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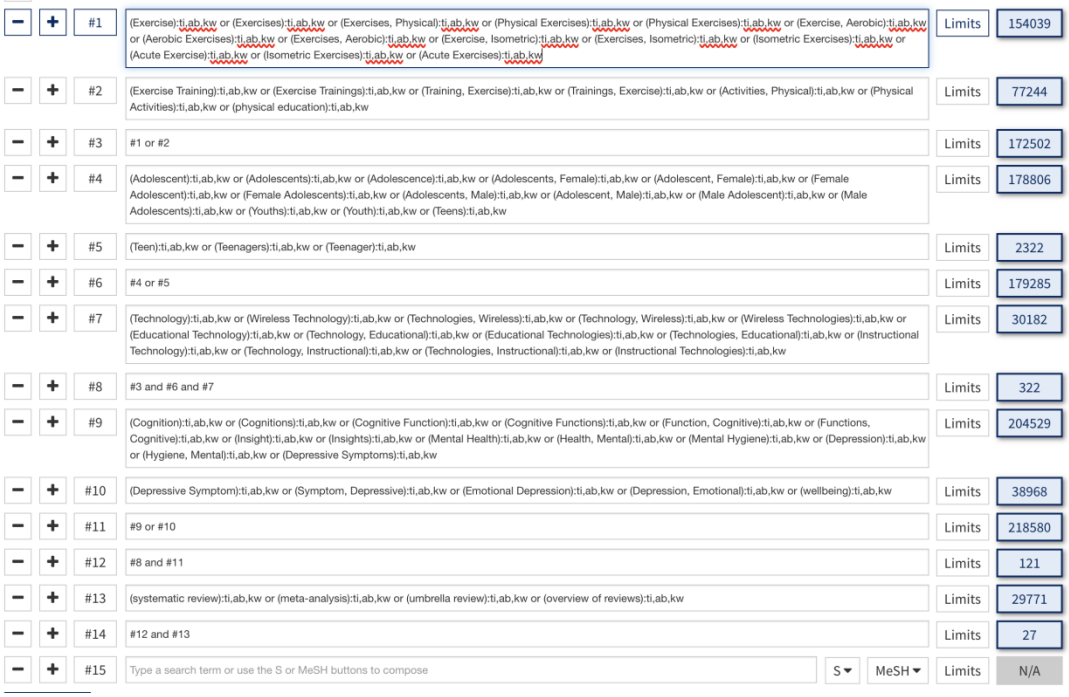

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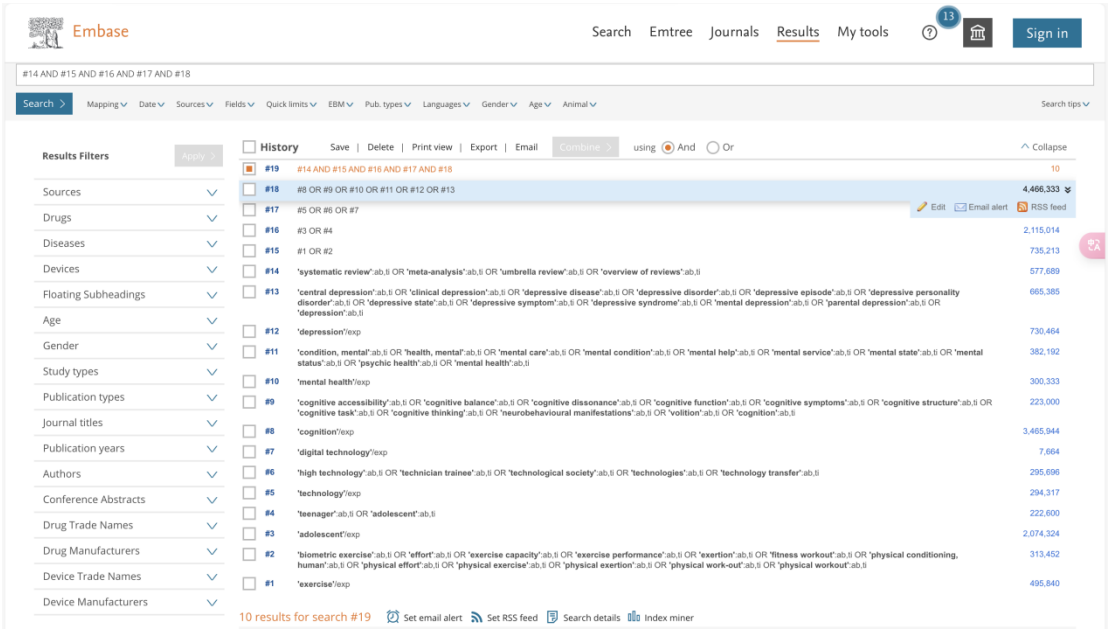

