

Review

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Review

Neural Correlates of Exergame Interventions in Older Adults with or without a Neurocognitive Disorder: A Systematic Review

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Abstract: Exergames (EG) are interactive video games that require physical activity and use gamification to make exercise more engaging. EG interventions have shown various benefits for older adults, such as improved mental health, quality of life, and reduced fall risk. Enhanced cognition is thought to drive these benefits. This review aimed to identify neural correlates underlying cognitive improvements in healthy older adults and those with neurocognitive disorders. We systematically searched major databases and included 13 studies from 2,095 records. Findings revealed that EG interventions led to structural brain changes and improved functional connectivity in healthy adults, Parkinson patients, and those with mild cognitive impairment (MCI). Increased activity in the frontal, temporal, and precuneus regions during rest was specific to adults with neurocognitive disorders. Neuroplastic changes, such as elevated BDNF levels and increased neurovascular coupling, were observed in both groups. However, methodological limitations in some studies highlight the need for further high-quality research.

Highlights:

- The benefits of exergame interventions in healthy older adults (structural changes, better neuroplasticity) were also found in Parkinson and MCI patients
- Some studies in healthy older adults showed changes in neural networks responsible for motor tasks, associated with exergame interventions
- After exergame interventions, older adults with a neurocognitive disorder particularly showed enhanced activities in some brain regions (frontal, temporal, precuneus) during resting state
- Certain findings, particularly those related to structural changes and functional brain connectivity, require validation through higher-quality neuroimaging studies

Keywords: exergame; older adults; neurocognitive disorders; brain; aging brain; EEG; MRI; neuroplasticity; BDNF

1. Introduction

Promoting health through physical activity (PA) has become a worldwide priority due to the well-documented benefits of the regular practice of PA (1). Older adults are particularly concerned, as PA effectively mitigates the consequences of age-related cognitive and functional decline, diseases, and comorbidities (2). Despite this, a significant number of older adults remain inactive (3) because of various personal factors (such as motivation, fear of injuries, and intrinsic capacities) and environmental factors (such as practice locations, transportation difficulties, and infrastructure risks) (4,5). To address these barriers, an emerging research field has identified Exergames (EG) as an effective strategy to engage more older adults in PA (6).

EG are interactive and immersive video games that require the player to be physically active (7). They leverage the benefits of gamification by adding an entertaining dimension, which facilitates greater engagement (8,9). EG often utilizes commercial home video game consoles, such as the Nintendo Wii® and Xbox Kinect®, where participants are required to perform some physical tasks to play. Some other formats require participants to step on platforms or floor mats, while responding to visual cues or movement instructions (10–12). Furthermore, there is also the opportunity to use technologies within the Extended Reality (XR) continuum allowing us to model the physical world in a digital immersive environment (13). This has been leveraged for safe PA practice in the form of EG in realistic immersive conditions, thereby limiting the constraints inherent to environmental factors (14–18), particularly in augmented or mixed reality setups (19).

A growing body of evidence supports the notion that EG interventions not only increase older adults' levels of PA but also yield numerous clinical benefits. Recent systematic reviews and meta-analyses reported that healthy older adults who engage in EG interventions improved their quality of life and mental health (20–22), and reduced the risk of fall incidents (12,23,24) and even had lower cognitive impairment cases (25). Moreover, numerous Randomized Controlled Trials (RCT) reported similar effects of EG in reducing falls or improving quality of life as compared to conventional PA interventions (aerobic fitness, resistance training, stretching...) (23,26). These benefits of EG interventions are even more relevant, as the clinical outcomes mentioned above affect most older adults, often imposing a substantial burden on their daily lives.

Moreover, since motor and cognitive functioning progressively decline in both normal and pathological aging (27,28), several studies have investigated whether improvement in such functions would be the principal targets that are responsible for the benefits of EG interventions. Most studies investigated cognitive abilities and demonstrated that EG would lead to improvement in global cognition (17,21,29,30) or in specific domains such as executive functions (31,32) or memory (33). Noteworthy, EG benefits on motor domains are more controversial (17,34) despite existing data on EG-related improved performance in balance or gait evaluations (35,36). Most studies suggest that this might be the result of the intensity of interventions which is insufficient to maximize improvements in motor functions (17,34). Overall, one can understand that improvement in cognitive and motor abilities would be the principal targets of EG interventions. Such improvements can be the result of modifications in several behavioral and physiological mechanisms. Therefore, it appears crucial to identify the underlying mechanisms that give rise to the above-mentioned benefits of EG interventions.

