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REVIEW

A Literature Review on the Effects of Exergames on Executive Function in Youth

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Exergames (video games that promote cognitive and physical activity simultaneously) benefit executive function (EF) in elderly populations. It has been suggested that exergames may induce larger effects than cognitive or exercise training alone, but few reviews have synthesized the causal factors of exergames on EF from experimental research with youth. This review investigates (a) the various types of exergames and associated comparison conditions; (b) the EF outcome assessments commonly utilized in exergame research with youth; (c) the efficacy of exergames by evaluating experimental studies that compared exergaming to cognitive, exercise, and passive control conditions inclusive of effect sizes; and (d) the potential mechanisms underlying the changes in EF induced from exergames. Eligible outcome data were available from 607 participants across 10 studies, with the age of participants ranging from 4 to 21 ($M_{\text{age}} = 10.46$). The findings indicate that exergames improve aspects of EF from both acute and chronic studies. Despite the high variability of exergame contexts, dosages, populations, and outcome assessments, improvements in EF comparing exergaming to passive control conditions were exhibited across all studies. While there is evidence of exergaming demonstrating advantages over passive control conditions, evidence is mixed when comparing exergaming to sedentary cognitive and exercise comparison conditions. Potential sources of these mixed results and future directions to address current gaps in the field are identified. As video game and technology use grows exponentially and concerns of childhood sedentary behavior and play deprivation increase, evidence-based practices that promote both physical and cognitive activity are needed.

Keywords: exergames, literature review, executive function, youth, experimental research

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Exergames are digital games that require physical body movements including skill-related components of coordination, balance, agility, power, and reaction time in order to participate (Oh & Yang, 2010), promoting cognitive engagement and physical activity simultaneously. The activity requires individuals to execute gross motor movements such as walking, running, sliding, jumping, throwing, and hitting—movements that are considered the building blocks of complex whole-body activity required in many "real-world"

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Data Availability: This article is a literature review designed to help develop, use, and assess the impact of exergames on executive function; thus, the descriptive statistics, analytic methods, and experimental materials of the studies included in the review are available to other researchers directly from the original articles. Partial η^2 was the most reported effect size across studies and was reported in this review as it was in the original articles. For consistency and interpretability, the one study that reported Cohen's d as effect sizes were converted to partial η^2, and the one study that did not report effect sizes were computed by first calculating Cohen's d and then subsequently converted to partial η^2. All equations and the values used to compute effect sizes are reported in the review in the Executive Function Outcome Measures: Effect Sizes section and in Table 2.

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sports and exercises—in a coordinated and controlled way to interact with the digital environment (Adams et al., 2009). Because exergames stimulate both body and mind, they are potentially a powerful tool for enriching cognitive development (Blumberg et al., 2019). The aim of the current review is to examine the limited experimental research on exergames' causal impact on cognition for youth.

Existing reviews covering experimental research on exergames in youth focus primarily on physical health outcomes (Williams & Ayres, 2020). This literature comparing exercise and sedentary cognitive conditions to exergame conditions shows improved cardiovascular fitness in healthy adults, balance and motor abilities in adults with neuromotor impairments (Monteiro-Junior et al., 2014), increased caloric expenditure (Graf et al., 2009; Graves et al., 2007), and decreased waist circumferences in youth (Ni Mhurchu et al., 2008). A relatively recent body of research has focused on whether exergames may also have cognitive health benefits, specifically executive function (EF).

Defining EF

EF is an umbrella term for cognitive processes that facilitate goal-directed behavior (Best & Miller, 2010; Werchan & Amso, 2017). Despite the high frequency with which EF is mentioned in the literature, there is no consensus on a standard definition of EF. Several frameworks posit that EF includes cognitive processes such as inhibitory control, working memory, and cognitive flexibility (Davidson et al., 2006; Diamond, 2013; Lerner & Lonigan, 2014; Miyake et al., 2000). Inhibitory control is the ability to deliberately override prepotent responses and focus on relevant information in the presence of distracting stimuli. Working memory is the ability to briefly store, manipulate, and update information. Cognitive flexibility is the ability to switch between tasks by adjusting to new demands, rules, or priorities. A commonality among theoretical frameworks is that EF involves the ability to resolve conflict: the ability to execute goal-relevant responses in the presence of competing goal-irrelevant stimuli (Zhou et al., 2012).

There is general agreement that (a) EF requires the ability to resolve conflict to fulfill goal-related demands in the environment and (b) EF is critical for success throughout life in occupations, interpersonal relationships, mental and physical health, and cognitive, social, and psychological development. For example, EF predicts pediatric obesity (Graziano et al., 2010), risky behaviors and addiction (Goldstein & Volkow, 2011), and the likelihood of committing violent crimes (Hancock et al., 2010). It is important to foster EF because EF predicts math and reading competence throughout all school years and predicts school readiness over and above intelligence quotient (IQ) and socioeconomic status (SES; Blair & Razza, 2007; Diamond & Lee, 2011; Eng et al., 2022; Fitzpatrick et al., 2014; Jacob & Parkinson, 2015; Liew, 2012; Pellicano et al., 2017). EF skills such as sustaining focus on task-relevant goals, ignoring distractions, inhibiting impulsive responses, and adapting to new situations are crucial for academic success (Liu et al., 2018; Rueda et al., 2010; Whedon et al., 2020). Prior research on EF and academic achievement suggests that it is not simply that case that youth who have higher IQ or grow up in high SES households have better EF and, therefore, higher educational outcomes. For example, in a 4-year longitudinal study conducted by Samuels et al. (2016), EF predicted reading, mathematics, science, social studies, and foreign language academic performance, over and above the effects of SES, sex, and having individual education plans. Sasser et al.'s (2015) longitudinal study found EF skills predicted later levels of mathematical, reading, overall academic functioning skills, and social–emotional adjustment (social competence, aggression), controlling for sex, race, verbal IQ, and baseline scores. Youth with worse EF at ages 3–11 exhibit poorer health, lower academic achievement, earn less as adults, and commit more crimes 30 years later than those with better EF as youth, controlling for IQ, sex, and SES (Diamond & Lee, 2011). Thus, examining the efficacy of exergames on EF in youth has pragmatic value working toward improving later developmental outcomes and overall well-being.

Exergames Provide Enrichment Through Multimodal Input

During exergame play, youth are stimulated cognitively and physically through the execution of body movements to interact with a cognitively engaging virtual environment. The physical effort imposed by exergames could produce the already known neurobiological mechanisms of exercise: increasing the synthesis and release of trophic factors such as brain-derived neurotrophic factor, vascular endothelial growth factor, insulin-like growth factor, glial cell-derived neurotrophic factor, and basic fibroblast growth factor 2, which subsequently stimulate neurogenesis, angiogenesis, neuroplasticity (Ding et al., 2006; Matta Mello Portugal et al., 2013), and exercise-induced changes in brain structure and function underlying EF development in youth (Khan & Hillman, 2014). The cognitively engaging features of exergames could foster EF skills and brain plasticity because youth need to inhibit and initiate actions, pay attention, process sensory information, plan, make decisions, and react quickly and accurately while playing. For example, in exergames, players need to constantly predict when and where events of interest may occur, identify goal-relevant information while suppressing goal-irrelevant, distracting sources of information, follow rules, and receive motivational feedback (positive rewards and anticipating competitors/obstacles; Bavelier et al., 2012; Green & Bavelier, 2012; Koepp et al., 1998).

Werchan and Amso's (2017) ecological account of EF highlights that environmental enrichment is critical in shaping the development of EF by providing increased quantity and quality of multimodal input to the brain. Thus, the combination of physical exercise and cognitive engagement from exergames may provide an enriching environment of increased quantity (kinesthetic, auditory, visual) and quality (video game play that engages conflict resolution and adaptive behavior) of multimodal input (Monteiro-Junior et al., 2016) that promotes EF. The cognitive engagement of active video games such as visuospatial processing, visuomotor integration, motor planning, and execution display a distinctive pattern of increased activation in striatal and medial prefrontal areas induced from skill acquisition (Palaus et al., 2017), while exercise in youth has found to induce vascularization, neural growth, and alter synaptic transmission in ways that alter thinking, decision making, and EF in the same regions of the prefrontal cortex (Donnelly et al., 2016). Thus, combining the cognitive engagement induced from active video games with the known neurobiological changes exercise has on the brain and EF has *synergistic*, *additive* effects on brain development, specifically the prefrontal cortex. It is theorized that this enriched context of multicomponent combined physical activity and high cognitive stimulation through exergames leads to repeated coactivation of activity-related brain regions, and this communication promotes interactions between brain areas that previously had substantially less efficient communication and, in turn, increases the efficiency of meeting EF-related demands.