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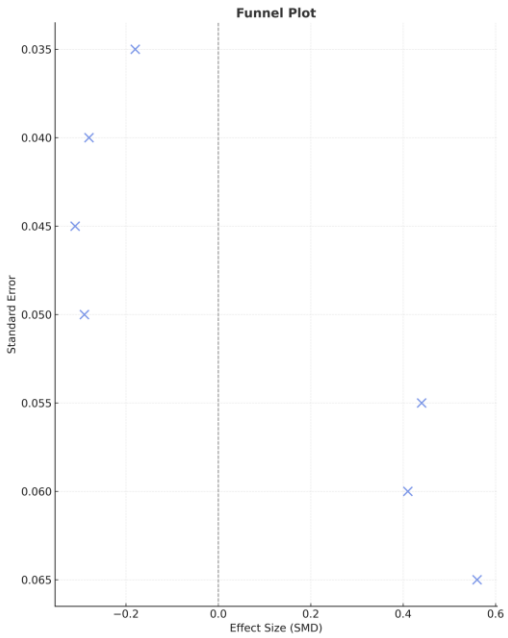
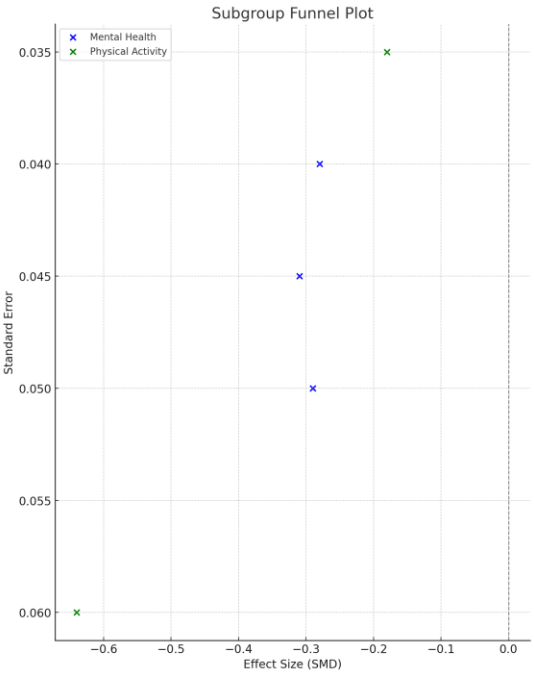
Web of Science

TS=("Exercise" OR "Exercises" OR "Exercise, Physical" OR "Exercises, Physical" OR "Physical Exercise" OR "Physical Exercises" OR "Exercise, Aerobic" OR "Aerobic Exercises" OR "Exercises, Aerobic" OR "Exercise, Isometric" OR "Exercises, Isometric" OR "Isometric Exercises" OR "Isometric Exercise" OR "Acute Exercise" OR "Acute Exercises" OR "Exercise, Acute" OR "Exercises, Acute" OR "Exercise Training" OR "Exercise Trainings" OR "Training, Exercise" OR "Trainings, Exercise" OR "Physical Activity" OR "Activities, Physical" OR "Activity, Physical" OR "Physical Activities" OR "physical education") AND TS=("Adolescent" OR "Adolescents" OR "Adolescence" OR "Adolescents, Female" OR "Adolescent, Female" OR "Female Adolescent" OR "Female Adolescents" OR "Adolescents, Male" OR "Adolescent, Male" OR "Male Adolescent" OR "Male Adolescents" OR "Youth" OR "Youths" OR "Teens" OR "Teen" OR "Teenagers" OR "Teenager") AND TS=("Technology" OR "Wireless Technology" OR "Technologies, Wireless" OR "Technology, Wireless" OR "Wireless Technologies" OR "Educational Technology" OR "Technology, Educational" OR "Educational Technologies" OR "Technologies, Educational" OR "Instructional Technology" OR "Technology, Instructional" OR "Instructional Technologies" OR "Technologies, Instructional") AND TS=("Cognition" OR "cognition" OR "Cognitive Function" OR "Cognitive Functions" OR "Function, Cognitive" OR "Functions, Cognitive" OR "Insight" OR "Insights" OR "Mental Health" OR "Health, Mental" OR "Mental Hygiene" OR "Hygiene, Mental" OR "Depression" OR "Depressive Symptoms" OR "Depressive Symptom" OR "Symptom, Depressive" OR "Emotional Depression" OR "Depression, Emotional" OR "wellbeing") AND TS=("systematic review" OR "meta-analysis" OR "umbrella review" OR "overview of reviews