Understanding the underlying mechanisms of EG interventions will enhance our knowledge and help us determine the key factors that could moderate the benefits, thereby optimizing the interventions for maximum efficacy. Given the fact that improvements in cognitive functions are the primary benefits of EG interventions (17,34), one can assume that these gains would be associated with key neural correlates. Interestingly, examining the effects of EG on brain is especially relevant, since the cognitive benefits of PA are believed to be associated with changes in the brain at three levels: structural, functional, and molecular (37,38). Indeed, there is existing evidence of PA (aerobic and resistance training) substantially modifying brain structure by augmenting brain volume in areas such as hippocampus or prefrontal cortex (PFC) (39,40). These effects of PA are supported by other findings suggesting improved resting state functional networks (e.g., Default Mode Network (DMN)) or other specific task-related networks (37,38). Other effects of PA such as elevated levels of neurotrophic factors (e.g., Brain-Derived Neurotrophic Factors (BDNF), Insulin-like Growth Factor (IGF)) (41–43) or enhanced neurovascular coupling (44,45) might further stimulate neuroplastic changes.

Thus, recent review studies have investigated the effects of EG interventions on brain functions (46–48). The results suggest neuroplastic changes that include augmented levels of BDNF and improved activity within neural networks during the processing of cognitive tasks (e.g., attention, working memory). This effect on neural networks was measured using functional Near-Infrared Spectroscopy (fNIRS) or scalp Electroencephalogram (EEG), with results suggesting higher recruitment of specialized neural networks and reduced reliance on compensatory networks. This is

particularly interesting considering the model of scaffolding theory of aging and cognition which explains how different brain variables, both structural and functional, are related to cognitive functions (49). Indeed, the CRUNCH hypothesis of this model may explain the benefits of EG interventions, particularly by suggesting that older adults, when relying on compensatory networks, recruit additional neural resources and display hyperactivation during low-demand tasks to meet performance demand (50,51). Overall, current evidence suggests that the cognitive behavioral benefits of EG interventions can be associated with the neurobiological aspects of age-related functional decline.

Nevertheless, some aspects of the effects of EG interventions on brain structures and functions were not covered in these previous review studies (46–48). First, there is a lack of studies investigating all three levels—structural, functional, and molecular of the effects on the brain. Additionally, since technologies for conducting EG continue to advance rapidly, there is a need for updated research and literature that examines these emerging tools and their impact on neural correlates. Most importantly, the previous review studies only considered healthy older adults while studying neural correlates. However, it is demonstrated that EG interventions can also benefit older adults with neurocognitive disorders (10,18,25,32,33,52,53). In addition, it is well established that neurocognitive disorders are progressive, affecting cerebral bases across all three levels—structural, functional, and molecular. Thus, it is particularly relevant to consider this population to investigate whether EG can trigger brain modifications that are relevant to neurocognitive disorders.

In the present study, our objective was two-fold. First, we aimed to expand on previous review studies by examining recent studies that shed light on the neural correlates of EG interventions in aging, focusing on changes in the brain structure, functional networks and molecular markers. Second, we extended the range of our population of interest to include older adults with a neurocognitive disorder, assessing whether EG interventions impacted neural correlates relevant to these diseases.

