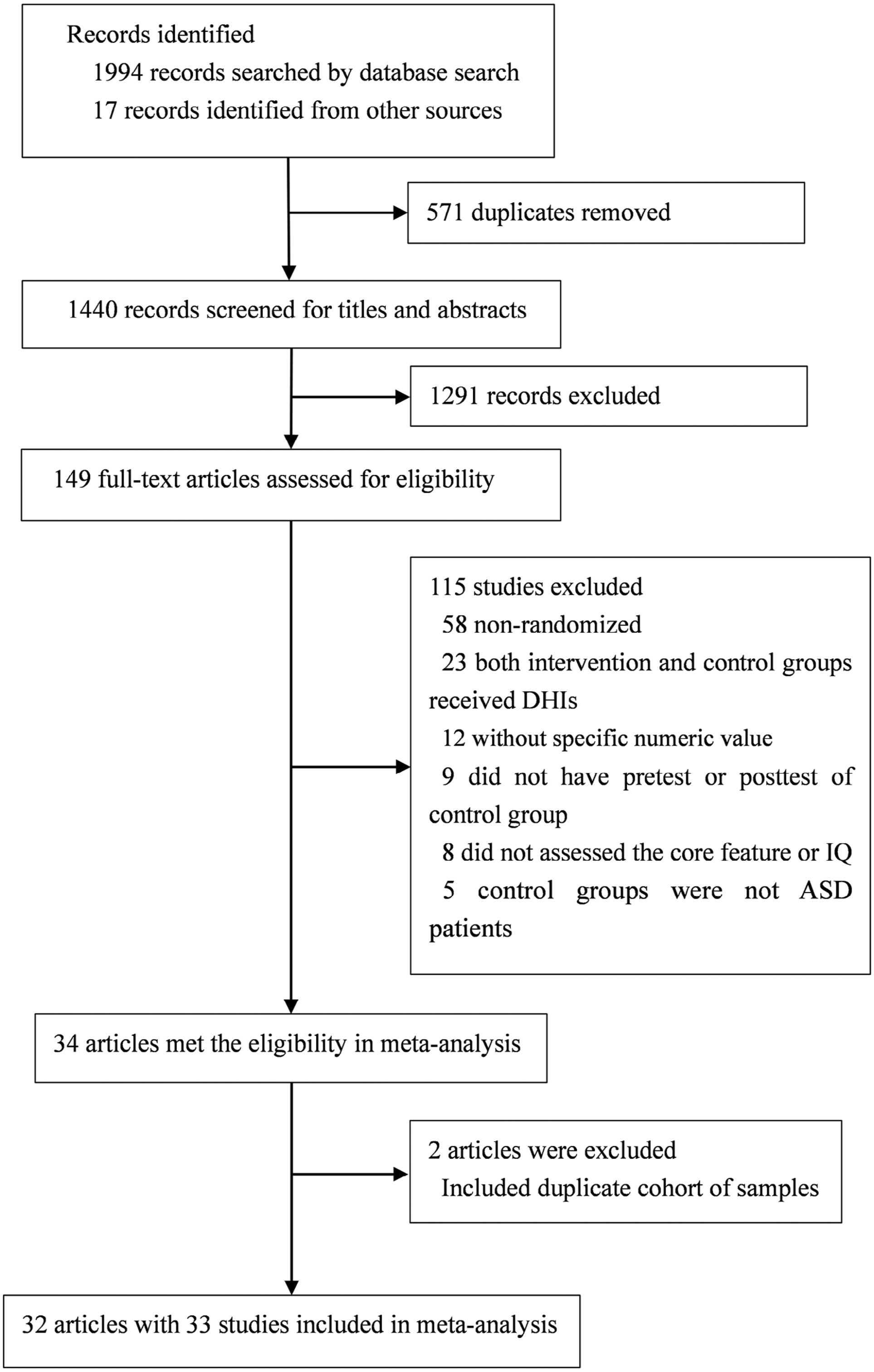

FIGURE 1 Flowchart of search and study selection process. DHIs, digital health interventions; ASD, autism spectrum disorder; IQ, intelligence quotient.

TABLE 1 Summary characters of included studies

Study	Intervention group size	Control group size	Male/ Female	Age (year)	Intervention	Control group type	Primary outcome assessment method
Voss et al., 2019	27	25	NA	6–12	Superpower Glass+applied behavioral analysis (ABA)	ABA	The Vineland Adaptive Behavioral Scales, Second edition (VABS-II)
Pellecchia et al., 2020	74	67	NA	5–9	Computer-assisted interventions: TeachTown: Basics software	Waitlist	Differential Ability Scales, second edition, Early Years Battery (DAS-II)
van den Berk-Smeekens et al., 2022	25	25	42/8	3–8	Pivotal response treatment (PRT)+robot	PRT	Social Responsiveness Scale, preschool and child version (SRS)-parent
Zheng et al., 2020	11	9	NA	1.5–3.5	NAO robot intervention	Waitlist	Screening Tool for Autism in Toddlers and Young Children (STAT)
Vasilevska Petrovska et al., 2019	16	16	23/9	7–15	Computer-based program: Ucime Emocii (Learning Emotions)	Treatment-as-usual	Face task (emotion understanding)
Holeva et al., 2022	22	22	35/9	6–12	NAO robot-assisted intervention	Therapist intervention	Childhood Autism Rating Scale (CARS2)
Zhao et al., 2022	22	22	35/9	3–6	Virtual reality with conventional rehabilitation training	Treatment-as-usual	The Psychoeducational Profile, Third Edition (PEP-3)
Kumazaki et al., 2018	16	12	19/9	5–6	CommU robot	Interacted with human	Performance during the joint attention task
So et al., 2019 (Ref 35)	13	13	23/3	1.5–4	NAO robot-based drama intervention	Waitlist	No-scale The number of clauses, the proportion of complex clauses, the number of goal-based stories, and the number of stories with cognitive and affective inferences used by the children
Marino et al., 2020	7	7	12/2	4–8	NAO humanoid robot	Therapist intervention	Test of emotional comprehension
Fletcher-Watson et al., 2016	27	27	43/11	1–6	iPad(™) apps	Treatment as usual	Brief observation of social communication change (BOSCC) Social communication total
Kumazaki et al., 2020	10	10	17/3	15–22	Tele-operated CommU robot	Therapist intervention	"Good at describing their thoughts to others" rated by their teacher
Smith et al., 2014	16	10	20/6	18–31	Virtual reality job interview training	Treatment-as-usual	Role-play performance total score
Thomeer et al., 2015	22	21	38/5	7–12	Interactive software program: Mind Reading	Waitlist	Cambridge Mindreading Face-Voice Battery for Children (CAM-C)

