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SURVEY ARTICLE

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The Design of Visual, Cognitive, and Physical Modalities in VR Games for Older Adults: A Systematic Review

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ABSTRACT
Simultaneous declines in dynamic visual, cognitive and physical modalities are common symptoms of aging which impact synergistically on the daily lives of older adults. VR game-based interventions offer promising alternatives for combining multimodalities (i.e., dynamic visual acuity, cognitive, and physical). This paper presents the first review of two aspects in immersive VR games for older adults using the PRISMA method: (1) psychology-based design mechanisms of visual, cognitive, and physical modalities; (2) experimental designs and intervention effects on cognitive and physical functions. Thirteen studies were identified—six involving healthy older adults and seven with mild cognitive impairment. Our findings revealed diverse game designs, reflecting a broad spectrum of features across visual, cognitive, and physical modalities, along with varying effects observed in cognitive and physical improvement. This study provides a comprehensive understanding of multimodal game design characteristics and intervention effects of VR games for older adults in the fields of psychology and human-computer interaction.

KEYWORDS
VR game; older adults; cognitive ability; physical ability; dynamic visual acuity

1. Introduction

The rapidly aging global population presents significant challenges and opportunities for healthcare innovation, particularly in the development of interventions that can enhance the quality of life for older adults. As this demographic change accelerates, incidences of decline in modalities of dynamic visual functions, for example, dynamic visual acuity (DVA) (Zhang et al., 2008), cognitive ability, for example, cognitive control/multitasking (Royall et al., 2004), and physical function, for example, balance (Nakano et al., 2014), are also increasing. The risk of disease and untimely death is also increasing due to the fact that these functions are closely linked. They also significantly impact independence in performing basic daily living tasks and in maintaining quality of life (Cahn-Weiner et al., 2000). For example, DVA plays a key role in maintaining balance and preventing falls when older adults are walking. Considering the potential and synergistic impacts available by integrating DVA, cognitive and physical functions to assist older adults, it is beneficial to consider the interplay among these three modalities when designing health interventions for older adults, especially to promote healthy aging (e.g., cognitive/physical enhancement). Traditional methods of engaging this population in cognitive and physical exercises have been effective to some extent but they often present challenges such as low adherence, accessibility issues, and lack of engaging features.

Virtual reality promises to address these challenges as it is more conducive to multimodality synergism as well (i.e., DVA, cognitive and physical functions). By immersing players in a 3D interactive environment, VR games have the potential to transform traditional health interventions into engaging and enjoyable activities, potentially increasing participation and effectiveness. They also offer controlled settings where these activities can be tailored to perform tailored and targeted visual, cognitive, and physical exercises offering a holistic approach to maintaining and enhancing important functional abilities of older adults. This multifaceted stimulation is hypothesized to be more effective than cognitive or physical interventions treated separately (Hötting & Röder, 2013), potentially leading to greater improvements in cognitive function, physical health, and overall well-being. Thus, intervention programs leveraging immersive VR games that synergize DVA, cognitive, and physical modalities offer promising avenues for implementing long-term engagement for older adults.

Thus, understanding the multimodal design mechanisms and effects of VR games can greatly advance the design of VR games specifically suited to the characteristics of older adults.

1.1. Understanding DVA, cognitive and physical function in the aging of older adults

DVA, cognitive ability and physical function deteriorate gradually during the normal aging process (Nakano et al.,

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2014; Royall et al., 2004; Zhang et al., 2008). DVA is defined as the ability to identify the details in visual targets when there are relative movements between subjects and objects (Burg & Hulbert, 1961). This includes two types of eye-movement: one is kinetic visual acuity (KVA, the recognition of approaching and receding objects); the other is dynamic visual acuity, the recognition of an object moving in the horizontal direction. DVA plays an important role in some environments in daily life where rapid body changes need to be made, such as walking, playing sports, and driving a motor vehicle (Hoffman et al., 1981; Nagahama, 1998; Uchida et al., 2013). Studies have shown a link between car accidents and low DVA scores, especially among older adults (Henderson & Burg, 1973).

Cognitive ability, which can be classified into several specialized cognitive domains such as processing speed, attention, memory, and executive control, is another important factor in healthy aging (Harada et al., 2013). Executive function, also known as executive control or cognitive control, is defined by a set of neural processes that allow us to interact with complex environments in a goal-directed manner (Diamond, 2013). These control processes are often challenged when humans attempt to simultaneously accomplish multiple goals (i.e., multitasking), resulting in interference due to fundamental limitations in information processing (Allen et al., 2014). Evidently, multitasking behavior is ubiquitous in daily life these days (Foehr, 2006). A large body of evidence suggests that many older adults experience multitasking difficulties and cognitive control deficits when performing multiple tasks simultaneously, whether they are simple (e.g., making arbitrary sensory-motor decisions) or complex (e.g., observing and responding to pedestrian signals while talking to a friend, driving, and making phone calls), even when the competing tasks do not overlap in sensory input or motor output modalities (Allen et al., 2014; Stuss & Knight, 2013).