2. Methods

2.1. Search Strategy

The research question of the present review was designed using the PICO framework as follows: Population (Older adults with or without a neurocognitive disorder), Intervention (Exergame), Control (One-arm study, passive (no activity, usual activity, education), or active (physical or cognitive)), Outcome (neural correlates: gray-matter volume, connectivity, neuroplasticity biomarkers). The search was conducted in accordance with updated PRISMA guidelines (Page et al., 2021), in June 2024 across the following electronic registries: PubMed, Cochrane Library, Embase, Science Direct, and Scopus. The search strings included terms combined with "OR" and "AND" operators as follows: (older adults OR elder OR elderly OR seniors OR aging OR ageing) AND (Exergame OR Exergaming OR Virtual Reality OR Mixed Reality OR Augmented Reality OR Extended Reality OR Wii OR Kinect OR PlayStation OR Interactive Videogame OR Active Video Game) AND (Neurobiology OR Neurophysiology OR Neural OR Brain).

2.2. Eligibility Criteria

The screening (duplicates, titles and abstracts, and full texts) was conducted by two independent researchers with a consensual meeting for conflict resolution afterwards. After the duplicate removals and the title and abstracts screening, the remaining reports were retrieved for full-text screening to determine eligibility for inclusion. Full-text articles were eligible for inclusion in this review study if they met the following criteria: 1) published in peer-reviewed scientific journals, 2) written in English, 3) included healthy older adults (mean age 60 or older), or older adults with a neurocognitive disorder, 4) examined the effects of an EG intervention in at least one group, and 5) performed a noninvasive measurement of neural correlates (brain structure or activity) was the primary or secondary outcome investigated in the study. Moreover, the studies with the following

intervention were not considered: technology-assisted PA without a gamified dimension, additional interventions alongside EG within a multidomain approach.

2.3. Data Extraction and Quality Assessment

For each article included, the following elements were independently extracted by two researchers, with a consensual meeting for conflict resolution afterwards. They reported the following items: 1) Metadata (Authors, year of publication country), 2) Characteristics of the study population, 3) intervention settings (design, duration, intensity), 4) type of EG 5) type of setup used for the measurement of neural correlates, and 5) main findings. Finally, the methodological quality was assessed through the risk of bias tool provided by Cochrane Collaboration (Higgins et al., 2011).

3. Results

3.1. Study Selection

We identified 2,095 records following the initial search. After removals of duplicates (n =375) and the title and abstract screening (n = 1676 removed), we searched for the full texts of 44 reports that were screened for eligibility criteria resulting in 31 additional removals (see Figure 1). Therefore, we included 13 studies in the present systematic review that investigated the neural correlates of EG interventions in older adults with or without a neurocognitive disorder. Tables 1 and 2 summarize the characteristics and findings of the included studies based on the items extracted as presented in the method section.