Gap: Reviews of Experimental Research on Exergames and EF With Youth

The current review fills a gap in the literature by focusing on experimental research examining the efficacy of exergame interventions on EF in youth populations. Thus far, reviews investigating the effects of exergames on EF have focused on elderly populations and clinical populations with neurological disabilities, concluding that compared to control groups and exercise training, exergames produced greater effects on EF (Stanmore et al., 2017; Zhu et al., 2016). While these reviews did not find evidence of exergames outperforming cognitive training, the researchers discussed that the null findings could be due to being underpowered, as few studies included single-component cognitive training conditions as control groups. In another review, Bruderer-Hofstetter et al. (2018) conducted a systematic review on the effects of exergames on EF in older populations with and without mild impaired cognition and found that exergames combining physical activity with structured computerized cognitive training with increasing challenge were the most effective for both healthy and neuroatypical adults.

Other reviews with elderly populations theorize that the combination of physical exercise and cognitive training may affect neuroplasticity additively, and multicomponent contexts may be more effective in improving EF than single-component cognitive or exercise training alone (Monteiro-Junior et al., 2016). Diamond and Ling's (2020) review on EF training across development state that exergames show encouraging results of improving EF and deserve further investigation. While there are well-documented beneficial effects of exergames on EF in elderly populations as forms of reactive maintenance and preventative measures of neurocognitive decline, further exploration on the impact of exergames in youth as forms of proactive maintenance and cognitive enhancement is needed.

Despite the breadth of reviews providing evidence of exergames improving EF in elderly populations, few reviews synthesize studies that employed experimental research; that is, employed comparison condition(s) and random assignment; on the effects of exergames on EF with youth. The lack of reviews and research in this area justify first conducting a literature review that examines the research comparing exergame play to traditional exercise or cognitively engaging activities to elucidate the unique contributions exergames may have on EF. This review addresses if exergames have causal effects on youth's EF by examining the experimental research that compares exergames to a variety of control groups. Research designs are needed that compare exergames to (a) sedentary video games that induce similar cognitive demands, (b) exercise conditions that exert the same physical activity as the exergames with less cognitive demands, and (c) age-matched passive control groups to determine the extent to which sedentary video games without the exercise component and physically active video games with less cognitive engagement impact EF relative to exergames. If research demonstrates that exergames have a stronger effect on EF than the other conditions, it could be concluded that the combination of exercise and cognitive engagement drives the effects. Alternatively, if exergames and sedentary video games have equivalent effects on EF, then it would seem that the more important factor is the cognitive engagement of the game play, whether physical or sedentary. If exergames and exercise conditions have an equivalent effect on EF, then it would seem that the more important factor is the physical activity.

It is hypothesized that the activities that will most successfully improve youth's EF are those that require and directly challenge EFs, are enjoyable, and increase youth's physical activity (Best, 2010; Diamond & Lee, 2011). Compared to single-component exercise training or cognitive training alone, multicomponent exergaming may be particularly effective due to their "double mission" of effectiveness and attractiveness in (a) increasing physical–cognitive fitness and coordination and (b) increasing enjoyment, motivation, and cognitive engagement (see Martin-Niedecken et al., 2021, for review). Therefore, this literature review provides an overview of studies addressing if exergames have causal effects on EF in youth by synthesizing (a) detailed descriptions of the various types of exergames and associated comparison control conditions; (b) the EF outcome assessments commonly utilized in exergame research with youth; (c) the efficacy of exergames by comparing exergame training to cognitive training, exercise training, and passive control groups; and (d) the potential mechanisms underlying the changes in EF induced from exergame play. The goal of this review is to help researchers, game designers, policymakers, caregivers, and practitioners improve the development and use of exergames for experimental research and application with youth populations.

Method

This literature review examines the efficacy of exergames on EF by comparing the outcome of exergames to the outcomes of cognitive and exercise training in youth populations, as well as passive age-matched control groups. A literature review is often conducted in preparation for conducting a systematic review or meta-analysis and seeks to identify research gaps and opportunities for evidence synthesis. This literature review (a) describes in more detail the findings and range of research in a particular area of study, thereby *providing a mechanism* for summarizing and disseminating research findings to practitioners, policymakers, and researchers who might otherwise lack time or resources to undertake such work themselves, and (b) draws conclusions from existing literature regarding the overall state of research activity specifically designed to *identify gaps* in the evidence base where research needs to be conducted to move the field forward. This review synthesizes the main findings, sample demographics, experimental design (i.e., within subjects vs. between subjects), single or group participation, and dose (sessions and duration), with an emphasis on EF outcome assessments, the nature of the exergames and comparison groups, and identifies gaps in the evidence base of experimental research on exergames and EF where future research needs to be conducted to move the field forward.

Literature Search Specifications

A comprehensive search strategy was used to gather research studies published from 2007: the year the term exergaming entered the English Dictionary (Collins English Dictionary, n.d.) and after exergame sales generated over $2 billion worldwide (Brice, 2009) to 2022. The search for articles was conducted using the Carnegie Mellon University Libraries Databases and eResources Tool in the following databases: APA PsycArticles, PsychInfo, Pubmed, ScienceDirect, Scopus, and Web of Science using the search queries (with an asterisk added to the root of the words to account for variations in word endings in the databases that allowed truncation searching): "exergame or exergaming/exergam* or health games/health gam* or dual-task training" "physical activity or active or exercise or motor" "executive function/executive function* or cognitive function or cognition/cogniti*" "cognitive training" "exercise training" "children/child* or adolescence/adolescen* or youth" and "experimental or random assignment or control" restricting the search to 2007–2022.

The studies were included in the review if they met the four criteria: (a) implemented an experimental design that randomly assigned participants to a passive control condition, a sedentary cognitive condition, and/or an exercise condition comparing the effects on EF to exergaming; (b) defined as an experiential activity promoting physical exertion and cognitive engagement simultaneously through interacting with a digital, video, or computer-based game that required gross motor movements that are more than sedentary activities and included skill-related components of coordination, balance, agility, power, and reaction time in order to participate (Oh & Yang, 2010); (c) reported at least one EF outcome measure defined as a task-based or report-based assessment of cognitive processes that facilitate goal-directed behavior such as cognitive flexibility, inhibitory control, or working memory; and (d) involved participants under 21-years-old with or without cognitive impairments. While there is no established age range for *youth*, the National Institutes of Health defines youth as an individual under the age of 21 and the Food and Drug Administration defines pediatric populations as 21 years of age or younger (National Institutes of Health, 2015; US Food & Drug Administration, 2021); thus, participants under the age of 21 were eligible for the scope of this review to ensure studies conducting intervention research focusing on cognitive and physical health outcomes involving human subjects considered youth were included.

Trained research assistants screened databases for the above-mentioned parameters with interrater reliability calculated using Cohen's κ (Cohen, 1960) having extensive discussions prior to coding about the criteria meeting experimental designs (κ = .95), exergames (κ = .82), and EF assessments (κ = .79), indicating substantial coder consistency. Duplicates were removed, and the results were compiled. In addition, we performed a manual search and reviewed the reference lists from the articles we found to fill gaps from the search. Studies that were correlational, observational, peer-reviewed protocols or conference abstracts without effect sizes or statistics to compute effect sizes (e.g., Benzing et al., 2018, 2020), did not report clear statistics and interpretable results, did not expose youth to a technological interface (e.g., Bedard et al., 2021; Egger et al., 2019; Schmidt et al., 2015), did not employ an exergame condition that promoted physical activity and cognitive engagement *simultaneously* but sequential exercise and cognitive training (e.g., Zinke et al., 2012), or did not randomly assign participants to conditions and have a comparison control group (e.g., Hilton et al., 2015) were excluded from the review.

Participants

Eligible outcome data were available from a total of 607 participants across 10 articles studies (10 published peer-reviewed journal and conference articles, containing a total of 22 usable effect sizes). In contrast to the existing reviews on the effects of exergames on EF with mean ages ranging from 69 to 74, the mean age of participants in this review is 10.46 years (range = 4–21 years). Eight studies were conducted with typically developing youth. Two studies were conducted with clinical samples of participants diagnosed with attention-deficit/hyperactivity disorder (AD/HD) and autism spectrum disorder (ASD). Table 1 summarizes the range and mean age of participants in years, location of recruitment, and the size of the samples in each study.

This review covers the experimental methodology employed in each study, the exergame dosage (sessions and duration), and the characteristics and features of the exergames. The comparison control groups, which include passive, cognitive, and exercise conditions, and the EF assessments that were utilized are investigated. Then, the main findings and interpreted results with effect sizes (Table 2) were extracted and evaluated.

Exergame and Comparison Conditions

Session Duration and Frequency

The studies varied by exergame length of sessions (in minutes), the number of sessions, and the study duration (acute single bouts of training vs. chronic several bouts of training over a period of time). The exergame sessions were 15- (Staiano et al., 2012), 20- (Anderson-Hanley et al., 2011; Benzing et al., 2016; Benzing & Schmidt, 2019; Best, 2012; Eng et al., 2020; Flynn & Richert, 2018; Xiong et al., 2019), or 30-min (Flynn et al., 2014; Gao et al., 2019) long, with 20 min being the most common session duration among studies. Five of the studies implemented one to two sessions of acute exergaming for 20 min (Anderson-Hanley et al., 2011; Benzing et al., 2016; Best, 2012; Eng et al., 2020; Flynn & Richert, 2018). The other four studies implemented chronic exergaming and varied in length ranging from 5 to 12 weeks, with the total sessions per week ranging from one session a week (Flynn et al., 2014; Staiano et al., 2012), three sessions a week (Benzing & Schmidt, 2019), to five sessions a week (Gao et al., 2019; Xiong et al., 2019). See Table 1 for details.