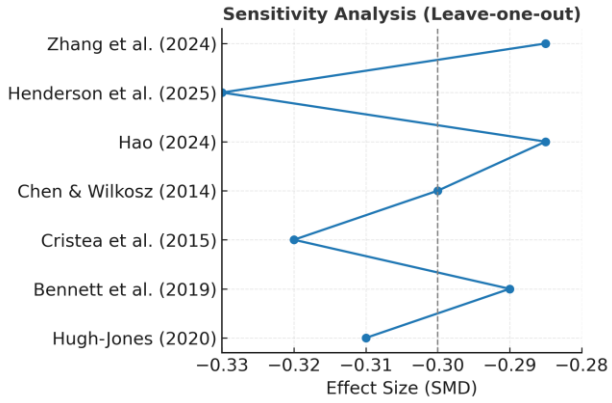


Supplementary Figure 1 Funnel plot for publication bias assessment. The funnel plot depicts the relationship between the effect sizes (standardized mean differences) and their corresponding standard errors for the included meta-analyses. Symmetry around the vertical line at zero indicates low risk of publication bias, while asymmetry suggests potential small-study effects. Each point represents an individual meta-analysis. SMD: Standardized mean difference.

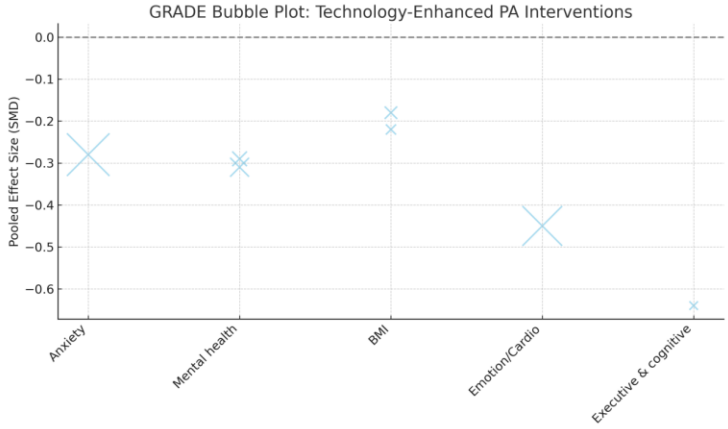


Supplementary Figure 2. Subgroup Funnel Plot for Publication Bias Assessment.

This funnel plot illustrates the distribution of effect sizes (standardized mean differences) against standard errors across subgroups. Blue markers represent meta-analyses related to mental health outcomes, while green markers indicate those related to physical activity outcomes. Asymmetry in the distribution may indicate the presence of publication bias or small-study effects within each subgroup. SMD: Standardized mean difference.

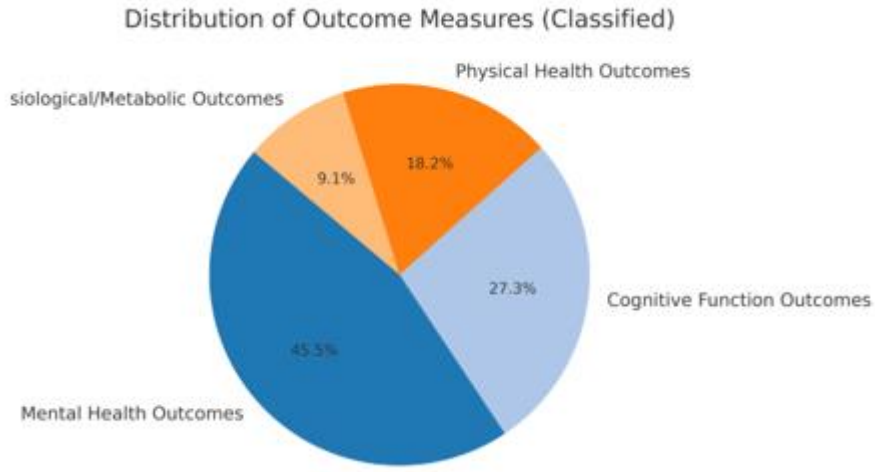


Supplementary Figure 3 Leave-one-out sensitivity analysis. This figure presents the results of a leave-one-out sensitivity analysis, where each meta-analysis is sequentially excluded to evaluate its influence on the overall pooled effect size (standardized mean difference). The vertical dashed line indicates the overall effect size. Stability in effect sizes after excluding individual studies suggests the robustness of the meta-analytic findings. SMD: Standardized mean difference.