(Continues)

TABLE 1 (Continued)

Study	Intervention group size	Control group size	Male/ Female	Age (year)	Intervention	Control group type	Primary outcome assessment method
Lindgren et al., 2020	21	17	32/6	1.5–7	Functional communication training via telehealth	Treatment-as-usual	Percentage of intervals with problem behavior in each 5-min session
Yun et al., 2017	8	7	15/0	4–7	CARO robot	Therapist intervention	Eye-contact rate
So et al., 2019 (Ref 36)	12	11	20/3	1.5–5	NAO Robot-based intervention	Therapist intervention	Proportion of trials with accurate gestural production
Whitehouse et al., 2017	39	36	NA	2.5–4	TOBY app plus treatment-as-usual	Therapy-as-usual	The Autism Treatment Evaluation Checklist (ATEC)
Conaughton et al., 2017	21	21	36/6	8–12	Internet-based cognitive behavior therapy program	Waitlist	The Children's Global Assessment Scale (CGAS)
Srinivasan et al., 2015	12	12	22/2	5–12	NAO robot intervention	Therapist intervention	Frequencies in standard time of stereotyped behaviors
Gentry et al., 2015	26	24	42/8	18–60	iPod Touch	Waitlist	Supports Intensity Scale
Novack et al., 2019	15	13	24/4	1–8	ABA programs	Waitlist	Subtracting the number of known targets in Probe 2 from the number of known targets in Probe 1
Hatfield et al., 2017	49	45	72/22	8–11	BOOST-A™ online program	Treatment as usual	Self-Determination Scale (AIR)
Teo et al., 2021	10	10	17/3	8–12	Electroencephalogram brain-computer interface	Waitlist	SRS
Lopata et al., 2016	18	18	34/2	7–12	SmmerMAX+mind reading (emotion-recognition) computer instruction	SummerMAX	CAM-C
Hayes et al., 2015	8	7	13/2	17–18	Mobile video modeling for employment interviews	Waitlist	Vairable: Presentation
Chen et al., 2022	12	13	23/2	6–12	Comprehensive attention training system (CATS)	Therapist social skills intervention	Trail-making test
Nally et al., 2021	15	16	26/5	4–18	Computer-assisted instruction (CAI)+Edmark® Mastery	Table-top instruction (TTI)+Edmark® Mastery	WIAT-II: Word reading
Strickland et al., 2013	11	11	22/0	16–19	JobTIPS: A transition to employment program	No treatment	Interview Rating Scale/Content scale
Golan et al., 2006	19	22	31/10	17.5–52	Mind Reading Software	No treatment	CAM-C

(Continues)

TABLE 1 (Continued)

Study	Intervention group size	Control group size	Male/Female	Age (year)	Intervention	Control group type	Primary outcome assessment method
Fridenson-Hayo et al., 2017†	18	20	35/3	6–9	Computerized intervention programs, also known as serious games	Waitlist	Face task
Fridenson-Hayo et al., 2017‡	16	20	31/5	6–9	Computerized intervention programs, also known as serious games	Waitlist	Face task
Golan et al., 2010	20	18	NA	4–7	The Transporters DVD guide	No treatment	Emotional vocabulary task

NA, not available.
†Study performed in Israel.
‡Study performed in Sweden.

control groups, including active, waitlist, treatment-as-usual, and none treatment. The effect size was 1.89 (Cohen's d, 95% CI: 1.26–2.52) (Figure 2).

Subgrouping of studies, including intervention type, DHI type, participant age, IQ, and control group type, significantly moderated the effect size (Figure 3). The 27 studies that used DHIs only in intervention groups demonstrated a large effect size (Cohen's d 1.98, 95% CI: 1.28–2.68), while the 6 studies that used DHIs combined with other treatments demonstrated insignificant effect size (Cohen's d 1.46, 95% CI: 0.10–2.83).

In addition, the type of DHIs including computer programs and other types showed a large effect size with Cohen's d of 2.83 (95% CI: 1.52–4.15) and 4.75 (95% CI: 0.86–8.64), respectively. Eleven studies used robot interventions, and two used virtual reality, however, show an insignificant effect size with Cohen's d 0.90 (95% CI: −0.04 to 1.83) and 1.23 (95% CI: −0.34 to 2.80). For participants who received robot intervention, different assessment domains were also analyzed. Participants who received robot intervention showed a small to large effect size in social interaction (Cohen's d 1.94, 95% CI: 0.49–3.40), while the effect size in the other three domains was insignificant (Figure 4).