Exergame Conditions

While there are ambiguous definitions of exergaming, we define exergaming as reported in the literature as an experiential activity of playing digital, video, or computer-based games that simultaneously promotes cognitive engagement and physical exertion through gross motor movements that are more than sedentary activities and include skill-related components of coordination, balance, agility, power, and reaction time to participate (Adams et al., 2009; Oh & Yang, 2010). Exergames record and send signals via various equipment (response mats, motion sensors, and/or cameras), allowing the interface to respond to participants' physical movements. In the studies reported, two-dimensional (2D) visual stimuli were presented on digital devices such as a television, monitor, or a wall or screen through a projector connected to a game console or computer that allowed participants to interact with the digital

Table 1
Study Designs, Measures, and Outcomes

Study	Main finding	Sample (*N*)	Age (years)	Design	EF outcome	Exergame (↑CE↑PE)	Exercise (↓CE↑PE)	Cognitive (↑CE↓PE)	Control (↓CE↓PE)
Study 1: Anderson-Hanley et al. (2011)	Working memory and ASD-related symptoms improved following the exergaming conditions compared with the control condition. Task-switching performance and time to complete cognitive flexibility task increased for the exergame conditions, but did not reach significance compared with the control condition.	22 youth with ASD Exp 1: 12 Exp 2: 10 Recruited from a school in the northeastern United States	Exp 1 *Range* 10–18 *M* 14.8 Exp 2 *Range* 8–21 *M* 13.2	*Within subjects* Exergame versus control *Single* Participation *Duration* Acute one session 20 min	*DVs:* 1. Backward Digit Span Scores 2. Color trails time of completion 3. Stroop time of completion 4. ASD symptoms: Gilliam Autism Rating Scale Scores, 2nd edition (GARS-2)	Experiment 1 DDR (game console not reported): Arrows scrolled across the screen and youth stepped in the coordinated direction of the topmost arrow while also attending to upcoming arrows Experiment 2 *Dragon chase* (Expresso Team, Expresso S3R Cybercycling): stationary bike interconnected with videogame displayed on a screen with the object of the game to move by pedaling and steering around an open landscape chasing floating coins and dragons. Players earned points based on speed and color matching	/	/	Watched a video of a previously recorded school talent show of the same duration at the exergame
Study 2: Best (2012)	Cognitive engagement had no effect on any aspect of task performance, exergame and exercise conditions enhanced inhibitory control.	33 TD youth Recruited from an afterschool program in a local elementary school and from the local community in the United States	*Range* 6–10 *M* 8.1	*Within subjects* Cognitive versus exergame versus exercise versus control *Single* Participation *Duration* Acute One session 20 min	*DVs:* 1. Flanker Task mean RT distribution using ex-Gaussian parameters between congruent and incongruent trials	Wii console *Active Life: Outdoor Challenge Mini-Exergames* (Bandai Namco Games, Nintendo). Jogged in place to move the character; moved from side to side to move the character horizontally on	Wii console *Active Life: Outdoor Challenge Marathon* (Bandai Namco Games, Nintendo). Ran as far as possible on a game mat the same duration at the exergame	Wii console *Super Mario World* (Nintendo, 2009) sedentary video game using a handheld controller to move character, duck to avoid obstacles, collect items, and battle opponents the same duration as the exergame	Watched an age-appropriate video on healthy living habits the same duration as the exergame

(*table continues*)

Table 1 (*continued*)

Study	Main finding	Sample (*N*)	Age (years)	Design	EF outcome	Exergame (↑CE↑PE)	Exercise (↓CE↑PE)	Cognitive (↑CE↓PE)	Control (↓CE↓PE)
						the screen; and jumped to avoid pits, rolling logs, or other obstacles. Minigames became more difficult (e.g., obstacles approached more randomly or unpredictably) as the child progressed			
Study 3: Benzing et al. (2016)	Exergame improved cognitive flexibility and participants rated the exergame as more cognitively engaging compared to exercise and passive control conditions.	65 TD male youth Recruited from two secondary schools in Switzerland	*Range* 13–16 *M* 14.51	*Between subjects* Exergame versus exercise versus control *Single* Participation *Duration* Acute One session 20 min	*DVs:* 1. Delis–Kaplan Executive Function System (D-KEFS) Design Fluency Test Scores	*n* = 21 Xbox console plus Kinect (Microsoft, 2010) *Shape UP* (Ubisoft Montreal, 2014) workouts trained strength, coordination, and cognitive demands on inhibition, switching, updating, attention, and speed (e.g., punching asteroids, squatting to the moon, bench pressing an elephant) Adaptive and automatically adjusted to the player's level	*n* = 23 Xbox console plus Kinect (Microsoft, 2010) *Your Shape: Fitness Evolved Run the World* (Ubisoft Montreal, 2010), participants ran through virtual streets with higher scores achieved by running faster	/	*n* = 21 Watched a video on a computer showing a documentary report about mountain running the same duration at the exergame

(*table continues*)

Table 1 (*continued*)

Study	Main finding	Sample (*N*)	Age (years)	Design	EF outcome	Exergame (↑CE↑PE)	Exercise (↓CE↑PE)	Cognitive (↑CE↓PE)	Control (↓CE↓PE)
Study 4: Benzing and Schmidt (2019)	Exergaming improved inhibitory control, cognitive flexibility, adult reports of ADHD symptoms, but not working memory.	51 youth with ADHD Recruited through an association for parents and caregivers of children and adults with ADHD in Switzerland	*Range* 8–12 *M* 10.63	*Between subjects* Exergame versus control *Single* Participation *Duration* Chronic Three sessions/ week 30 min 8 weeks	*DVs:* 1. Simon Task RT 2. Flanker Task RT 3. Backward Color Span Scores 4. ADHD symptoms: Conners–3 scale scores	$n = 28$; 86.4% M Xbox console plus Kinect (Microsoft, 2010) Shape UP (Ubisoft Montreal, 2014) workouts trained strength, coordination, and cognitive demands on inhibition, switching, updating, attention, and speed Adaptive and automatically adjusted to the player's level	/	/	$n = 23$; 81.8% M Wait-listed control
Study 5: Eng et al. (2020)	Exergame and cognitive training improved performance on the trained EF task. Exergame increased prefrontal cortex connectivity and performance on the transfer EF tasks, while the cognitive, exercise, and control conditions did not.	49 TD youth Recruited from a preprimary laboratory school in the mid-Atlantic United States	*Range* 4–5 *M* 4.89	*Between subjects* Exergame versus exercise versus cognitive versus control *Single* Participation *Duration* Chronic Two sessions/ week 20 min	*DVs:* 1. Flanker Task accuracy 2. Stroop-Like Day Night Task accuracy 3. Behavior Rating Inventory of Executive Function (BRIEF) total scores 4. Mean prefrontal cortex connectivity	$n = 13$ Custom developed in Unity Technologies (2010) Gamified Flanker Task projected on wall with participants responding by stepping left or right quickly and accurately on a modified DDR game mat's arrows depending on the direction that the central target was facing with increasing challenge as levels progressed	$n = 12$ Custom developed in Unity Technologies (2010) Gamified Flanker Task projected on wall with participants responding by stepping left or right on a modified DDR game mat's arrows, but the central target fish was not surrounded by distractor fish	$n = 11$ Custom developed in Unity Technologies (2010) Gamified Flanker Task projected on wall with participants sitting and responding by pressing left or right on a modified DDR game mat's arrows depending on the direction that the central target was facing	$n = 13$ Age/sex/classroom-matched group continued typical activities during break
Study 6: Flynn et al. (2014)	Exergaming significantly improved EF. Number of exergame	94 African American and Hispanic/Latino low-income youth Recruited from a	*Range* 10–16 *M* 13.72	*Between subjects:* Exergame versus cognitive versus exercise *Single*	*DVs:* 1. Delis–Kaplan Executive Function System	$n = 70$ Wii console Wii Fit (Tadashi, 2007) youth played five games	$n = 14$ Five regular sports sessions	$n = 10$ Wii console Boom Blox (Spielberg et al., 2008), a sedentary	/

(*table continues*)

Table 1 (*continued*)