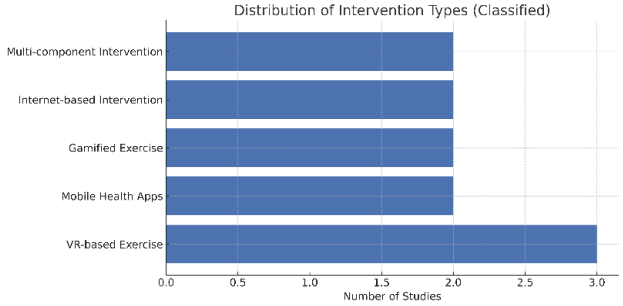


Supplementary Figure 4 Grading of Recommendations Assessment, Development and Evaluation bubble plot for technology-enhanced physical activity interventions. This bubble plot illustrates the pooled effect sizes [standardized mean

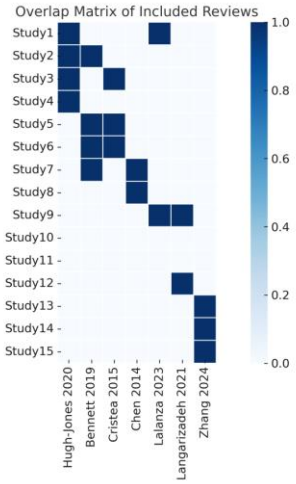
difference (SMD)] of technology-enhanced physical activity interventions across different outcome domains. The X-axis lists specific health and cognitive outcomes, while the Y-axis represents the corresponding pooled SMDs. The size of each bubble reflects the number of studies contributing to that outcome. Negative values indicate favorable intervention effects. Overall, the plot suggests consistent beneficial effects across multiple domains, particularly in executive and cognitive function and emotion/cardio outcomes. GRADE: Grading of Recommendations Assessment, Development and Evaluation; PA: Physical activity.



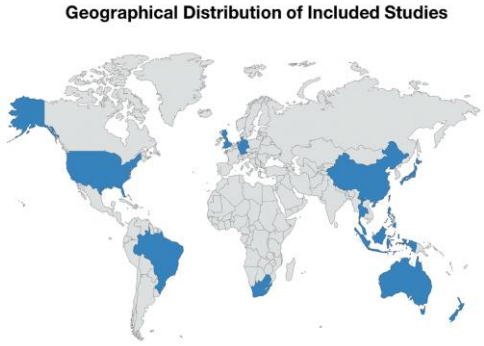
Supplementary Figure 5 Distribution of classified outcome measures. This pie chart illustrates the distribution of outcome measures across four predefined categories: Mental health outcomes (45.5%), cognitive function outcomes (27.3%), physical health outcomes (18.2%), and physiological/metabolic outcomes (9.1%). The figure highlights the predominance of mental health-related outcomes in the included studies, suggesting a research emphasis on psychological well-being in technology-enhanced physical activity interventions.



Supplementary Figure 6 Distribution of classified intervention types. This bar chart displays the distribution of intervention types identified in the included studies. Virtual reality-based exercise was the most frequently implemented approach (n = 3), followed by mobile health apps, gamified exercise, internet-based interventions, and multi-component interventions (each n = 2). The figure underscores the diversity of technology-enhanced physical activity modalities explored in the literature.

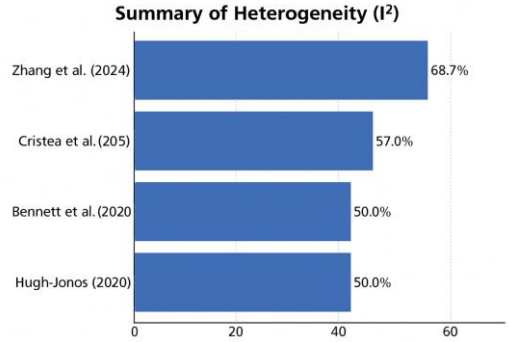


Supplementary Figure 7 Overlap matrix of included reviews. This heatmap depicts the overlap matrix of primary studies across the included systematic reviews. Each row represents an individual primary study, and each column corresponds to a review. Dark blue cells indicate the presence of a given study in the corresponding review. The matrix highlights a low degree of overlap among the reviews, suggesting that the included reviews are largely independent and contribute unique evidence to the umbrella review.



Supplementary Figure 8 Geographical distribution of included studies. This world

map illustrates the geographical origins of the primary studies included in the umbrella review. Countries highlighted in blue indicate the locations where the studies were conducted. The distribution demonstrates a wide global representation, with studies originating from North America, South America, Europe, Asia, Oceania, and Africa, suggesting broad international interest and applicability of technology-enhanced physical activity interventions.