Regarding different age groups, the 26 studies that enrolled pediatrics (Cohen's d 2.03, 95% CI: 1.31–2.76), demonstrated a large effect size, and the five studies that enrolled adults demonstrated a small to large effect (Cohen's d 1.09, 95% CI: 0.28–1.90). Twelve studies enrolled participants with an IQ $\geq$ 70 (Cohen's d 2.44, 95% CI: 1.37–3.51) showed larger effect sizes than those without limitation of IQ $\geq$ 70 (Cohen's d 1.93, 95% CI: 0.90–2.95). The type of control condition significantly moderates the effect size, explaining 28.5% of the heterogeneity in the total between-study variance. Studies with treatment-as-usual, waitlist, and no treatment control demonstrated large effect size of (Cohen's d 3.41, 95% CI: 0.84–5.97), (Cohen's d 4.27, 95% CI: 1.95–6.59) and (Cohen's d 4.52, 95% CI: 2.98–6.06) respectively, while 12 studies with active control revealed an insignificant effect size (Cohen's d 0.73, 95% CI: 0.12–1.33). Twelve studies evaluated the overall performance (Cohen's d 2.02, 95% CI: 0.77–3.27) and 11 studies evaluated social interaction (Cohen's d 2.80, 95% CI: 1.60–3.99), and demonstrated a large effect size. Six studies evaluated communication demonstrated a moderate to large effect size (Cohen's d 4.51, 95% CI: 0.46–8.57), while four studies evaluated behaviors demonstrated an insignificant effect size (Cohen's d 0.77, 95% CI: −0.41 to 1.94) (Figure 3).

The risk of bias according to the RoB 2 was low in 33 studies for the randomization process, in 32 studies for deviation from the intended intervention, in 26 studies for missing outcome data, in 27 studies for the measurement of outcome, and in 33 studies for the selection of the reported selection. According to the overall risk of bias, 20 studies were considered to have a low risk of bias, while 13 studies were considered to have a moderate risk of bias.

Egger's test indicated asymmetry in the funnel plot upon visual inspection. The sensitivity analysis using the Duval and Tweedie trim-and-fill procedure was performed, and 14 missing studies were added. The effect size was 2.04 (95% CI, 1.04–4.02, $P = 0.039$) indicating that the correction for potential publication bias did not alter the significant association. Heterogeneity between studies was substantial ($I^2 = 84.1\%$), with effect sizes ranging from −0.90 to 49.70.

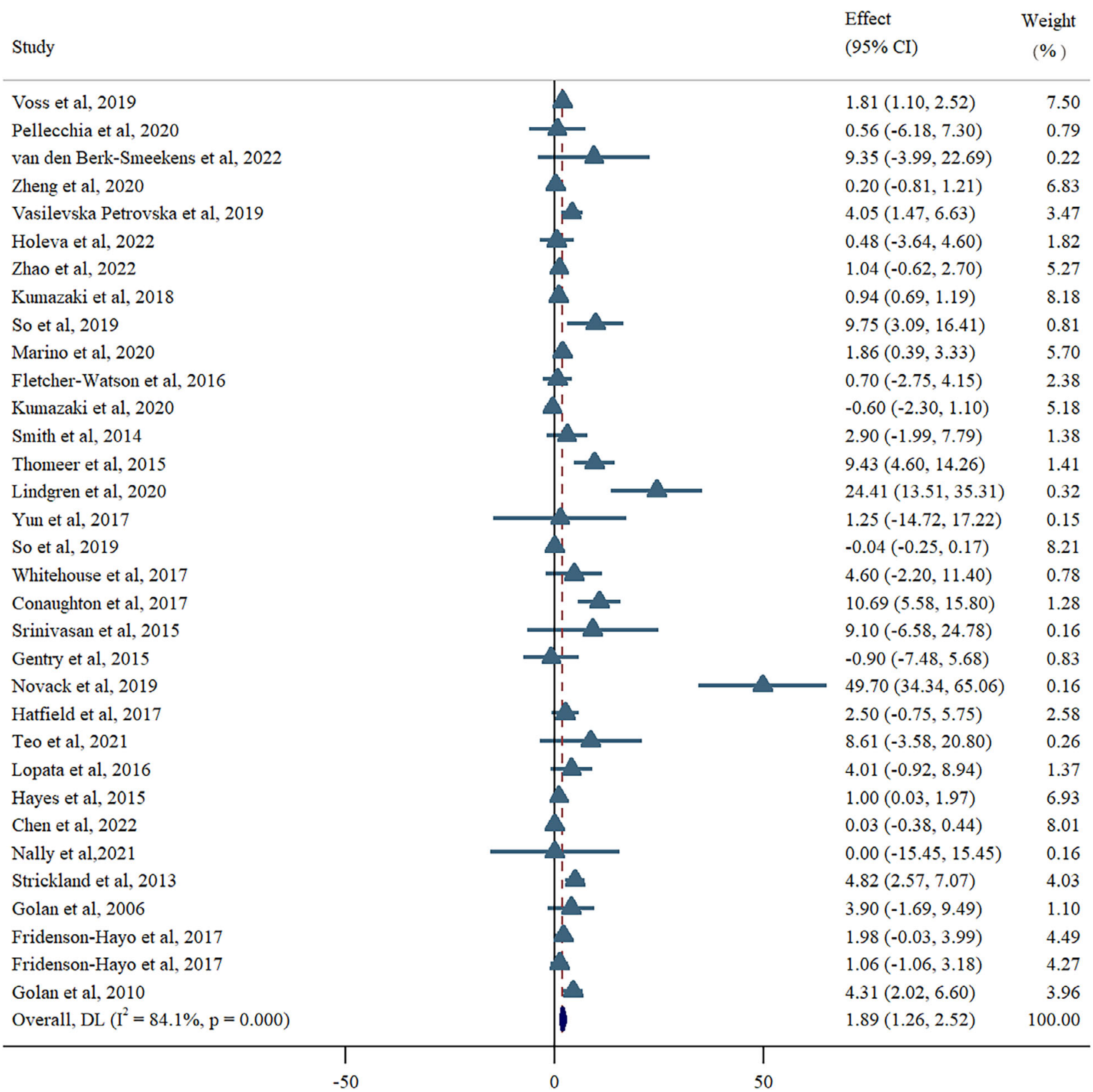

FIGURE 2 Forest plot of studies comparing digital health interventions with controls for improving the performance of autism spectrum disorder. DL, Dersmionian-Laird.