Study	Main finding	Sample (*N*)	Age (years)	Design	EF outcome	Exergame (↑CE↑PE)	Exercise (↓CE↑PE)	Cognitive (↑CE↓PE)	Control (↓CE↓PE)
	sessions, level of achievement during game play, and level of enjoyment predicted posttest EF scores; while frustration and boredom during gameplay were negatively related to EF. Regression analysis showed the number of exergame sessions significantly predicted EF posttest scores controlling for pretest EF scores.	summer camp from low-income youth in New York City in the United States		Participation *Duration* Chronic One session/week 30 min 5 weeks Total duration completion varied: 42% all five sessions, 19% four sessions, 21% three sessions, 14% two sessions, 4% one session	(D-KEFS) Design Fluency Test Score	at each weekly session: Step Aerobics, Hula Hoop, Table Tilt, and two additional games from the *Wii Fit* package. Progress was tracked with level achieved (e.g., number of stars or points accrued) and fitness achievement (e.g., calories burned)		puzzle action video game consisting of a series of physics-based puzzles, with the goal being either to keep structures made of blocks from being knocked down or to knock them over	
Study 7: Flynn and Richert (2018)	The exergame and cognitive conditions improved on the switch-task flanker accuracy and standard flanker RT compared with participants in the exercise and control conditions.	147 TD youth Recruited from Southern California in the United States	*Range* 7–12 *M* 9.5	*Between subjects* Exergame versus exercise versus cognitive versus control *Single* Participation *Duration* Acute One session 20 min	*DVs:* 1. Flanker Task switch accuracy 2. Flanker Task RT	*n* = 35; 51% M Wii console *DDR*: Arrows scrolled across the screen and participants focused on the direction of the topmost arrow stepping in the coordinated direction, while also attending to upcoming arrows for a series of 12 songs	*n* = 36; 51% M Participated in a series of 12 aerobic exercises with similar movements to those used while playing DDR stepping left, right, up, down the same duration as the exergame	*n* = 35; 54% M Wii console Participants sat in a chair and used a hand-held video game controller to play DDR the same duration as the exergame	*n* = 41; 46% M Participants sat and engaged in minimal conversation with a researcher the same duration as the exergame
Study 8: Gao et al. (2019)	Youth in the exergame group showed significantly greater increases in cognitive flexibility compared to the control group over time.	32 TD youth Recruited from the Twin Cities area in Minnesota in the United States	*Range* 4–6 *M* 4.72	*Between subjects* Exergame versus control *Single* Participation *Duration* Chronic Five sessions/week 30 min 12 weeks	*DVs:* 1. Dimensional Change Card Sort (DCCS) Task Scores	*n* = 18 LeapTV console (LeapFrog Enterprises, 2014): educational exergame that required body movements while learning cognitive skills for reading,	/	/	*n* = 14 Participated in their regular activity patterns, with exergaming gameplay prohibited

(*table continues*)

Table 1 (*continued*)

Study	Main finding	Sample (*N*)	Age (years)	Design	EF outcome	Exergame (↑CE↑PE)	Exercise (↓CE↑PE)	Cognitive (↑CE↓PE)	Control (↓CE↓PE)
						mathematics, science, problem-solving and encouraged participants to learn through motion as they jumped, danced, and hopped			
Study 9: Staiano et al. (2012)	Competitive exergaming improved EF compared to cooperative exergaming and control condition. Improvement in EF was positively correlated with weight loss for the competitive exergame group ($r = .479$, $p = .038$) but not for the cooperative and passive control groups.	54 low-income overweight and obese African American youth Recruited from a larger intervention program to treat obesity at a high school in a low-income inner city in Washington, District of Columbia, in the United States	*Range* 15–19 *M* 16.46	*Between subjects* Competitive exergame versus cooperative exergame versus control Both *single and paired* participation *Duration* Chronic One session/week 15 min 10 weeks	*DVs:* 1. Delis–Kaplan Executive Function System (D-KEFS) Design Fluency Test and Trail Making Test composite score	Wii console *Electronic Arts Sports Active: Personal Trainer* (EA Canada, 2009): routines of cardio, strength training, sports games and progressed by earning points and expending calories *Competitive:* $n = 19$ compared individual progress with others and encouraged to win by earning the top score and expending the most calories *Cooperative:* $n = 19$ worked together to progress as a team to earn the highest possible score and expend the most calories as a pair	/	/	$n = 16$ Participants continued their typical activities after school or during part of the lunch break
Study 10: Xiong et al. (2019)	Exergame improved EF and perceived social acceptance	60 TD youth Recruited from a childcare center in	*Range* 4–5	*Between subjects:* Exergame versus exercise	*DVs:* 1. Dimensional Change Card	$n = 30$ Wii console Nickelodeon Fit	$n = 30$ Traditional physical activity of tag	/	/

(*table continues*)

Table 1 *(continued)*

Study	Main finding	Sample (*N*)	Age (years)	Design	EF outcome	Exergame (↑CE↑PE)	Exercise (↓CE↑PE)	Cognitive (↑CE↓PE)	Control (↓CE↓PE)
	in comparison to exercise, but not perceived physical competence.	a metropolitan area in Southern China	*M* 4.55	*Group* Participation Four stations, with 2–4 per station *Duration* Chronic Five sessions/ week 20 min 8 weeks	Sort (DCCS) Task scores	(High Voltage Software) Just Dance for Kids (Land Ho! Ubisoft) Wii Sports (Nintendo): Interactive gameplay targeting motor skill development, balance, coordination, cardiovascular fitness, upper and lower body strength, and core muscle strength	games, locomotion activities, and soccer		

Note. CE = cognitive engagement; PE = physical exertion; TD = typically developing; ASD = autism spectrum disorder; ADHD = attention-deficit/hyperactivity disorder; DVs = dependent variables; RT = reaction time; M = male; / = did not administer the comparison condition in the study; Exp = experiment; DDR = Dance Dance Revolution (Konami & Bemani, 2007). Wii console (Iwata, 2006). Acute = short-term single bouts of training; chronic = long-term several bouts of training over a period of time; EF = executive function.

environment through body movements. All exergames in the studies reported were accompanied by music, audio, visual instructions, and cues throughout the games.

Game Type

The nature of the exergame varied with the most common platform being the Wii console (Iwata, 2006), which uses Wii remotes that have accelerometers and optical sensor technology that permits motion sensing capability and gesture recognition to communicate player movement to a sensor bar. Four studies used the Wii console and projected exergames onto a television or screen. Studies varied by the specific games used (see Table 1, for details) and some studies utilized additional equipment. Two studies had participants play the Wii Fit (Tadashi, 2007) exergame with a connected response mat that recorded participants' movements related to agility (e.g., stepping quickly and easily), power (e.g., stepping with maximal force in as short a time as possible), and coordination (e.g., stepping congruent to the goal-relevant stimuli; Best, 2012; Flynn et al., 2014). One study had Wii controllers held in the hand or placed in leg straps of participants to communicate player movements to the console and a resistance band to use in strength exercises (Staiano et al., 2012). One study employed a variety of exergames using the Wii console, all of which did not require any additional equipment besides the controllers (Xiong et al., 2019). Two studies utilized an *Xbox* console (Microsoft, 2001) with a *Kinect* (Microsoft, 2010) accessory, which used infrared projectors and detectors to capture gesture recognition and body skeletal detection, which allowed players to control and interact with the game interface through their body movements (Benzing et al., 2016; Benzing & Schmidt, 2019). One study used a stationary bicycle interconnected with a video game displayed on a screen with the goal to move by pedaling and steering to earn points based on speed and color matching, requiring coordination, strength, and agility (Anderson-Hanley et al., 2011). One study used a *LeapTV* console (LeapFrog Enterprises, 2014) developed for educational exergames that required body movements while teaching core cognitive skills for reading, mathematics, science, and problem-solving that encouraged participants to learn through motion as they jumped, danced, and hopped (Gao et al., 2019).

Two studies used *Dance Dance Revolution* (*DDR*; Konami & Bemani, 2007), an exergame that requires controlled stepping movements in the same sequence as on-screen arrows to songs in which participants used a response mat with up, down, right, and left arrows; one study did not report the game console used (Anderson-Hanley et al., 2011); and the other study reported using the Wii console (Flynn & Richert, 2018). One study programmed a custom exergame in *Unity* (Unity Technologies, 2010)—a game engine permitting custom features—in which the exergame was projected onto a wall with a modified DDR game mat, with the modification of only having left and right response arrows (as opposed to the standard configuration of up, down, left, and right), so the gross motor movements were age-appropriate for the preschool-aged participants (Eng et al., 2020). Youth played an exergame version of the Flanker Task (see Supplemental Materials, for task description) in which the game was projected onto a wall while participants responded by stepping left or right on the physical game mat's arrows as quickly and accurately as possible depending on the