Supplementary Figure 9 Summary of heterogeneity (I^2) for included meta-analyses. This figure illustrates the heterogeneity (I^2 statistic) of the included meta-analyses, reflecting the degree of variability among study results that is due to heterogeneity rather than chance. An I^2 value above 50% indicates moderate to substantial heterogeneity. The highest heterogeneity was observed in Zhang *et al*[14], while Bennett *et al*[23] and Hugh-Jones *et al*[24] showed relatively lower level.

Supplementary Table 1 Summary of included studies in the umbrella review

Ref.	Year	Country	Sample size	Age	Intervention	Control	Duration	Outcome measure
Hugh-Jones *et al*[24]	2020	United Kingdom	20 studies (RCT and non-RCT)	Children and adolescents (varied)	School-based prevention interventions for anxiety (cognitive behavioral therapy, mindfulness, skills training etc.)	Active/passive controls or usual school practice	4 weeks to 12 months (varied)	Anxiety symptoms reduction (various scales used)
Bennett *et al*[23]	2019	Multi-country (Mainly United Kingdom, Netherlands, Germany)	*N* = 3396 (self-help); *N* = 1100 (face-to-face); *N* = 2366 (control)	Mean age < 18 (children and adolescents)	Unguided and guided self-help (bibliotherapy, computerised, online materials)	Wait-list control, treatment as usual, face-to-face therapy	Variable across studies	Depression, anxiety, disruptive behaviour symptoms, treatment acceptability

Cristea *et al*[22]	2015	Multi-country (Mainly Romania, Italy, Netherlands, United States)	23 RCTs, *N* = 28 per condition	Mean age = 12.71 years (children and adolescents < 18)	CBM, including Attention Bias Modification and Interpretation Bias Modification (CBM-I)	Wait-list control, no-contingency training, sham training, treatment as usual	1-12 sessions (most studies used 1 session)	Mental Health Symptoms (anxiety, depression), cognitive bias change, treatment acceptability
Chen and Wilkosz[17]	2014	United States	14 studies included; *N* ranged from 21 to 473 per study	Adolescents aged 12-18 years	Technology-based interventions (internet-based programs, active video games) focused on diet and physical activity	Wait-list control, Treatment as usual, non-technology-based interventions	10 weeks to 2 years (varied across studies)	BMI, Body fat percentage, physical activity level, dietary behavior, psychosocial outcomes
Hao *et al*[15]	2024	Multi-country (Mainly	18 studies included; *N*	Children and adolescents <	Home-based virtual reality	Usual care, wait-list control, general	4 to 12 weeks (one study 6-10	Motor function (upper

	United States, Australia, Taiwan, United Kingdom,, Belgium)	ranged from 8 to 51 per study	18 years with cerebral palsy	rehabilitation (nintendo wii, Kinect, customized VR systems, VR-integrated constraint-induced therapy)	physical activity at home	months)	extremity, gross motor), strength, balance, bone density, cognition, daily activity performance, participation
Henderson *et al*[20]	2025	Multi-country (Mainly Canada, United States, Australia, Europe)	73 RCTs included; total *N* = 6305; 53% female	Children and adolescents 0-18 years with obesity	Behavioural and psychological interventions including physical activity, nutrition, psychological therapy, technology-based, multicomponent interventions	Usual care, wait-list control, no intervention	≥ 3 months follow-up, Intervention duration varied (0-6 months or 7-12 months)	BMI, BMI z-score, weight, health-related quality of life, anxiety, depression, cardiometabolic outcomes (blood pressure, lipids, insulin

								resistance), adverse events
Lalanza *et al*[19]	2023	Multi-country (Mainly Spain, United States, Netherlands, Australia)	143 studies included; *N* varies across studies	Children, adolescents, adults (varied by included study)	HRV Biofeedback with different protocols: Optimal RF, individual RF, preset-pace RF	Usual care, no intervention, sham breathing, treatment as usual (varied by included study)	1 to 12 weeks (most commonly 2-8 weeks); minutes per session: 10-20 minutes	Cardiovascular health, mental health (anxiety, stress reduction), performance outcomes, HRV parameters
Langarizadeh *et al*[16]	2021	Multi-country (Mainly United States, Canada, Australia, Italy, Sweden)	9 studies included; *N* = 19 to 361 per study; total *N* = 978	Children and adolescents aged 4.5-16.5 years	Mobile app-based interventions for weight management (diet, physical activity, behavior change)	Usual care, traditional weight loss program, no intervention	3 weeks to 6 months (varied across studies)	Body weight, BMI, waist circumference, fat mass, physical activity level (step count)
Li *et al*[21]	2021	China	50 students in a middle	Adolescents < 18 years	Exercise intervention based	Resting control group without exercise	Acute exercise: 15 minutes	Inhibitory control function