DISCUSSION

DHIs represented the most promising interventions for ASD in both pediatric and adult populations. In this meta-analysis, we analyzed data from 33 RCT studies including 1285 participants with ASD from 14 countries. The DHIs in ASD showed a large effect size in improving performance compared with control conditions.

The present study found the effect size with Cohen's d of 1.89 indicating the large positive effect of DHIs in ASD. A previous meta-analysis study conducted by Grynszpan et al.[54] enrolled 14 controlled studies and reported a medium effect size of technology-based interventions in ASD, with a Cohen's d of 0.47. Additionally, Sandgreen et al.[16] conducted a meta-analysis that included 19 studies and demonstrated a small effect size of DHIs in ASD with a Cohen's d of 0.32. Both of the previous studies utilized posttest controlled studies to calculate the mean effect size. The present studies used a pretest and posttest design to assess the DHIs and found a greater effect size than

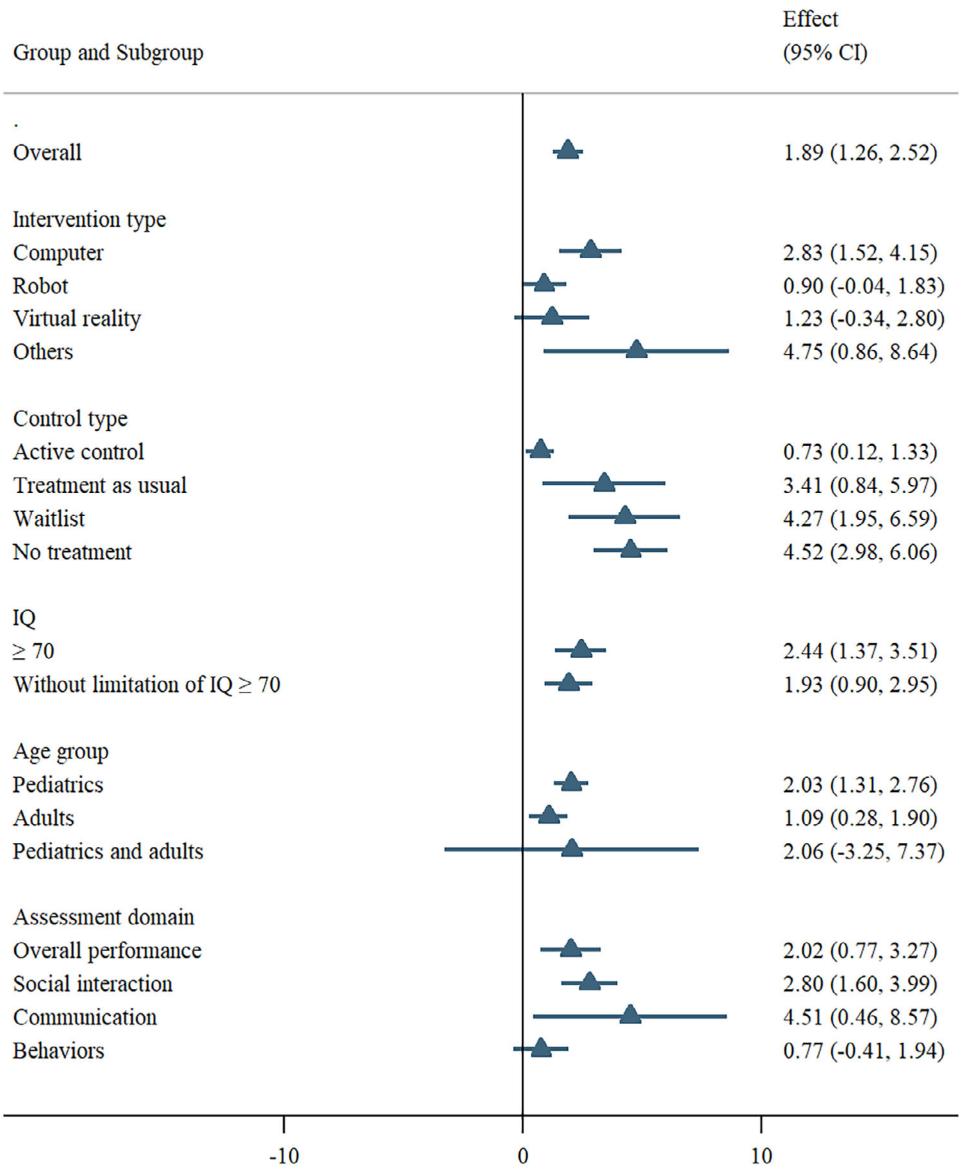

FIGURE 3 Forest plot of studies comparing digital health interventions with controls for improving the performance of autism spectrum disorder in different subgroups. IQ, intelligence quotient.

previous studies.[16,54] Besides, the inclusion and exclusion criteria, type of control group, pretest and posttest design, and innovative digital interventions could contribute to different effect sizes.

Consistent with the distinction between active and inactive control groups previously reported,[55,56] the intervention efficiency was associated with different types of control in the present study. Studies that used waitlist control groups or no intervention control groups showed larger effect sizes than those with a treatment-as-usual control condition. What's more, the effect size of DHI groups compared with active control groups was insignificant in the present study, indicating a comparable treatment effect. The effect size could be emphasized when compared with a waitlist and no treatment control, while it could be underestimated when compared with an active control.[55] In the present study, the large effect size of DHIs compared to the waitlist and no intervention control group could reflect the significant treatment efficiency. Furthermore, the relative efficacy of DHIs in comparison to treatment-as-usual or active control groups suggests that DHIs could be effective interventions for ASD.[57]

It is controversial whether age and IQ could influence the effect of DHI treatment in ASD patients. Different