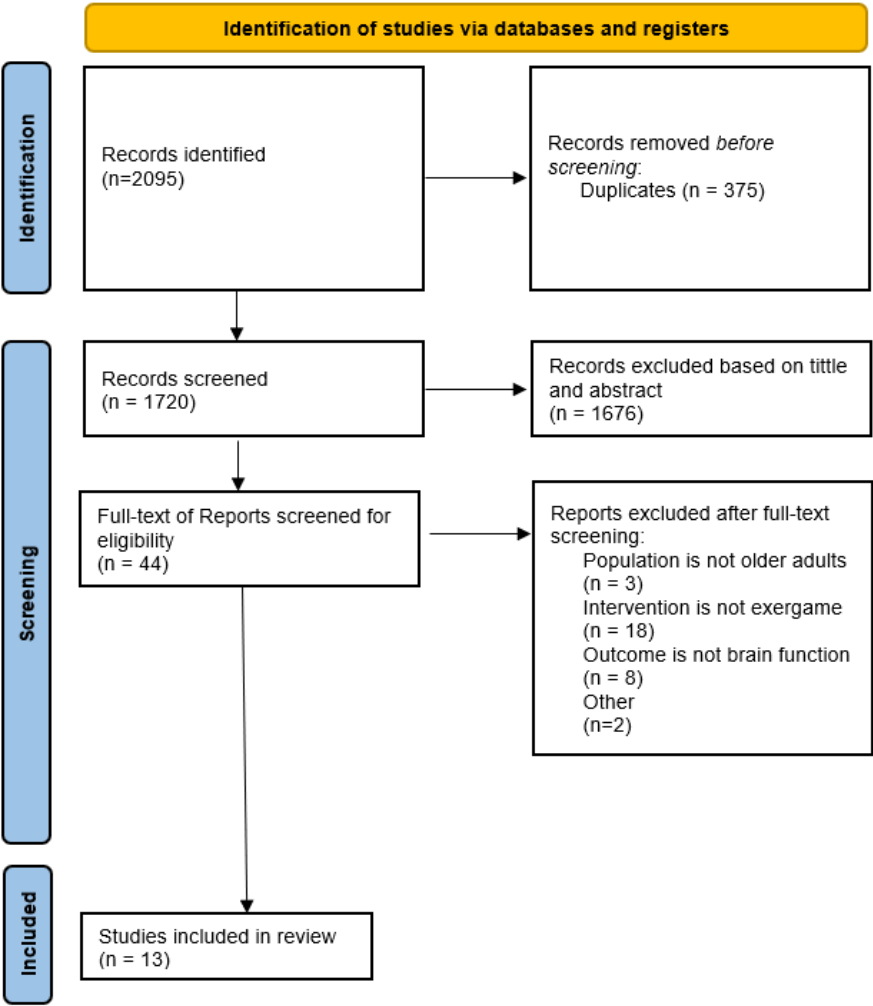


Figure 1. Flowchart of study selection.

3.2. Study Participants, Design and Interventions

Ten studies included healthy older adults (mean age = 72 years), while the remaining three involved participants with a neurocognitive disorder: Parkinson's disease (n=1; mean age = 66 years) and MCI (n=2; mean age 75 years). The studies were conducted worldwide, including in the USA, Europe, South America, and Asia. Most studies (n=10) utilized a randomized controlled approach, one was non-randomized and the remaining two were one-arm where all participants performed the EG intervention.

The interventions lasted between 4 to 24 weeks (mean duration = 10 weeks), averaging three sessions per week which lasted 20-100 minutes. Most of the studies (n=8) indicated that a moderate to vigorous intensity was applied for the tasks, while the others (n=5) did not mention intensity levels. The EG utilized two types of technology: console-based formats such as Wii, Microsoft Kinect, computer-based or TV-based (n=11), and digital environments implemented in virtual reality (VR) (n=2). The primary focus of EG was balance, stepping and sometimes sport-based movements (i.e., soccer, baseball...). Cycling was also leveraged, with added cognitive tasks on screen to enhance the gamified experience. Two studies involving Parkinson or MCI patients, used games that targeted upper-limb coordination.

3.3. Neural Correlates of Exergame Interventions

The effects were structured regarding the impact on: gray-matter volume, connectivity, and neuroplasticity biomarkers.

3.3.1. Healthy Older Adults

A first Magnetic Resonance Imaging (MRI) study with a voxel-based-morphometric analysis reported no gray-matter volume change after EG intervention on 31 participants (54). On the contrary, another study found an increase in the global volume of whole-brain gray matter as well as in superior parietal lobule and frontal gyrus. However, this latter study used less conservative statistical threshold (uncorrected for multiple comparisons) and did not include covariates such as sex or the total intracranial volume (55). Critically, both studies reported improved global cognition or executive functions (54,55).

Regarding neurofunctional results, a first study involving a justified sample size of 52 older adults and corrected statistical threshold showed low movement-related EEG features (event-related desynchronization (ERD), contingent negative variation (CNV)) during stepping tasks, particularly during gait initiation (56). EG-related brain changes were also found during cognitive tasks (attention, working memory) as outlined by low oxyhemoglobin in the PFC assessed by fNIRS (57). There were also reduced hemodynamic activity within PFC, sensory or motor cortices during motor tasks (balance, stepping or walking) with both fNIRS (58) and functional MRI (fMRI) methods (59). Furthermore, changes in characteristic EEG features of event related potentials (delayed latency of N2 and P3 after stimulus presentation) were also found in other studies, though with a limited number of participants (60,61). Noteworthy, each time where the above-mentioned functional markers were observed, the studies also reported enhanced performances during cognitive evaluations (56,58–61).

In addition to the previous macroscopic structural and functional changes, there was an increase in BDNF levels (62,63), cerebral blood flow (CBF) and cerebrospinal fluid (CSF)(55), suggestive of vascular resistance and increased neuroplasticity.