Table 2

Effect Sizes of Exergaming on Executive Function

Exergame study	Executive function assessment							
	Observer report	Backward span	Color trails	DCCS	D-KEFS	Flanker	Simon	Stroop
Study 1 (Anderson-Hanley et al., 2011); Exp 1	$\eta_p^2 = .47$	$\eta_p^2 = .20$	ns_{TT}	/	/	/	/	$\eta_p^2 = .19_{\text{TT}}$
Study 1 (Anderson-Hanley et al., 2011); Exp 2	$\eta_p^2 = .24$	$\eta_p^2 = .22$	/	/	/	/	/	/
Study 2 (Best, 2012)	/	/	/	/	/	$\eta_p^2 = .10_{\text{RT}}$	/	/
Study 3 (Benzing et al., 2016)	/	/	/	/	$\eta_p^2 = .10$	/	/	/
Study 4 (Benzing & Schmidt, 2019)	$\eta_p^2 = .32^{\text{a}}$	ns	/	/	/	$\eta_p^2 = .30_{\text{RT}}{}^{\text{a}}$	$\eta_p^2 = .26_{\text{RT}}{}^{\text{a}}$	/
Study 5 (Eng et al., 2020)	$\eta_p^2 = .26$	/	/	/	/	$\eta_p^2 = .18_{\text{ACC}}$	/	$\eta_p^2 = .27_{\text{ACC}}$
Study 6 (Flynn et al., 2014)	/	/	/	/	$\eta_p^2 = .20^{\text{b}}$	/	/	/
Study 7 (Flynn & Richert, 2018)	/	/	/	/	/	$\eta_p^2 = .04_{\text{ACC}}$ $\eta_p^2 = .05_{\text{RT}}$	/	/
Study 8 (Gao et al., 2019)	/	/	/	$\eta_p^2 = .19$	/	/	/	/
Study 9 (Staiano et al., 2012)	/	/	$\eta_p^2 = .15_{\text{CS}}{}^{\text{c}}$	/	$\eta_p^2 = .15_{\text{CS}}{}^{\text{c}}$	/	/	/
Study 10 (Xiong et al., 2019)	/	/	/	$\eta_p^2 = .17$	/	/	/	/

Note. η_p^2 = partial η^2: indicates statistically significant changes in executive function from exergaming with α set at 0.05 for all statistical tests. ns = not significant: indicates no statistically significant changes in executive function from exergaming. / = did not administer the assessment in the study. DCCS = Dimensional Change Card Sort Task (Zelazo, 2006); D-KEFS = Delis–Kaplan Executive Function System (Delis et al., 2001); RT = reaction time; ACC = accuracy; TT = total time to complete task, did not reach significance compared with gains made in the control condition; Exp = Experiment.

[a] Effect sizes in Study 4 were computed by converting Cohen's d to η_p^2 using the sample size ($n = 28$) and Cohen's d (Jin, 2020) reported in the original articles: Simon Task Cohen's $d = 0.58$, Flanker Task Cohen's $d = 0.65$, Conners-3 Cohen's $d = 0.68$. [b] Effect size in Study 6 was determined by computing Cohen's d (0.493), calculated using pre- and posttest mean executive function scores, the standard deviation of the means, and the correlation between the scores reported in the original article ($M_{\text{Pre}} = 12.73$; $SD = 11$; $M_{\text{Post}} = 19.33$; $SD = 14.92$; $r = .50$) and then converted to η_p^2 with the sample size ($n = 70$). All equations are reported in article text. [c] CS = composite D-KEFS color trails + D-KEFS design fluency scores, individual subtest scores not reported.

direction that the central target arrow was facing. The included game features were based on those included in commercially available exergames to preserve ecological validity: goals, levels, player feedback, and a computational algorithm to provide incremental challenge by continuously adapting the difficulty level based on performance.

Comparison Conditions

All studies in this review had one or more comparison conditions to determine the causal effects of exergaming. These conditions included a combination of three different comparison groups, all of which help to understand exergaming's unique effects: (a) passive control conditions to test practice effects; (b) exercise conditions to compare exergaming to more traditional exercise of repetitive movements (e.g., running), which allows for an understanding if there are contributions beyond the physiological aspects of the activity; and/or (c) cognitive conditions to compare exergaming to another cognitively engaging activity (i.e., sedentary video game play), which allows for an understanding if combining physiological and cognitive aspects through exergames leads to greater improvements in EF (see Figure 1, for circular barplot of the effect sizes, by comparison group; R Core Team, 2022).

Passive Control Conditions

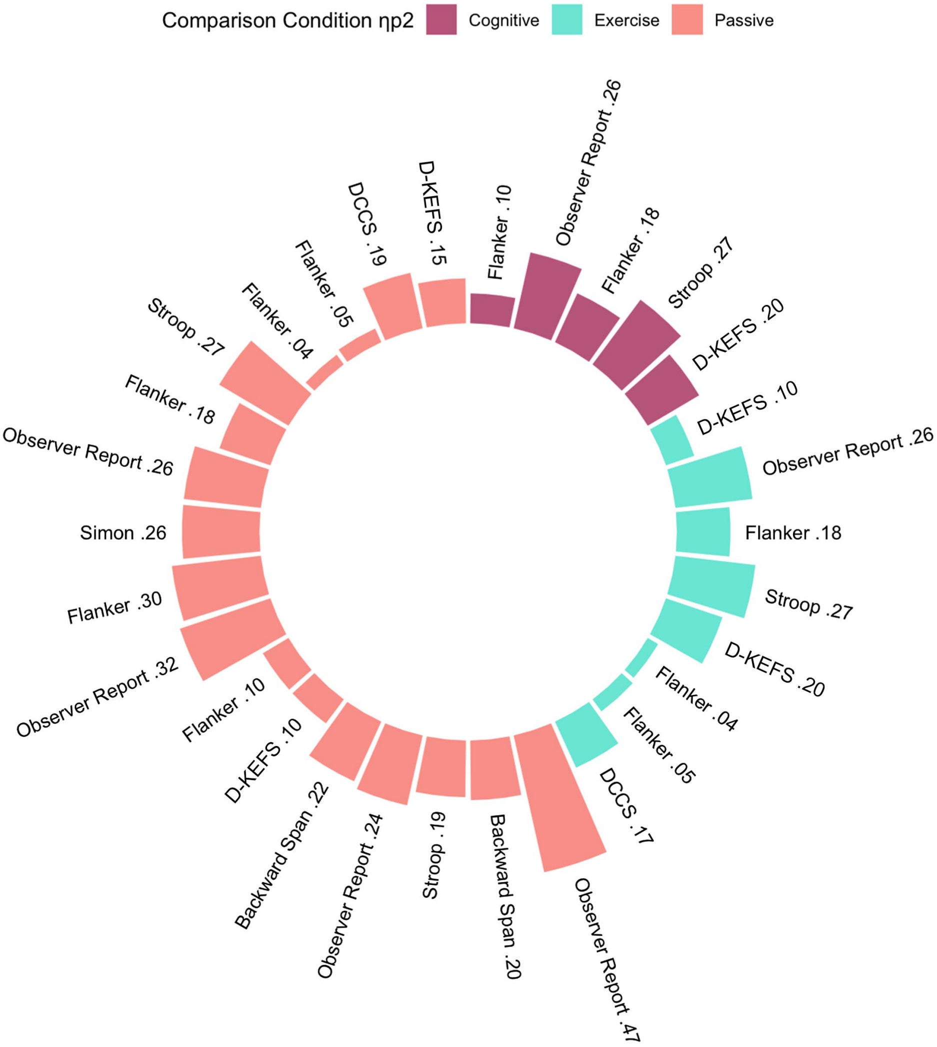
Eight out of the 10 studies included passive control conditions. Studies that show exergame conditions improve EF more than passive control groups would suggest a main effect of exergaming and that the change was not due to practice effects, maturation, or repeated measures alone. Four studies solely had passive control conditions without the addition of an exercise or cognitive condition. Passive control conditions involved watching videos for the same duration as the exergame on healthy living habits (Best, 2012), a documentary on mountain running (Benzing et al., 2016), and a recorded school talent show (Anderson-Hanley et al., 2011). Other control groups consisted of youth continuing their typical activities after school, during a class break, or at home (Eng et al., 2020; Gao et al., 2019; Staiano et al., 2012), put on a wait list (Benzing & Schmidt, 2019), or engaged in minimal conversation with the researcher the same duration of time as the exergame group (Flynn & Richert, 2018). Across all studies, improvements in EF were found in the exergame condition compared to passive control conditions. While passive control groups are important—especially in developmental research to control for maturation effects—a limitation of having no cognitive or exercise comparison conditions is that causal conclusions cannot be drawn as to whether the effects are driven by the exercise, cognitive, or combined cognitive and physical components of exergaming.

Exercise Conditions

There is an ongoing debate in the literature about the impact of physical activity on EF development, particularly whether physical activity alone in the absence of cognitive and/or social engagement has a positive impact on EF development (e.g., Diamond & Ling, 2016, 2019, 2020; Hillman et al., 2018). Six out of the 10 studies included exercise conditions and can therefore contribute insights to

Figure 1

Circular Barplot of the Effect Size Estimates—Partial Eta^2(η_p^2)*—of Exergaming on Executive Function From Each Study, Grouped by Comparison Condition (R Core Team, 2022)*



Note. DCCS = Dimensional Change Card Sort (Zelazo, 2006). D-KEFS = Delis–Kaplan Executive Function System (Delis et al., 2001).

this ongoing conversation in the literature. If exergaming and exercise conditions have an equivalent effect on EF, then it would suggest that the causal factor is physical activity. Two exercise conditions consisted of participating in traditional physical education activities like tag games and soccer (Xiong et al., 2019) and sports activities in camp settings (Flynn et al., 2014). A strength of these exercise conditions is that they preserve ecological validity, but the limitations are the disparities between the type and intensity of physical activity between the exergame and exercise groups, as well as the potential confounds of social and group interaction.