			school		on medical imaging monitoring; Different intensities (low, medium, high) aerobic exercise intervention	intervention	session; chronic exercise cycle: 12-24 weeks, 50-90 minute/week, 2-3 times/week	(stroop task response time and accuracy), cardiopulmonary function, vital capacity, step test index
Liang *et al*[18]	2023	Multi-country (Sweden, Hong Kong, United States, Spain, Taiwan, Peru, Indonesia)	10 studies included; *N* = 13 to 944 per study	Children and adolescents aged 5-18 years	Playing Pokémon GO game (augmented reality game promoting physical activity and social interaction)	Non-player control group, usual care, no intervention (varied across studies)	6 to 10 weeks of gameplay (varied across studies)	Physical activity level, emotional intelligence, sociability, internet gaming disorder, well-being, body composition (BMI, fat mass)
Zhang *et*	2023	China	8 RCTs	Minors with	VR-based sports	Control group	4-16 weeks	Executive

al[14]		included; *N* = varied		attention-deficit hyperactivity disorder (<18 years)	games intervention	without VR-based sports games	intervention duration; 2-5 sessions per week	function (response inhibition, working memory, cognitive flexibility); cognitive function (attention, memory, problem solving)

This table provides an overview of the key characteristics of the included studies, including author, publication year, study location, sample size, participant age range, intervention type, control condition, intervention duration, and outcome measures. The studies encompass a range of digital and non-digital mental health interventions targeting children and adolescents, and vary in design, delivery format, and evaluation metrics. BMI: Body mass index; CBM: Cognitive bias modification; HRV: Heart rate variability; RCTs: Randomized controlled trials; RF: Radio frequency; VR: Virtual reality.

Supplementary Table 2 Methodological quality assessment of included reviews using the A Measurement Tool to Assess Systematic Reviews tool

Document number	Ref.	Year of publication	Did the research questions and inclusion criteria for the review include the components of patient, intervention, comparison, outcome	Did the report of the review contain an explicit statement that the review methods were established prior to the conduct of the review and did the report justify any significant deviations	Did the review author explain their selection of the study designs for inclusion in the review	Did the review authors use a comprehensive literature search strategy	Did the review authors perform study selection in duplicate	Did the review authors perform data extraction in duplicate	Did the review authors provide a list of excluded studies and justify the exclusions	Did the review authors describe the included studies in adequate detail that were included in the review	Did the review authors use a satisfactory technique for assessing the RoB in individual studies that were included in the review	Did the review authors report on the sources of funding for the studies included in the review	If meta-analysis was performed, did the review authors use appropriate methods for statistical combination of results	If meta-analysis was performed, did the review authors assess the potential impact of RoB in individual studies on the results of the meta-analysis or other evidence synthesis	Did the review authors account for RoB in individual studies when interpreting/discussing the results of the review	Did the review authors provide a satisfactory explanation for, and discussion of, any heterogeneity observed in the results of the review	If they performed quantitative synthesis, did the review authors carry out an adequate investigation of publication bias (small study bias) and discuss its likely impact on the results	Did the review authors report any potential sources of conflict of interest, including any funding they received for conducting the review	Overall quality rating

				ns from the protocol															
1	Hugh-Jones *et al*[24]	2020	Yes	Yes	Yes	Yes	Yes	Yes	Partial yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Moderate
2	Bennett *et al*[23]	2019	Yes	Yes	Yes	Yes	Yes	Yes	Partial yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	High
3	Cristea *et al*[22]	2015	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	High
4	Chen and Wilkosz[17]	2014	Partial yes	Yes	Yes	Yes	Yes	Yes	Partial yes	Yes	Yes	N/A	N/A	Partial Yes	Yes	N/A	N/A	Yes	Moderate
5	Hao *et al*[15]	2024	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Moderate
6	Henderson *et al*[20]	2025	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Moderate
7	Lalanza *et al*[19]	2023	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	High
8	Langarizadeh *et al*[16]	2021	Yes	Yes	Yes	Yes	Yes	Yes	Partial yes	Yes	Yes	No	N/A	N/A	Yes	Yes	N/A	Yes	Moderate
9	Li *et al*[21]	2021	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Partial yes	Partial yes	Partial yes	No	Partial yes	Yes	Moderate
10	Liang *et al*[18]	2023	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes		Partial yes	Partial yes	Partial yes	No	No	Yes	Moderate
11	Zhang *et*	2024	Yes	Yes	Yes	Yes	Partial	Yes	Yes	No	Yes	Yes	Yes	Partial	Yes	Yes	Yes	Yes	Moder

al[14]	yes	yes	ate

This table summarizes the methodological quality ratings of the included systematic reviews based on A Measurement Tool to Assess Systematic Reviews checklist. Each item corresponds to a specific domain of review rigor, including protocol registration, literature search strategy, risk of bias assessment, and synthesis methods. Ratings are provided for all 16 domains, along with an overall quality judgment (high, moderate, low, or critically low) for each review. N/A: Not applicable; RoB: Risk of bias.