3.3.2. Older Adults with a Neurocognitive Disorder

An MRI study exhibited a correlation between increased volumes in the PFC, the anterior cingulate cortex and improved performance on cognitive evaluations in 8 MCI patients (64). Other changes in brain activity were reported during resting state period and included fMRI data of enhanced precuneus activity in Parkinson patients (65) but without direct comparison between classical brain network mapped during resting state (i.e., DMN, VIS, DAN, etc.). One study also

found EEG markers of enhanced resting-state activity in MCI patients, including decreases in parietal theta activity, the theta-to-beta ratio (TBR), and the delta-to-alpha ratio (DAR) in frontal and temporal lobes, along with increased alpha connectivity (66). However, the study primarily compared EG interventions to a conventional exercise group, and post-hoc statistical comparisons with a passive control group were not reported. In addition, BDNF levels also increased in one study involving MCI patients (64). Furthermore, one study revealed that the inclusion of challenging cognitive tasks in the EG would increase the benefits (enhanced activity in some regions during resting state) in MCI patients (64). Noteworthy all these neural correlates of EG interventions in older adults were accompanied by enhanced performances in evaluations of global cognition and executive functioning (64–66).

3.3.3. EG vs Conventional Interventions

The studies that compared EG interventions and conventional trainings yielded controversial results. Four studies with healthy older adults suggested that EG interventions and conventional trainings had the same effects on brain functions(56–58,60), whereas two studies suggested that EG interventions induced more benefits (BDNF level and theta activity) than conventional aerobic and resistance trainings (61,63). This superiority regarding the effects of EG was also found in another study with Parkinson patients with enhanced activity in the precuneus during resting state (65). Only one study, conducted in MCI patients, found more benefits (enhanced activity during resting state) in conventional trainings compare to EG interventions (66).

3.4. Quality Assessment

Among the 13 studies reviewed, 6 were identified as having a low risk of bias(54,56–58,61,65), three had a moderate risk of bias (59,63,64), and the remaining four were highly biased (55,60,62,66). The moderate risk of bias was primarily due to an unclear explanation of the randomization process. Regarding the four studies with a high risk of bias the reasons were the following: absence of randomization or calculation of a sample size with sufficient statistic power before the experiment, and one-arm studies lacking a control group.

Additionally, several neuroimaging studies faced methodological limitations that may hinder the interpretation and generalizability of their findings. In studies examining brain volume changes, appropriate morphometric analyses to avoid the risk of false positive results were not consistently applied. Furthermore, key task- or rest-related neural networks were often overlooked, with a focus placed instead on specific brain regions relevant to the task, which may have obscured a comprehensive understanding of the activity within classical neural networks assessed during resting-state paradigm

4. Discussion

The present review focused on the neural correlates of EG interventions in older adults with or without a neurocognitive disorder. The post-intervention effects identified in healthy older adults included increased brain volumes and changes in the activities of certain brain regions during the execution of both cognitive and motor tasks. In addition, EG interventions also benefited Parkinson and MCI patients with positive changes in the brain structure and particularly enhanced activities in certain brain regions during resting state. Moreover, these benefits were accompanied by neuroplastic changes with augmented BDNF levels or improved neurovascular coupling in both populations.

4.1. Neural Correlates of EG Interventions in Healthy Older Adults

A summary of the current knowledge can be found in Figure 2 which displays key neural correlates of EG interventions relevant for brain health in both healthy and pathological aging.