Two exercise conditions consisted of running-based video games with repetitive gross motor movements participants rated as significantly less cognitively engaging (through perceived cognitive engagement questionnaires) compared to the exergame conditions. These exercise conditions consisted of a video game on the Xbox console with a Kinect accessory (Microsoft, 2001, 2010) in which participants ran through virtual streets (Benzing et al., 2016) and a video game on the Wii console (Iwata, 2006) in which youth ran as far as possible by jogging in place on a response mat (Best, 2012). The strengths of these exercise conditions are that participants were exposed to the same game console and associated accessories to capture their motor movements, and the duration of playing in these exercise conditions was the same as the exergame conditions. A limitation to these exercise conditions is that the body movements (i.e., running) differed from the exergame conditions (i.e., punching, squatting, moving side to side horizontally, jumping to avoid obstacles), potentially making the physical exertion not systematically controlled for across exergame and exercise conditions.

Flynn and Richert (2018) and Eng et al. (2020) carefully controlled the type of body movements between the exergame and exercise groups. Flynn and Richert (2018) had youth in the exercise condition participate in a series of 12 exercises with similar movements to those used in the exergame (12 DDR songs), such as stepping left, right, up, and down, designed based on a series of pilot tests. Each exercise series was the same length of time as a DDR song, and youth were given a short break between exercises that mirrored the break between songs in the DDR exergame. Eng et al. (2020) implemented an exercise condition that was identical to the exergame condition of a projection of a gamified Flanker Task on a wall with participants responding by stepping left or right on a physical game mat's arrow, but the central target fish was not surrounded by distractor fish, therefore keeping the exercise movements the same but decreasing the cognitive demands. The play duration and gross motor movements were identical between the exergame and exercise conditions.

Cognitive Conditions

There is evidence that video game play that places demand on cognitive control, and working memory has positive effect on structural and functional changes in prefrontal areas in adults (see Palaus et al., 2017, for review) and that computerized cognitive training can have positive effect on EF in youth ages 3–6 and prefrontal development (Rueda et al., 2012; Scionti et al., 2020). Therefore, it is possible that cognitive training is largely responsible for the positive effect of exergames on EF. Four studies incorporated the use of a sedentary cognitive condition. If exergaming and the sedentary cognitive conditions have equivalent effects on EF, then it would suggest the causal factor is the cognitive engagement of the game play, whether physical or sedentary, provides a context to improve EF in youth. Cognitive engagement defined in the context of these studies is the level of attentional resources and cognitive effort needed to acquire skills (Benzing et al., 2016), and cognitively engaging activities are ones that engage higher order EF processes (e.g., planning, problem-solving) in a challenging environment, in contrast to repetitive activities that require less adaptation or conflict resolution in the environment (Best, 2012). Two cognitive conditions consisted of participants playing a sedentary video game on the Wii console while sitting using hand-held controllers, in contrast to interacting with the digital environment standing using body movements requiring more physical exertion. The sedentary video games were *Super Mario World* (Nintendo, 2009): A linear-level video game consisting of a narrative adventure populated with obstacles and enemies that involved a user-controlled character protagonist dashing, jumping, and dodging or defeating enemies (Best, 2012), and *Boom Blox* (Spielberg et al., 2008): A puzzle action video game consisting of a series of physics-based puzzles, with the goal to either keep structures made of blocks from being knocked down or to knock the structures over (Flynn et al., 2014). A limitation to these cognitive conditions is that participants were exposed to different game features, music, visuals, and player feedback than the exergame conditions, prohibiting a direct exploration of cognitive engagement.

Flynn and Richert (2018) carefully controlled for the type of cognitive engagement between conditions by having the cognitive condition of using the same game (DDR) as the exergame but participants used a handheld controller while sedentary; thus, they were exposed to the same cognitive engagement induced from the exergame with identical game features such as music, visuals, feedback, and visual–spatial perception but with decreased physical exertion. Similarly, Eng et al. (2020) implemented a cognitive condition in which participants played the same game as the exergame, with the one difference being that the participants were sedentary and responded by pressing left or right on the physical game mat's arrows while sitting rather than stepping, keeping the cognitive engagement constant while decreasing physical exertion.

EF Outcome Measures: Assessments

All studies included in this review reported the use of commonly utilized article and pencil or computerized task-based psychometric assessments of EF such as cognitive flexibility or inhibitory control (e.g., Color Trails Test, Day Night Task, Dimensional Change Card Sort Task, Delis–Kaplan EF System, Flanker Task, Simon Task, Stroop Task), working memory (e.g., Backwards Color Span, Backwards Digit Span), or adult-report questionnaires of EF-related behavior (Conners-3; Behavior Rating Inventory of EF, Gilliam Autism Rating Scale). Versions of the Flanker Task and the Delis–Kaplan EF System were the most common outcome measures of EF used across studies. Detailed descriptions of the EF assessments, parameters, and modifications from the original tasks are provided in the Supplemental Materials to report the design of each measure in a centralized way to streamline accessibility and encourage reproducibility.

EF Outcome Measures: Effect Sizes

Partial η^2 (η_p^2) was the most reported effect size across studies. η_p^2 indicates the proportion of variability from the effect of exergaming when the variability associated with all other effects in the analysis is removed (Fritz et al., 2012), with $\eta_p^2 < .01$ indicating no significant effect; $\eta_p^2 = .01-.059$ indicating a small effect; $\eta_p^2 = .06-.139$ indicating an intermediate effect; and $\eta_p^2 > .14$ indicating a large effect (Lenhard & Lenhard, 2016). Eight out of the 10 studies computed η_p^2 for effect sizes and are in Table 2 as they were reported in the original articles. For consistency and interpretability, studies (e.g., Benzing & Schmidt, 2019) that reported Cohen's *d* as effect sizes were converted to η_p^2 using the sample size (*N*) and Cohen's *d* reported in the original articles (Jin, 2020):

$$\eta_p^2 = \frac{\text{Cohen's}\, d^2 \times N}{\text{Cohen's}\, d^2 \times N + N - 1}. \tag{1}$$

The studies (e.g., Flynn et al., 2014) that did not report effect sizes were computed by first calculating Cohen's *d* using the means (*M*), the standard deviation of the means (*SD*), and the correlation between the two means (*r*) reported in the original article:

$$d = \frac{M_1 - M_2}{\sqrt{SD_1 + SD_2 - (2rSD_1SD_2)}}. \tag{2}$$

Then, Cohen's *d* was subsequently converted to η_p^2 using Equation 1.

Summary of Results

The next three sections provide the findings from each study based on the type of comparison groups included. The first section summarizes the results from studies that only had a passive control condition. The second section summarizes the results from studies that included an exercise condition but not a sedentary cognitive condition. These studies may also have included a passive control group. The third section summarizes the results from studies that included a cognitive condition, and these studies may also have included an exercise and passive control group. While effect sizes in this section are reported, a meta-analysis was not conducted because the eligible studies that fit the review criteria are not sufficiently homogeneous regarding the number of comparison conditions, the populations (which vary widely by age and clinical diagnosis), setting, and training dosage to provide a meaningful summary for a meta-analysis.

Does Exergaming Improve EF Compared to Passive Control Conditions?

Four studies compared exergaming to only a passive control group, which can draw conclusions whether improvements from exergaming are not due to practice or maturation effects alone. Benzing and Schmidt (2019) found that exergaming improved youth ages 8–12 with AD/HD's performance on an inhibitory control task, a cognitive flexibility task, and parent ratings of EF-related behavior (AD/HD symptoms), but not performance on a working memory task compared to a passive control group. Staiano et al. (2012) investigated an aspect of exergaming with low-income overweight and obese African American youth ages 15–19 by considering that exergaming can involve competition or cooperation among players. Participants in competitive exergaming were encouraged to earn the highest score (exergame points and calorie expenditure) compared to others, whereas those in the cooperative exergaming were encouraged to progress as a team by obtaining a high score together. The researchers found that competitive exergaming improved EF (problem-solving, simultaneous processing while following the rules and restrictions of the task, inhibitory control, cognitive flexibility) compared to cooperative exergaming and a passive control group. Gao et al. (2019) found that exergaming improved youth ages 4–6's performance on a cognitive flexibility task compared to a control group. Anderson-Hanley et al. (2011) found that exergaming across two experiments with different exergames (DDR with youth ages 10–18 and cybercycling with youth ages 8–21, respectively) improved performance on a working memory task and decreased observer ratings of ASD symptoms such as repetitive behaviors compared to a passive control condition. Cognitive flexibility (only assessed in Experiment 1) and inhibitory control performance increased for the exergame conditions, but improvements in performance did not reach significance compared with the control condition. The authors report that this discrepancy is most likely due to the large initial practice effects noted on these timed tests exhibited by the control group.