Supplementary Table 3 Risk of bias summary for included randomized controlled trials

Ref.	Random sequence generation	Allocation concealment	Blinding of participants and personnel	Blinding of outcome assessment	Incomplete outcome data	Selective reporting
Hugh-Jones *et al*[24]	Low	Low	High	Low	Low	Low
Bennett *et al*[23]	Low	Low	High	Low	Low	Low
Cristea *et al*[22]	Low	Low	High	Low	Low	Low
Chen and Wilkosz[17]	Low	Low	High	Low	Low	Low
Hao *et al*[15]	Low	Low	High	Low	Low	Low
Henderson *et al*[20]	Low	Low	High	Low	Low	Low
Lalanza *et al*[19]	Low	Low	High	Low	Low	Low
Langarizadeh *et al*[16]	Low	Low	High	Low	Low	Low
Li *et al*[21]	Unclear	Unclear	Unclear	Unclear	Low	Low
Liang *et al*[18]	Unclear	Unclear	High	Unclear	Low	Low
Zhang *et al*[14]	Low	Low	High	Low	Low	Low

This table summarizes the risk of bias assessments across key domains for the randomized controlled trials included in each systematic review. Domains evaluated include random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data, and selective reporting. Each item is rated as low, high, or unclear risk of bias according to the criteria of the cochrane risk of bias tool.

Supplementary Table 4 Summary of heterogeneity estimates from included meta-analyses

Ref.	Number of studies (*n*)	Heterogeneity (I^2)
Hugh-Jones *et al*[24]	81	50%

Bennett *et al*[23]	50	50%
Cristea *et al*[22]	23	57%
Chen and Wilkosz[17]	14	Range: 50%-75%
Hao *et al*[15]	18	Not reported
Henderson *et al*[20]	73	Moderate to high
Lalanza *et al*[19]	143	Range: 40%-60%
Langarizadeh *et al*[16]	9	Range: 50%-70%
Li *et al*[21]	Multiple studies	NR
Liang *et al*[18]	10	NR
Zhang *et al*[14]	10	68.7%

This table presents the number of studies included and the corresponding heterogeneity statistics (I^2 values) for each eligible meta-analysis. Heterogeneity was assessed as reported in the original publications, and is expressed as either a single percentage or a range, where available. Reviews that did not report I^2 values are indicated accordingly. NR: Not reported.

Supplementary Table 5 Summary of key findings from included meta-analyses

Ref.	Population	Intervention	Outcome	Number of studies (*n*)	Total sample size	Pooled effect size (95%CI)	Heterogeneity (I^2)	Conclusion
Hugh-Jones *et al*[24]	Children and adolescents	School-based indicated prevention programs for anxiety, incorporating digital technology and physical activity components	Anxiety symptoms	81	17224	-0.28 (-0.36 to -0.20)	50	Small but significant reduction in anxiety symptoms
Bennett *et al*[23]	Children and adolescents with anxiety, depression, or disruptive behaviour disorders	Unguided and guided self-help interventions incorporating digital tools (apps, online platforms) combined with physical activity interventions	Mental health outcomes, Treatment acceptability	50	3396	-0.31 (-0.40 to -0.22)	50	Small to moderate effect on reducing mental health symptoms

Cristea *et al*[22]	Children and adolescents with anxiety, depression, or emotional disorders	Cognitive bias modification interventions, with technology-enhanced delivery systems	Mental health outcomes	23	2043	-0.29 (-0.47 to -0.11)	57	Moderate effect on anxiety and depression symptoms
Chen and Wilkosz[17]	Adolescents aged 12-18 years, overweight or obese	Technology-based interventions (web-based, e-learning, and active video games)	BMI, PA, diet behaviors, Psychosocial function	14	1472	-0.18 (-0.24 to -0.12) for BMI reduction	50%-75%	Technology-based interventions had a small but significant effect on reducing BMI and improving PA and diet in adolescents