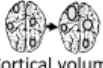
EG Interventions		Neural correlates of EG interventions		
		 Cortical volume	 Task-related networks	 Biomarkers
Healthy Older Adults	 VR-based : cycling	↑Whole gray matter, superior parietal lobule, and frontal <i>Sakhare et al., 2021</i>	No study	↑CBF and CSF <i>Shakare et al., 2021</i>
	 Console-based: balance, stepping, and coordination	Absence of effects <i>Adcock et al., 2020</i>	Changes in the activity of neural networks for: attention, working memory, balance, postural control, and gait initiation <i>Chuang et al., 2015; Eggenberger et al., 2016; Schättin et al., 2016; Kubica et al., 2019; Olyaei et al., 2021; Liao et al., 2021</i>	↑BDNF <i>Anderson Hanley et al., 2018; Montebianco Calvacante et al., 2021</i>
Parkinson or MCI patients	VR-based : Coordination	No study	Enhanced activities in parietal, frontal and temporal lobes during resting state <i>Yang et al., 2022</i>	No study
	 Console-based: balance, coordination and cycling	↑ prefrontal and anterior cingulate <i>Anderson Hanley et al., 2018</i>	Enhanced activity in the precuneus resting state <i>Hajebrahimi et al., 2022</i>	↑ BDNF <i>Anderson Hanley et al., 2018</i>

Figure 2. Summary of the current literature on the neural correlates of exergame (EG) interventions in older adults with or without cognitive disorders. The left column lists various types of EG interventions, and the technologies used to implement them. The right column details the post-intervention effects of EG. The rows represent the segregation of older adults according to their health status. MCI: Mild Cognitive Impairment; VR: virtual reality; CBF: Cerebral Blood Flow; CSF: Cerebrospinal Fluid; BDNF: Brain-derived Neurotrophic Factor.

Regarding healthy older adults, several findings on the effects of EG interventions are in line with the results of the previous review studies conducted on the topic: changes of activity in brain regions during cognitive tasks (e.g., attention, working memory), and elevated levels of BDNF (46–48).

Furthermore, restricting the search strategy exclusively to studies that investigated neural correlates proved beneficial, as we identified three recent studies involving healthy older adults that were not included in previous review studies. One such study found after the EG intervention, increased brain volumes including in parietal and frontal regions in MRI scans, which is a new finding (55). The absence of the effects of EG intervention on brain volume has been previously explained by the light intensity of intervention (54). This might align with the findings of Sakhare et al. (55), whose intervention involved moderate to vigorous intensity. Nevertheless, it is important to note that these findings remain preliminary with some methodological concerns. Indeed, the study employed a one-arm design without limiting the risk of inflation for Type I error or accounting for covariables such as sex and total brain volume. More conservative neuroimaging studies are required to confirm this result. Noteworthy, they further identified new insights into the effects of EG regarding neuroplastic changes including increased CBF and CSF dynamics (55) which align with the known positive effects of exercise on cardiovascular fitness (67) and the clearance and dynamics of CSF(68,69).

Moreover, other studies reported in the present review also suggest that compared to baseline values, there was a decrease in hemodynamic activity in brain areas responsible for postural control (59), and reduced motor-related EEG features (ERD and CNV) during gait initiation (56), after the intervention. One can hypothesize that this could be a result of efficient processing of neural networks during the execution of these tasks. This would be a consequence of EG interventions that benefited motor functions by improving their cognitive control (measured here by changes in neural networks). Indeed, it is well documented that EG involves several cognitive-motor challenges (34), thereby enhancing the need for supplementary cognitive control of motor tasks. Thus, increases in attentional

control required during these complex situations are thought to benefit task-related neural networks and to enhance performance (70–72). Nevertheless, as the effects of EG interventions on physical abilities are not widely documented (17,34), it remains to be confirmed whether improvements in motor functions following EG interventions are linked to changes in well identified neural networks.

4.2. Neural Correlates of EG Interventions in Older Adults with a Neurocognitive Disorder

Extending the population to include older adults with neurocognitive disorders revealed new and interesting findings of the neural correlates of EG interventions in MCI and Parkinson patients. A study found increased volumes in prefrontal and anterior cingulate cortices following EG interventions in MCI patients (64). This is particularly interesting as it suggests that EG interventions lead to increased volume in regions crucial for cognitive functions such as memory, attention, and executive functions, which are especially relevant for patients with this neurocognitive disorder. Consequently, such interventions could potentially slow the reduction of brain volume in these areas, leading to functional benefits. However, this study employs correlational methods and analyzed the data of only 8 participants exposing some serious statistical limits. Since one may recognize the challenges of patient recruitment, future studies using statistical methods tailored for small sample sizes could offer valuable insights (73).