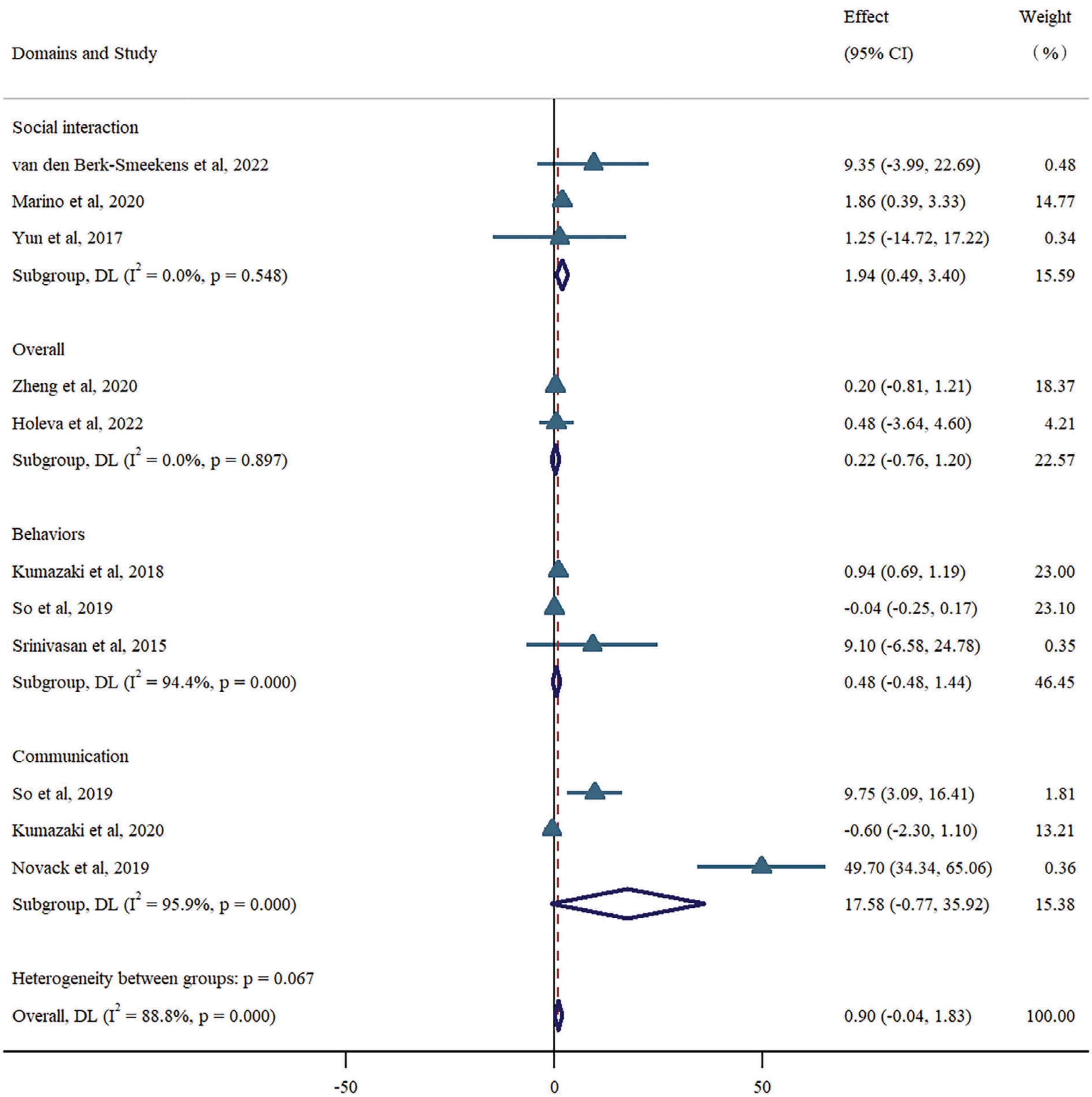

FIGURE 4 Forest plot of studies comparing robotic interventions with controls for improving performance in different assessment domains. DL, Dersmionian-Laird.

from previous studies,[16,54,58] age groups were significantly associated with the intervention effect. Pediatrics showed greater DHI treatment efficiency than adults, suggesting the importance of early intervention.[59] Nevertheless, the significant treatment efficacy in adults indicates that patients could benefit from treatment regardless of the timing of initiation. Previous studies have found that ASD individuals with higher IQ showed greater improvements in social skills interventions.[58] We also found that DHIs in patients with IQ $\geq$ 70 showed greater improvement compared to those without limitation of IQ $\geq$ 70. The variation in adaption and acceptance of DHIs may be attributed to differences in IQ levels. Future DHIs could be designed to match the age group and IQ levels of patients with ASD to improve the treatment efficiency. Regarding the different outcome assessments, DHIs significantly improved the social function of ASD. However, the effectiveness of DHIs in reducing stereotyped and repetitive behaviors was not statistically significant when compared with control groups. Future studies may aim to design DHIs more specifically to improve behaviors.

Among different DHI types, we found that ASD patients who received computer programs showed greater improvement compared to those who received other types of DHIs, including robotic intervention and virtual reality. Given that children with ASD have a strong interest in robots, applying human-robot interaction for ASD intervention has been considered promising.[60] We also found that robotic intervention led to significantly greater improvement in social interaction. However, the robotic interventions showed an insignificant effect on ASD treatment compared with the control group in overall performance, behavior, and communication. The active control type, participants' age, and IQ could influence the effectiveness of the robotic intervention in this study. Future studies should be conducted with consistent control groups to evaluate the treatment effect of robotic interventions.

The present study used a pretest-posttest method to correct for preexisting group differences, regardless of random allocation. A large sample size was enrolled to comprehensively evaluate the treatment's effectiveness. However, there were several limitations. First, the variation in types of DHIs, age, and IQ levels, control group types, and outcome assessments could have contributed to substantial heterogeneity, limiting the generalizability of DHIs in ASD treatment. Secondly, due to the limited and inconsistent follow-up periods in most studies, we were unable to assess the long-term outcome effects of DHIs. Thirdly, although the Duval and Tweedie test suggests insignificant publication bias, the study results should be interpreted considering the potential for publication bias.