Overall, these studies show that some aspects, and not always the same aspects of EF exhibited improvement from exergaming in typically developing, low-income, and neurodiverse youth compared to passive control groups. A limitation to these studies was that there were no cognitive or exercise comparison groups; thus, conclusions could not be drawn as to whether the effects were driven by the exercise, cognitive, or combined cognitive and physical components of the exergames. Prior research has demonstrated that baseline EF influences improvements from EF interventions, and those with the lowest baseline EF improve the most (Diamond & Lee, 2011). Thus, the results from these studies may be due to the law of initial value—the magnitude of a response being dependent on the initial baseline level—in which case any intervention would lead to improvement for youth with low EF relative to a passive control condition. The following sections address this limitation by evaluating studies that included additional and/or active comparison conditions.

Does Exergaming Improve EF Compared to Exercise Alone?

One study compared an exergame condition to both an exercise and passive control condition, and one study only used an exercise condition as a comparison. Benzing et al. (2016) found that exergaming improved EF performance in an exergame group compared to an exercise group and passive control group. This study only included male youth ages 13–16, limiting the generalizability of these findings. Xiong et al. (2019) found that youth ages 4–5 in an exergaming condition improved performance on a developmentally appropriate EF (Dimensional Change Card Sort) task and perceived social acceptance compared to an exercise condition who played group sports. In both conditions, youth were exposed to group social interactions, but only the exergame group exhibited improvement in EF and social acceptance indicating additive value for the exergame. These results are consistent with the possibility that the combination of cognitive engagement and physical activity may induce larger effects on EF compared to exercise alone. The limitation of these studies was that there were no cognitive comparison conditions; thus, causal conclusions could not be made on whether the cognitive component alone from the exergames without the exercise component would be enough to induce changes in EF.

Does Exergaming Improve EF Compared to Cognitive Training Alone?

Four studies used a combination of comparison conditions, including a cognitive condition, to compare the effects of EF to exergaming. Flynn et al. (2014) found that exergaming with youth ages 10–16 improved EF compared to a cognitive group and a passive control group. The sizes of the control groups (n = 14 in the exercise condition, n = 10 in the cognitive condition) were underpowered relative to the exergame condition (n = 70). Given this limitation, the researchers focused on individual difference factors accounting for changes in EF of the exergame group. The researchers found that the number of exergame sessions (out of five), level of achievement during game play, and level of enjoyment predicted posttest EF, while frustration and boredom during game play were negatively related to EF.

Best (2012) found that exergaming with youth ages 6–10 improved EF in an exergame condition and an exercise condition compared to a cognitive condition and a passive control condition. The findings from Best (2012) suggested that the exercise component of exergames, not the cognitive component, enhances EF because EF only improved after participation in the exergame and exercise conditions. A limitation to this study was the game mechanics of the exergame condition (a series of minigames consisting of moving and jumping to avoid obstacles, with each minigame becoming increasingly difficult with more obstacles approaching more randomly and unpredictably as participants progressed) differed from the game mechanics of the cognitive condition (a narrative adventure video game, with the goal of completing levels filled with helpful items, harmful obstacles, enemies and power-ups to unlock the next level in a larger world map), making it unclear if exergaming had a stronger influence on EF than the cognitive condition when the cognitive engagement induced from the cognitive condition and exergame conditions were not systematically the same.

Flynn and Richert (2018) worked toward resolving the limitation of the disparities between the type of physical activity between the exergame and exercise groups and cognitive engagement between the exergame and sedentary groups by randomly assigning youth ages 7–12 to an exergame, cognitive, exercise, or control group, but ensured participants in the exercise group executed gross motor movements identical to the exergame group and that youth were exposed to the same video game in the exergame and cognitive conditions. The researchers found that both the exergame group requiring physical exertion to play DDR and the cognitive group using a sedentary controller to play DDR improved EF performance compared to the exercise and control group. Contrary to the results of Best (2012), findings from this study suggest that the cognitive component of exergames has a stronger influence on EF than the exercise component. Although the exercise group performed similar gross motor movements as the exergame group, the exercise group did not have to inhibit or receive feedback from a video game interface to modify their responses, making the feedback participants received in the exergame and cognitive conditions different from the exercise condition.

Eng et al. (2020) worked toward resolving the limitation of the disparities between the feedback system of the exergame and exercise groups by randomly assigning youth ages 4–5 to an exergame, cognitive, exercise, or control group, but ensured the exercise condition received the same visual feedback in a digital environment identical to the exergame and cognitive conditions. The study found that exergaming improved EF performance and associated neural substrates (prefrontal cortex connectivity) compared to the exercise, cognitive, and control conditions. Findings from this study suggest that the combination of cognitive engagement and physical activity of exergames enhances EF over single-component exercise or cognitive training alone.

Discussion

This literature review provides a mechanism to draw conclusions from the existing literature regarding the overall state of research activity and identifies gaps in the evidence base where research needs to be conducted to move the field forward: More carefully controlled studies with exergame, and systematically designed cognitive, exercise, and control comparison conditions with follow-up assessments are needed to clarify the unique efficacy of exergames on EF in typically developing and neurodiverse youth and the mechanisms underlying the functional changes induced from exergame play. Despite the high variability in exergame context, dosage, and samples (age, sex, neurodiverse populations), the improvements in EF from exergames were evident across all studies. The findings show that there is evidence of exergames demonstrating advantages over passive control and exercise conditions, but evidence is mixed when comparing exergame conditions to cognitive conditions with youth populations. These mixed results could be due to the varying nature of the exergames (game features and duration), as well as the variation in EF task outcome metrics and parameters, which are covered in depth in the Supplemental Materials.

The identification of similar findings is of significant interest, given the lack of methodological congruence between each of the included studies. First, across all studies, there is evidence that it is possible to improve EF in youth from exergaming. The findings indicate that exergaming has beneficial effects on inhibition, cognitive flexibility, and observer reports of EF-related behavior in youth with AD/HD (Benzing & Schmidt, 2019), improved performance on a working memory task, and decreased ASD symptoms in youth diagnosed with ASD (Anderson-Hanley et al., 2011), improved inhibitory control and cognitive flexibility in youth from low-income backgrounds (Staiano et al., 2012), and improved cognitive flexibility in typically developing youth (Gao et al., 2019) compared to passive control conditions. Benzing and Schmidt (2019) found that exergaming had beneficial effects on EF in youth with AD/HD. AD/HD is believed to be a result of abnormalities in the prefrontal cortex and associated subcortical structures and circuits, and underpinning these abnormalities are disturbances of catecholamine neurotransmission (Prince, 2008). Benzing and Schmidt (2019) theorize that because individuals with AD/HD have depleted levels of dopamine and norepinephrine, the stimulation of motor and cognitive functions underlying the prefrontal cortex during exergaming induces catecholamine neurotransmission, which subsequently leads to neurogenesis and angiogenesis and neuroplasticity in brain regions underlying EF performance and AD/HD symptomatology, which consequently improves aspects of EF. Staiano et al. (2012) found that competitive exergaming is more effective than cooperative exergaming in improving EF. The researchers theorize that competitive exergaming may enhance EF more so than cooperative exergaming because competitive demands higher levels of EF than cooperative demands do, and the prefrontal cortex has been found to be activated by competition but not by cooperation (Decety et al., 2004). These theories are consistent with the findings of Eng et al.'s (2020) finding of increased prefrontal cortex neural connectivity following exergaming, and the increased connectivity strength in the prefrontal cortex was positively associated with behavioral changes in EF, but only for the exergame group.

The studies that included exercise conditions found that exergaming improved EF compared to exercise alone across developmentally diverse samples in youth ages 13–16 (Benzing et al., 2016), 7–12 (Flynn & Richert, 2018), and 4–5 (Eng et al., 2020; Xiong et al., 2019), but significant differences were not found between exergaming and exercise with youth ages 6–10 (Best, 2012). Best (2012) hypothesized that the reason the exergame did not have a stronger effect than the exercise condition may be due in part to the unintentional cognitive engagement induced from the exercise condition from the game interface: the complexity of movement during the exergame condition (coordinating running, jumping, and crouching on a response pad) was intended to be more cognitively engaging than the exercise condition (jogging in place on a response pad); however, jogging on a response pad required the balls of participants' feet to directly target the pressure-sensitive buttons, requiring youth to continually monitor and adjust their position and motions on the response pad in addition to being physically active. Thus, compared to other types of repetitive exercise such as jogging or running, the exercise condition likely induced more cognitive engagement than intended (Best, 2012).