Some other authors further reported changes in post-intervention resting-state activity in some brain regions [decreases in parietal theta, TBR and DAR, increase in alpha (66) and increased activity in the precuneus cortex (65)] compared to baseline values, in Parkinson patients. These findings on resting-state connectivity are interesting as the neuroimaging indicators reported are closely associated with networks such as the DMN (74–76) which is known to be enhanced by PA (37,38). However, there remain certain limitations regarding the neuroimaging indicator reported, including the lack of investigation into specific networks or weak effect sizes in the results. In addition, it remains to be determined whether there exists a direct relationship between EG interventions and improvements in brain functional connectivity during resting state. This information is even more relevant since most neurocognitive disorders in aging are progressive, with each stage of the disease affecting functional brain connectivity differently (77,78). Therefore, future studies are warranted to identify which specific aspects of functional connectivity are improved by EG and to apply the intervention at the most appropriate stage of the disease.

4.3. Moderators of the Effects of EG Interventions on Brain Functions

Interestingly, the technology used to perform the EG appears to target different neural correlates (Figure 2). One study using VR-based EG interventions improved cortical volume (55) in healthy older adults. Given that the immersive nature of VR technologies has been shown to significantly impact brain activity (79), it can be assumed that VR-based EG interventions may engage different neural networks compared to console-based EG. Nevertheless, with the current state of knowledge and the design of studies included in this review, it is speculative to conclude about the specific effects of different technologies on brain functions. Given the significant potential of VR-based or more generally XR-based EG in engaging older adults in PA, further research is needed to clarify its specific benefits.

Furthermore, only a few studies in the present review have analyzed how specific features impact the effects of EG interventions on the brain. Most studies reported moderate intensity levels of PA for EG, suggesting that this intensity is sufficient to induce benefits. However, none of the studies considered the intensity as a variable to examine its impact on the effects of EG. One study showed that incorporating complex cognitive tasks positively influence brain outcomes (increased brain volume; (64)). Since additional cognitive tasks require increased executive control, it might be possible that the recruitment of certain networks during the EG execution correlates with post-intervention benefits. To confirm this hypothesis, it is necessary to determine which specific networks are activated during this addition of more cognitive tasks during EG execution. However, to achieve this, it is crucial to understand how EG execution alters brain in the first place. Our search in the present review indicates that this information is still missing from the existing literature.

4.4. Real-Time Neural Responses to the Execution of EG

While the post-intervention effects of EG interventions on brain functions have been well described in the studies included in this review, evidence of how EG modifies brain functions during gameplay is still lacking. This information is crucial for deepening our understanding of the benefits of the efficiency of neural networks by clarifying how executing EG contributes to strengthening the recruitment of specialized networks (80). In addition, it may also shed light on the strategies that older adults employ to adapt to complex situations in the EG, particularly whether they rely on compensatory mechanisms as suggested by the CRUNCH hypothesis (50,51). During our literature search, we found two studies that have examined how the brain behave during the execution of the EG. We could not include these studies in the present review as they did not meet the eligibility criteria. However, we discussed below their intriguing insights which deserve to be confirmed in future studies.

The first study conducted in healthy older adults found that engaging in balance and stepping EG triggered increased theta activity in the frontal region (81). Authors attributed this to the heightened attentional demand during the EG, as frontal theta activity is strongly associated with attentional control(82–84). This study also observed a decrease in alpha-activity in the parietal lobe, which also aligns with increase attentional demand in previous findings involving a dual-task training among older adults (85). In the second study involving Parkinson patients, there was an increase in overall beta activity, as well as temporal and frontal alpha activity during the execution of a VR-based EG with upper-limb coordination (86). This result supports the previous one in healthy older adults (81) since the role of beta activity in attentional process is well studied (87). However, it was unexpected that EG would trigger a rise in alpha activity, which is known to occur in relaxation states. The authors speculated that the immersive nature of VR-based EG, which minimizes external environmental interference, might enhance this relaxation and thus memory capacity as previously suggested (88). This is noteworthy as VR-based EGs, or more generally XR-based, have the potential to overcome environmental barriers and engage more people in PA (15–18). Nevertheless, it is important to consider that Munoz et al.'s study (86) was conducted in Parkinson patients and include only upper-limb coordination movements in the EG. Thus, it remains to be determined whether baseline health status or other types of EG can influence the observed effects of immersive VR technology on brain functions. Overall, these two studies present evidence supporting the idea that while executing an EG there could be an increase in attentional demand and memory capacity in older adults which can be measured by EEG features (81,86)