In conclusion, the present meta-analysis study found significantly greater improvements in social function and overall performance in pediatric and adult patients with ASD who received DHIs compared to those in control conditions. DHIs show promise in addressing the socioeconomic, physical distance, and time deficiency gap in ASD.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. American Psychiatric Association. *Diagnostic and Statistical Manual of Mental Disorders: DSM-5™*. 5th ed. American Psychiatric Association; 2013.
2. Maenner MJ, Shaw KA, Bakian AV, Bilder DA, Durkin MS, Esler A, et al. Prevalence and characteristics of autism spectrum disorder among children aged 8 years - Autism and developmental disabilities monitoring network, 11 sites, United States, 2018. *MMWR Surveill Summ.* 2021;70:1-16. DOI: 10.15585/mmwr.ss7011a1
3. Zhou H, Xu X, Yan W, Zou X, Wu L, Luo X, et al. Prevalence of autism spectrum disorder in China: a nationwide multi-center population-based study among children aged 6 to 12 years. *Neurosci Bull.* 2020;36:961-971. DOI: 10.1007/s12264-020-00530-6
4. Warrier V, Zhang X, Reed P, Havdahl A, Moore TM, Cliquet F, et al. Genetic correlates of phenotypic heterogeneity in autism. *Nat Genet.* 2022;54:1293-1304. DOI: 10.1038/s41588-022-01072-5
5. Yap CX, Henders AK, Alvares GA, Wood D, Krause L, Tyson GW, et al. Autism-related dietary preferences mediate autism-gut microbiome associations. *Cell.* 2021;184:5916-5931. DOI: 10.1016/j.cell.2021.10.015. e17.
6. Eack SM, Hogarty SS, Greenwald DP, Litschge MY, Porton SA, Mazefsky CA, et al. Cognitive enhancement therapy for adult autism spectrum disorder: results of an 18-month randomized clinical trial. *Autism Res.* 2018;11:519-530. DOI: 10.1002/aur.1913
7. Wood JJ, Kendall PC, Wood KS, Kerns CM, Seltzer M, Small BJ, et al. Cognitive behavioral treatments for anxiety in children with autism spectrum disorder: a randomized clinical trial. *JAMA Psychiatry.* 2020;77:474-483. DOI: 10.1001/jamapsychiatry.2019.4160
8. Sikich L, Kolevzon A, King BH, McDougle CJ, Sanders KB, Kim SJ, et al. Intranasal oxytocin in children and adolescents with autism spectrum disorder. *N Engl J Med.* 2021;385:1462-1473. DOI: 10.1056/NEJMoa2103583
9. Jefferies S, French N, Gilkison C, Graham G, Hope V, Marshall J, et al. COVID-19 in New Zealand and the impact of the national response: a descriptive epidemiological study. *Lancet Public Health.* 2020;5:e612-e623. DOI: 10.1016/S2468-2667(20)30225-5
10. Norman S, Atabaki S, Atmore K, Biddle C, DiFazio M, Felten D, et al. Home direct-to-consumer telehealth solutions for children with mental health disorders and the impact of COVID-19. *Clin Child Psychol Psychiatry.* 2022;27:244-258. DOI: 10.1177/13591045211064134
11. Szymona B, Maciejewski M, Karpiński R, Jonak K, Radzikowska-Büchner E, Niderla K, et al. Robot-assisted autism therapy (RAAT). Criteria and types of experiments using anthropomorphic and zoomorphic robots. Review of the research. *Sensors (Basel).* 2021;21:3720. DOI: 10.3390/s21113720
12. Mehta S, Peynenburg VA, Hadjistavropoulos HD. Internet-delivered cognitive behaviour therapy for chronic health conditions: a systematic review and meta-analysis. *J Behav Med.* 2019;42:169-187. DOI: 10.1007/s10865-018-9984-x
13. Karyotaki E, Efthimiou O, Miguel C, Bermpohl F, Furukawa TA, Cuijpers P, et al. Internet-based cognitive behavioral therapy for depression: a systematic review and individual patient data network meta-analysis. *JAMA Psychiatry.* 2021;78:361-371. DOI: 10.1001/jamapsychiatry.2020.4364
14. Araya R, Menezes PR, Claro HG, Brandt LR, Daley KL, Quayle J, et al. Effect of a digital intervention on depressive symptoms in patients with comorbid hypertension or diabetes in Brazil and Peru: two randomized clinical trials. *JAMA.* 2021;325:1852-1862. DOI: 10.1001/jama.2021.4348
15. Wright JH, Mishkind M, Eells TD, Chan SR. Computer-assisted cognitive-behavior therapy and mobile apps for depression and anxiety. *Curr Psychiatry Rep.* 2019;21:62. DOI: 10.1007/s11920-019-1031-2