Hao *et al*[15]	Children and adolescents with cerebral palsy	Home-based virtual reality rehabilitation	Hand function, gross motor function, walking capacity	18	683	Hand: 0.41 (0.14-0.68); gross motor: 0.56 (0.29-0.83); walking: 0.44 (0.11-0.77)	Not reported	Significantly improved hand function, gross motor function, and walking capacity
Henderson *et al*[20]	Children and adolescents with obesity, aged 0–18 years	Physical activity, nutrition, psychological, technology-based, and multicomponent interventions	HRQoL, depression, anxiety, blood pressure, cholesterol, insulin resistance, BMI	73	6305	Varies across different outcomes	Varies	Improvements in HRQoL, cardiometabolic markers, and anthropometric measures
Lalanza	Adolescents	Heart rate variability	Cardiova	143	15000	-0.45 (-0.62 to	40%-60%	Moderate effects

et al[19]	with stress, anxiety, and cardiovascular issues (ages 12-18)	biofeedback combined with digitalized physical activity interventions	scular health markers, emotional regulation, overall well-being			-0.28) for emotion; -0.35 (-0.50 to -0.18) for cardiovascular	on improving emotional regulation, cardiovascular health, and overall well-being
Langarizadeh *et al*[16]	Children and adolescents with overweight or obesity, aged 6-18 years	Mobile apps for weight management (self-monitoring, behavior change, exercise tracking, diet monitoring)	BMI, weight loss, PA, dietary behaviors, treatment adherence	9	978	-0.22 (-0.35 to -0.08) for BMI reduction	50%-70%	Small but significant effect in reducing BMI and improving PA and dietary behaviors

Li *et al*[21]	Adolescents	Exercise intervention based on medical images	Inhibitory control function	Multiple studies (assumed)	Not specified	Not provided	Not provided	Exercise intervention improves inhibitory control function in adolescents
Liang *et al*[18]	Children and adolescents (under 18 years old)	Pokémon GO game (augmented reality game)	Physical activity and psychosocial well-being	10	Varied from 13 to 944	No meta-analysis conducted	Not applicable	Positive effects on PA; mixed effects on psychosocial well-being; further research needed
Zhang *et al*[14]	Children and adolescents with ADHD	Virtual reality-based sports games	Executive and cognitive functions	10	683	-0.64 (-0.82 to -0.46)	68.70%	Virtual reality sports games significantly improve executive and

											cognitive functions in children with ADHD

This table summarizes the key characteristics and findings of the meta-analyses included in the umbrella review. It includes information on the target population, intervention type, outcome measures, number of studies and participants, pooled effect sizes with 95%CI, heterogeneity estimates (I^2), and authors' overall conclusions. The interventions evaluated span various digital and behavioral strategies targeting mental and physical health outcomes in children and adolescents. ADHD: Attention-deficit hyperactivity disorder; BMI: Body mass index; HRQoL: Health-related quality of life; PA: Physical activity.

Supplementary Table 6 Matrix of overlapping studies across included systematic reviews

	Hugh-Jones *et al*[24]	Bennett *et al*[23]	Cristea *et al*[22]	Chen and Wilkosz[17]	Lalanza *et al*[19]	Langarizadeh *et al*[16]	Zhang *et al*[14]
Study 1	1	0	0	0	1	0	0
Study 10	0	0	0	0	1	0	0
Study 11	0	0	0	0	1	0	0
Study 12	0	0	0	0	0	1	0
Study 13	0	0	0	0	0	0	1
Study 14	0	0	0	0	0	0	1
Study 15	0	0	0	0	0	0	1
Study 2	1	0	0	0	0	0	0
Study 3	1	1	0	0	0	0	0
Study 4	1	1	0	0	0	0	0
Study 5	0	1	1	0	0	0	0
Study 6	0	1	1	0	0	0	0
Study 7	0	0	1	0	0	0	0
Study 8	0	0	0	1	0	0	0
Study 9	0	0	0	1	0	1	0

This table displays a binary matrix indicating the presence (1) or absence (0) of each primary study across the included systematic reviews. Each row corresponds to an individual study, and each column represents a specific review. This matrix was used to assess the degree of overlap between reviews and to calculate the Corrected Covered Area, which quantifies redundancy in evidence synthesis.

Supplementary Table 7 Egger's test for small-study effects

Intercept	Slope	*P* value
1.239124839124841	-181.2784213	0.0926706305343946

This table presents the results of Egger's regression test used to detect small-study

effects across the included meta-analyses. The table reports the regression intercept, slope coefficient, and the associated *P* value. A statistically significant intercept (typically $P < 0.10$) suggests potential publication bias or small-study effect.