To make conclusions on whether the cognitive engagement alone from the exergame without the physical activity component would be enough to induce changes in EF, this review extrapolated findings from the few studies that included cognitive comparison groups. It was found that compared to sedentary cognitive conditions, exergaming improved EF in a group of low-income African American and Hispanic/Latino youth ages 10–16 (Flynn et al., 2014) and in typically developing youth ages 6–10 (Best, 2010) and ages 4–5 (Eng et al., 2020). Significant differences in EF were not found between the exergame and sedentary cognitive groups with youth ages 7–12 (Flynn & Richert, 2018). A potential explanation for why the exergame did not have a stronger effect than the cognitive condition is that both the exergame condition (DDR using a game mat's arrows) and sedentary cognitive condition (DDR using a hand-held game controller's arrows) required youth to engage in processes similar to the main assessment of EF—the Flanker Task—of executing goal-relevant responses in the presence of competing goal-irrelevant stimuli by focusing on the direction of a target arrow while simultaneously anticipating upcoming arrows, requiring selective attention, inhibitory control, and reduction of conflict interference.

A concern of EF training in general is (a) how robust exergaming is and (b) how the skills youth gain transfer to real-world behavior. The studies that administered the Flanker Task as a main EF assessment showed improved performance from various other types of exergames (Benzing & Schmidt, 2019; Best, 2012; Eng et al., 2020) and not just from DDR (Flynn & Richert, 2018) exemplifies the robustness of exergames. Across all studies that employed observer reports (parent ratings, teacher ratings, standardized clinical observations of EF-related behavior), significant improvements from exergaming compared to the comparison groups were found. Thus, these findings suggest various types of exergames impact task-based assessments and, additionally, transfer to observer reports of EF-related behavior in ecologically relevant settings.

Limitations and Future Directions

While Benzing and Schmidt (2019), Staiano et al. (2012), and Gao et al. (2019) found that exergaming improved performance on cognitive flexibility and inhibitory control tasks compared to passive control conditions, Anderson-Hanley et al. (2011) did not. A core difference between the three studies that did find significant improvements employed 8-, 10-, and 12-week long studies, while Anderson-Hanley et al. (2011) employed a single bout of exergaming. It is possible that if the study was chronic, greater differential benefits would have emerged and findings would be more consistent across studies. Donnelly et al.'s (2016) review found studies examining acute exercise on EF in youth yielded mixed results, which the authors discuss were difficult to explain because the studies employed similar designs regarding exercise duration, physical activity intensity, and EF outcome measures but that the mixed results could be due to differences in the participants' *cognitive strategies*, and future research is needed to confirm this potential explanation. Diamond and Ling's (2020) review on EF training found that within the range of durations studied, longer durations of computerized cognitive training produced better results than shorter durations, and studies of enriched exercise with higher cognitive demands showed suggestive evidence of EF benefits compared to repetitive exercise, with more EF improvement from enriched exercise compared to repetitive exercise compared to control groups found on twice as many EF measures.

A limitation of these chronic bout studies is that EF was assessed after the last session after weeks of exergaming, making it impossible to conclude whether EF improvements were from the most recent exergame session or from the accumulation of training. It would be beneficial to investigate the precise environmental manipulations required to facilitate chronic EF change and identify whether exergaming transiently facilitates EF or if it has a more fundamental impact on development. Research that follows youth longitudinally incorporating an immediate EF evaluation after one exergaming session and a follow-up delayed test after weeks of exergaming propels a future forefront to investigate the extent to which exergaming enhances EF in youth, and if these effects are sustained over time.

Another core difference is that Anderson-Hanley et al. (2011) analyzed the mean *total time to complete the tasks* as the main inhibitory control and cognitive flexibility EF task-dependent variables, while other studies employing similar EF tasks focused on the mean total correct trials, accuracy, or reaction time. It is unclear whether findings would not be mixed if the EF dependent variable metrics were recorded and reported consistently or if they were scored as they were in the original tasks, but it cannot be ruled out as a possibility. We are not implying all EF training experimental studies should evaluate and compare each of the outcome metrics that can be derived from task-based EF assessments between conditions, but encouraging that the variables (raw scores, standardized scores, reaction time, accuracy, correct trials, errors, etc.) should be reported for consistency and reproducibility to determine corroborative or disputed evidence.

While Anderson-Hanley et al. (2011) and Benzing and Schmidt (2019) both found exergaming improved observer reports of EF-related behavior in youth with AD/HD and ASD, Anderson-Hanley et al. (2011) found improvements in working memory, while Benzing and Schmidt (2019) did not. These mixed findings have a few implications: single bouts of exergaming have an immediate beneficial effect on working memory, but not after delayed exergaming; exergaming may be especially beneficial for working memory in youth with ASD, but not for youth with AD/HD. More studies with clinical samples are needed to understand the unique efficacy of exergaming across neurodiverse youth populations.

The scope of this review extracted studies that employed exergame contexts in which participants engaged in activities in 2D digital environments. With increased accessibility, virtual reality (VR) in three-dimensional (3D) environments has shown to be a promising tool for healthy and clinical adult populations to practice learned cognitive skills and as an evaluative tool of EF skills (Ancis, 2020; Costa et al., 2019). VR is currently recommended for individuals ages 13-years-old and older due to younger populations having greater risks of injury and adverse effects (Oculus Safety Manual); but with the increasing development of VR exercise applications and the exponential growth and acceptance of video game play in childhood, investigating whether the beneficial effects on EF induced from exergames in 2D environments generalize to 3D immersive VR environments in youth is a promising avenue to explore when the technology evolves to be developmentally appropriate for younger populations.

Finally, results should be cautiously interpreted because of the limited number of experimental studies with youth available for synthesis. Reflecting time and budget constraints, only studies published between 2007 and 2022 were included in this review. While we had to adopt these limits for practical reasons, it is noted that potentially relevant articles could have been excluded as a result. Future studies should also consider individual difference factors relating to participant demographics (e.g., gender, SES, neurodiversity) and player experience (e.g., game enjoyment, single vs. group participation). When additional research is available, a future meta-analysis would be useful to quantify the size of effects and possible role of individual difference factors. There is a risk that literature reviews and empirical work do not all adopt the same standards in terms of protection against bias; however, the framework for conducting this review was underpinned by the view upheld by proponents of systematic reviews that the methods used were conducted in a rigorous and transparent way, with the goal of the review to identify gaps in the evidence base of experimental research with youth on exergames and EF where future research needs to be conducted to move the field forward.

Exergames From a Practical Perspective

Exergames are relatively inexpensive, widely available, require a small amount of space, adapt to individual performance, and are perceived as enjoyable by youth (Best, 2010). At least 162 million people in the United States own video game consoles, with 53% of U.S. households reporting owning at least one video game console (Owens, 2022). On average, youth among 0- to 8-year-olds spend approximately 23 min daily playing video games (Common Sense Media, 2020); 71% of parents report video games were a much-needed break for their children during the pandemic and three quarters of parents reported video games making their children's transition to distance learning easier (Entertainment Software Association, 2021).

Not only is gaming prevalent in homes, but it has made its way into formal education settings in an increasing number of U.S. schools: When the Every Student Succeeds Act of 2015 was passed, states must give students access to technology and use evidence-based methods of incorporating technology into curricula and instruction to improve academic success. States are starting to specifically include digital games in their curriculum policies; for example, the New Jersey Curriculum Core Content Standards include digital games in their curricula starting from kindergarten to high school and as a younger generation of teachers enter classrooms and adults enter parenthood, they are likely to be gamers themselves and therefore more accepting of gamification in learning than earlier generations of parents and teachers (Blumberg et al., 2019). This review is timely because, as technology use grows at an exponential rate and reports of sedentary behavior and cognitive impairments increase in the wake of the global pandemic, evidence-based practices that promote both physical activity and cognitive engagement are needed (World Health Organization, 2020). Exercise is especially important because it reduces stress, prevents weight gain, and boosts the immune system and exergames are capable of not only safely promoting physical activity but also executive functioning by interweaving exercise into gameplay that encourages calorie-burning body movements in a cognitively engaging environment.

Conclusion

Exergames can easily be implemented in everyday lifestyles and have high potential to improve essential EF skills that are crucial for academic success for youth, as well as prevent and remediate symptoms associated with cognitive disorders such as AD/HD and ASD. Exergames are also ideal for use by youth because they contain nonviolent content and may be especially useful for youth from low socioeconomic households who may not have access to safe recreational equipment, and for youth with low physical activity self-efficacy or for youth who are uncomfortable exercising around others. Psychosocial impediments to physical activity engagement (e.g., individuals with negative perceptions of exercising around others or low physical activity self-efficacy and enjoyment) discourage youth from fully engaging and participating in exercise activities and group sports (Best, 2010).

Youth is a developmental period where individuals start to become critical of their own performance, compare themselves to peers, and care about what others think of them. If youth feel they are not performing as well as their peers in group fitness activities or sports—they become discouraged—which may lead to less engagement and negative perceptions of physical activity outside of the classroom and in the future. It is important for youth to learn that exercise can be an enjoyable activity and that physical competence is not fixed but a quality that can be improved with effort and persistence. Participating in an enjoyable physical activity through exergaming might just be the window youth need to learn this.

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