16. Sandgreen H, Frederiksen LH, Bilenberg N. Digital interventions for autism spectrum disorder: a meta-analysis. *J Autism Dev Disord.* 2021;51:3138-3152. DOI: 10.1007/s10803-020-04778-9
17. Luo D, Wan X, Liu J, Tong T. Optimally estimating the sample mean from the sample size, median, mid-range, and/or mid-quartile range. *Stat Methods Med Res.* 2018;27:1785-1805. DOI: 10.1177/0962280216669183
18. Sterne J, Savović J, Page MJ, Elbers RG, Blencowe NS, Boutron I, et al. RoB 2: a revised tool for assessing risk of bias in randomised trials. *BMJ.* 2019;366:l4898. DOI: 10.1136/bmj.l4898
19. Chu CS, Li CT, Brunoni AR, Yang FC, Tseng PT, Tu YK, et al. Cognitive effects and acceptability of non-invasive brain stimulation on Alzheimer's disease and mild cognitive impairment: a component network meta-analysis. *J Neurol Neurosurg Psychiatry.* 2021;92:195-203. DOI: 10.1136/jnnp-2020-323870
20. Higgins JP, Thompson SG, Deeks JJ, Altman DG. Measuring inconsistency in meta-analyses. *BMJ.* 2003;327:557-560. DOI: 10.1136/bmj.327.7414.557
21. Duval S, Tweedie R. Trim and fill: a simple funnel-plot-based method of testing and adjusting for publication bias in meta-analysis. *Biometrics.* 2000;56:455-463. DOI: 10.1111/j.0006-341x.2000.00455.x
22. Voss C, Schwartz J, Daniels J, Kline A, Haber N, Washington P, et al. Effect of wearable digital intervention for improving socialization in children with autism spectrum disorder: a randomized clinical trial. *JAMA Pediatr.* 2019;173:446-454. DOI: 10.1001/jamapediatrics.2019.0285
23. Pellecchia M, Marcus SC, Spaulding C, Seidman M, Xie M, Rump K, et al. Randomized trial of a computer-assisted intervention for children with autism in schools. *J Am Acad Child Adolesc Psychiatry.* 2020;59:373-380. DOI: 10.1016/j.jaac.2019.03.029
24. Zheng Z, Nie G, Swanson A, Weitlauf A, Warren Z, Sarkar N. A randomized controlled trial of an intelligent robotic response to joint attention intervention system. *J Autism Dev Disord.* 2020;50:2819-2831. DOI: 10.1007/s10803-020-04388-5
25. Smith MJ, Ginger EJ, Wright K, Wright MA, Taylor JL, Humm LB, et al. Virtual reality job interview training in adults with autism spectrum disorder. *J Autism Dev Disord.* 2014;44:2450-2463. DOI: 10.1007/s10803-014-2113-y
26. Thomeer ML, Smith RA, Lopata C, Volker MA, Lipinski AM, Rodgers JD, et al. Randomized controlled trial of mind reading and in vivo rehearsal for high-functioning children with ASD. *J Autism Dev Disord.* 2015;45:2115-2127. DOI: 10.1007/s10803-015-2374-0
27. Lindgren S, Wacker D, Schieltz K, Suess A, Pelzel K, Kopelman T, et al. A randomized controlled trial of functional communication training via telehealth for young children with autism spectrum disorder. *J Autism Dev Disord.* 2020;50:4449-4462. DOI: 10.1007/s10803-020-04451-1
28. Srinivasan SM, Park IK, Neelly LB, Bhat AN. A comparison of the effects of rhythm and robotic interventions on repetitive behaviors and affective states of children with autism spectrum disorder (ASD). *Res Autism Spectr Disord.* 2015;18:51-63. DOI: 10.1016/j.rasd.2015.07.004
29. Gentry T, Kriner R, Sima A, McDonough J, Wehman P. Reducing the need for personal supports among workers with autism using an iPod Touch as an assistive technology: delayed randomized control trial. *J Autism Dev Disord.* 2015;45:669-684. DOI: 10.1007/s10803-014-2221-8
30. Novack MN, Hong E, Dixon DR, Granpeesheh D. An evaluation of a mobile application designed to teach receptive language skills to children with autism spectrum disorder. *Behav Anal Pract.* 2019;12:66-77. DOI: 10.1007/s40617-018-00312-7
31. Lopata C, Thomeer ML, Rodgers JD, Donnelly JP, McDonald CA. RCT of mind reading as a component of a psychosocial treatment for high-functioning children with ASD. *Res Autism Spectr Disord.* 2016;21:25-36. DOI: 10.1016/j.rasd.2015.09.003
32. Hayes GR, Custodio VE, Haimson OL, Nguyen K, Ringland KE, Ulgado RR, et al. Mobile video modeling for employment interviews for individuals with autism. *J Voc Rehabil.* 2015;43:275-287. DOI: 10.3233/JVR-150775
33. Strickland DC, Coles CD, Southern LB. JobTIPS: a transition to employment program for individuals with autism spectrum disorders. *J Autism Dev Disord.* 2013;43:2472-2483. DOI: 10.1007/s10803-013-1800-4
34. Zhao J, Zhang X, Lu Y, Wu X, Zhou F, Yang S, et al. Virtual reality technology enhances the cognitive and social communication of children with autism spectrum disorder. *Front Public Health.* 2022;10:1029392. DOI: 10.3389/fpubh.2022.1029392
35. So WC, Cheng CH, Lam WY, Wong T, Law WW, Huang Y, et al. Robot-based play-drama intervention may improve the narrative abilities of Chinese-speaking preschoolers with autism spectrum disorder. *Res Dev Disabil.* 2019;95:103515. DOI: 10.1016/j.ridd.2019.103515
36. So WC, Wong MK, Lam WY, Cheng CH, Ku SY, Lam KY, et al. Who is a better teacher for children with autism? Comparison of learning outcomes between robot-based and human-based interventions in gestural production and recognition. *Res Dev Disabil.* 2019;86:62-75. DOI: 10.1016/j.ridd.2019.01.002
37. Chen MT, Chang YP, Marraccini ME, Cho MC, Guo NW. Comprehensive attention training system (CATS): a computerized executive-functioning training for school-aged children with autism spectrum disorder. *Int J Dev Disabil.* 2022;68:528-537. DOI: 10.1080/20473869.2020.1827673
38. Whitehouse A, Granich J, Alvares G, Busacca M, Cooper MN, Dass A, et al. A randomised controlled trial of an iPad-based application to complement early behavioural intervention in autism spectrum disorder. *J Child Psychol Psychiatry.* 2017;58:1042-1052. DOI: 10.1111/jcpp.12752
39. Conaughton RJ, Donovan CL, March S. Efficacy of an internet-based CBT program for children with comorbid high functioning autism spectrum disorder and anxiety: a randomised controlled trial. *J Affect Disord.* 2017;218:260-268. DOI: 10.1016/j.jad.2017.04.032
40. Hatfield M, Falkmer M, Falkmer T, Ciccarelli M. Effectiveness of the BOOST-A™ online transition planning program