Interestingly, it is plausible that the benefits of EG interventions on neural networks might be the result of neuroplastic changes (e.g., synaptogenesis, potentiation) due to the repetitive recruitment of such networks during the execution of the EG (80). This hypothesis is particularly enlightening given the fact that reduced frontal theta activity was one of the post-intervention effects of EG interventions (58,61) and that the execution of a similar EG triggered an increase in the same frontal theta activity (81). Thus, training to recruit specialized networks during the EG execution might be one of the reasons of the benefits on neural networks in related tasks measured here with frontal theta activity. Nevertheless, this hypothesis remains to be confirmed as brain activity during EG was delineated at the lobe level (81,86) and thus need to be investigated with neuroimaging techniques with higher spatial resolution. The fMRI stands out as a strong option but is limited to the application of motor imagery to perform an EG as participants need to limit movements in the MRI scanner. Conversely, EEG could offer valuable insights as it can be applied during motor tasks and allows for analyses such as signal coherence or phase synchronization-based measures, which can serve as proxies for MRI brain functional connectivity measures (89–91).

Moreover, the two studies that investigated how EG modifies brain functions (81,86) provided averaged brain activity across the entire EG session without specific information about each stage of the games. Since EG involves complex decision-making processes (6), different stages of the game may differentially impact neural networks. Thus, some stages might be more cognitively demanding or more effective in recruiting and strengthening neural networks, than others. This information is crucial for optimizing the potential of EG in enhancing neural network efficiency.

4.5. Future Directions

Considering the present findings, we propose a series of experiments to better understand the underlying neurobiology of an EG, which has shown clinical benefits and is well accepted by older adults. First, it is crucial to investigate how EG modifies brain functions by examining attentional control networks and other specialized networks throughout different stages of the game and according to the intensity and the type of technology used. Additionally, it could be valuable to investigate the emotional states and motivation of participants during each stage of the EG by leveraging well-described EEG features associated with relaxation or focus (92,93). Identifying such markers could help boost positive emotions, encouraging more older adults to engage in EG, as its primary goal is to use the gamified elements to improve adherence (6). This approach will allow us to optimize the game design, enhancing stages that are most likely to induce the most neural efficiency or positive emotions. Comparing older adults to younger counterparts could help determine if certain effects are more pronounced or specific to older adults. At this stage, an optimized game design of EG can be developed leveraging neural correlates that are the most positively impacted during the EG execution. Following this, post-intervention effects should be examined with neuroimaging techniques with high spatiotemporal resolution to identify specific changes (e.g., functional connectivity, brain volume) that can be indicative of certain stages of neurocognitive disorders or other age-related diseases. This will aid in designing appropriate interventions for patients at various stages of these conditions. EEG technique can be applied in this study of the brain activity during mobility, as it offers a reliable solution to detect age-related brain changes that are relevant to various types of neurocognitive disorders (94).

5. Conclusion

The present systematic review aimed to deepen our understanding of the neural correlates of EG interventions in older adults, both with and without neurocognitive disorders. On average, moderate-intensity EG interventions led to increased brain volumes in crucial areas for brain health, such as the PFC, and changes in neural networks responsible for postural control and gait initiation in healthy older adults. Notably, individuals with MCI and Parkinson's disease also experienced similar benefits from EG interventions, showing increased brain volume and improved neural networks, particularly in resting activity networks. To be fully validated, some of these findings, especially those related to changes in brain structure or functional networks, require further investigations in higher-quality studies. Moreover, the structural and functional changes in brain functions were further supported by evidence on markers of enhanced neuroplasticity. The present findings highlight the potential of EG interventions to improve brain functions and suggest that carefully considering these effects can help maximize the benefits.

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