for adolescents on the autism spectrum: a quasi-randomized controlled trial. *Child Adolesc Psychiatry Ment Health.* 2017;11:54. DOI: 10.1186/s13034-017-0191-2
41. Fletcher-Watson S, Petrou A, Scott-Barrett J, Dicks P, Graham C, O'Hare A, et al. A trial of an iPad™ intervention targeting social communication skills in children with autism. *Autism.* 2016;20:771-782. DOI: 10.1177/1362361315605624
42. Golan O, Baron-Cohen S. Systemizing empathy: teaching adults with Asperger syndrome or high-functioning autism to recognize complex emotions using interactive multimedia. *Dev Psychopathol.* 2006;18:591-617. DOI: 10.1017/S0954579406060305
43. Golan O, Ashwin E, Granader Y, McClintock S, Day K, Leggett V, et al. Enhancing emotion recognition in children with autism spectrum conditions: an intervention using animated vehicles with real emotional faces. *J Autism Dev Disord.* 2010;40:269-279. DOI: 10.1007/s10803-009-0862-9
44. Kumazaki H, Yoshikawa Y, Yoshimura Y, Ikeda T, Hasegawa C, Saito DN, et al. The impact of robotic intervention on joint attention in children with autism spectrum disorders. *Mol Autism.* 2018;9:46. DOI: 10.1186/s13229-018-0230-8
45. Kumazaki H, Muramatsu T, Yoshikawa Y, Haraguchi H, Sono T, Matsumoto Y, et al. Enhancing communication skills of individuals with autism spectrum disorders while maintaining social distancing using two tele-operated robots. *Front Psychiatry.* 2020;11:598688. DOI: 10.3389/fpsyt.2020.598688
46. Holeva V, Nikopoulou VA, Lytridis C, Bazinas C, Kechayas P, Sidiropoulos G, et al. Effectiveness of a robot-assisted psychological intervention for children with autism spectrum disorder. *J Autism Dev Disord.* 2024;54:577-593. DOI: 10.1007/s10803-022-05796-5
47. Fridenson-Hayo S, Berggren S, Lassalle A, Tal S, Pigat D, Meir-Goren N, et al. 'Emotiplay': a serious game for learning about emotions in children with autism: results of a cross-cultural evaluation. *Eur Child Adolesc Psychiatry.* 2017;26:979-992. DOI: 10.1007/s00787-017-0968-0
48. Nally A, Holloway J, Lydon H, Healy O. The Edmark® reading program: a comparison of computerized and table top presentation in reading outcomes in students with autism spectrum disorder. *J Dev Phys Disabil.* 2021;33:259-278. DOI: 10.1007/s10882-020-09747-9
49. van den Berk-Smeekens I, de Korte M, van Dongen-Boomsma M, Oosterling IJ, den Boer JC, Barakova EI, et al. Pivotal response treatment with and without robot-assistance for children with autism: a randomized controlled trial. *Eur Child Adolesc Psychiatry.* 2022;31:1871-1883. DOI: 10.1007/s00787-021-01804-8
50. Vasilevska Petrovska I, Trajkovski V. Effects of a computer-based intervention on emotion understanding in children with autism spectrum conditions. *J Autism Dev Disord.* 2019;49:4244-4255. DOI: 10.1007/s10803-019-04135-5
51. Marino F, Chilà P, Sfrazzetto ST, Carrozza C, Crimi I, Failla C, et al. Outcomes of a robot-assisted social-emotional understanding intervention for young children with autism spectrum disorders. *J Autism Dev Disord.* 2020;50:1973-1987. DOI: 10.1007/s10803-019-03953-x
52. Yun SS, Choi J, Park SK, Bong GY, Yoo H. Social skills training for children with autism spectrum disorder using a robotic behavioral intervention system. *Autism Res.* 2017;10:1306-1323. DOI: 10.1002/aur.1778
53. Teo SJ, Poh XWW, Lee TS, Guan C, Cheung YB, Fung DSS, et al. Brain-computer interface based attention and social cognition training programme for children with ASD and co-occurring ADHD: a feasibility trial. *Res Autism Spectr Disord.* 2021;89:101882. DOI: 10.1016/j.rasd.2021.101882
54. Grynszpan O, Weiss PL, Perez-Diaz F, Gal E. Innovative technology-based interventions for autism spectrum disorders: a meta-analysis. *Autism.* 2014;18:346-361. DOI: 10.1177/1362361313476767
55. Karlsson P, Bergmark A. Compared with what? An analysis of control-group types in Cochrane and Campbell reviews of psychosocial treatment efficacy with substance use disorders. *Addiction.* 2015;110:420-428. DOI: 10.1111/add.12799
56. Darling SJ, Goods M, Ryan NP, Chisholm AK, Haebich K, Payne JM. Behavioral intervention for social challenges in children and adolescents: a systematic Review and meta-analysis. *JAMA Pediatr.* 2021;175:e213982. DOI: 10.1001/jamapediatrics.2021.3982
57. Ferri M, Amato L, Davoli M. Alcoholics anonymous and other 12-step programmes for alcohol dependence. *Cochrane Database Syst Rev.* 2006:CD005032. DOI: 10.1002/14651858.CD005032.pub2
58. Gates JA, Kang E, Lerner MD. Efficacy of group social skills interventions for youth with autism spectrum disorder: a systematic review and meta-analysis. *Clin Psychol Rev.* 2017;52:164-181. DOI: 10.1016/j.cpr.2017.01.006
59. Dimian AF, Symons FJ, Wolff JJ. Delay to early intensive behavioral intervention and educational outcomes for a medicaid-enrolled cohort of children with autism. *J Autism Dev Disord.* 2021;51:1054-1066. DOI: 10.1007/s10803-020-04586-1
60. Saleh MA, Hanapiah FA, Hashim H. Robot applications for autism: a comprehensive review. *Disabil Rehabil Assist Technol.* 2021;16:580-602. DOI: 10.1080/17483107.2019.1685016

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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