Physical function decline such as balance ability makes older adults easily fatigued and weak, increasing the risk of falls. The loss of functions which include DVA, cognitive ability, and physical function, may lead to a sharp decline in the health of older adults, further exacerbating an inactive lifestyle and impacting their quality of life and independence (Coyle et al., 2017; Hedden & Gabrieli, 2004; Lee et al., 2005).

The relationships between DVA, cognitive ability, and physical function modalities is complex and interrelated, synergistically impacting daily living and the quality of life in older adults (Baydan et al., 2020; Cahn-Weiner et al., 2000; Cheong et al., 2013; Elyashiv et al., 2014; Holtzer et al., 2007; Rizzo et al., 2000; Yogev-Seligmann et al., 2008).

1.2. Current approaches to improving cognitive and physical functions and DVA

To deal with these problems, traditional interventions have focused on a single modality, either cognitive or physical (i.e., cognitive or physical training) or on two modalities (i.e., a combination of cognitive and physical). Traditional cognitive training traditionally involves standardized cognitive psychological tasks or paradigms that optimize specific cognitive functions conducted on a PC (Kueider et al., 2012), for example, the Go/No-Go task and the multitasking paradigm. Included among the physical training types used to improve cognition are resistance training (Cassilhas et al., 2007), balance training (Liu-Ambrose et al., 2008), aerobic training (Chapman et al., 2013) and walking (Sink et al., 2015). As well as considering physical and cognitive training separately, some studies have also shown that the combination of cognitive and physical training may lead to greater functional benefits than any single focus training approach (Lauenroth et al., 2016; Tait et al., 2017; Zhu et al., 2016); this is due to physical and cognitive training playing distinct but complementary roles in brain plasticity. Bamidis et al. (2015) found that based on the individual beneficial effects of physical and cognitive training, a combined (synergizing) approach can overcome the shortcomings of the limited generalized effects on the global cognition of a single modality training. It has been suggested that the enhanced neuronal metabolic processes induced by physical activity can only be effectively utilized when the brain is simultaneously challenged by cognitive demands (Bamidis et al., 2014; Oswald et al., 2006). On the other hand, single mode, either cognitive training or physical training, mostly only focuses on cognitive or physical outcomes respectively, while synergized training can achieve multiple outcomes for both cognitive and physical modes. This is also more beneficial for older adults who perform a large number of cognitive-physical multi-modal tasks in daily activities (e.g., cooking).

Although much evidence strongly supports the positive effects of traditional cognitive and physical training in preventing cognitive decline in healthy older adults (Ball et al., 2002; Bherer et al., 2008; Borella et al., 2010; Heo, 2010; Liu-Ambrose et al., 2010; Mahncke et al., 2006; Martin et al., 2011), there are issues with traditional approaches (Anguera et al., 2012; Anguera & Gazzaley, 2015; Persson et al., 2007). Intense demand and a lot of repetition can lead to boredom and a lack of enjoyment and engagement (Anguera & Gazzaley, 2015). Overtraining can cause cognitive fatigue and reduced motivation (Anguera et al., 2012; Anguera & Gazzaley, 2015; Persson et al., 2007). Consequently, this may limit the effectiveness of the training and reduce adherence to the program, making it hard for older adults to achieve satisfactory results. One way to make traditional designs more accessible and engaging is by incorporating gameplay into the environment; this could be called "Digital Medicine." In general, video games are designed to be enjoyable and engaging. The use of carefully designed game mechanisms can make therapies both challenging and fun resulting in sustained player engagement. One influential tailored laboratory video game called *NeuroRacer* (Anguera et al., 2013) combines the Go/No-Go task and multitasking in a game environment using a game-pad. This game asks players to make traffic signal judgments while driving a car according to a given route.

The most popular method of training dynamic visual acuity is to read the letters written on outside signs and telephone poles from the train window or to read the numbers or letters written on a thrown ball to train kinetic visual acuity. Two apps that support this kind of training are *Shinsoku* (Labo, 2024) and *Kinetic Visual Acuity* (Kinetic Visual Acuity Lite app. (n.d.)). Studies on improving dynamic vision functions have mostly focused on young people or athletes, and have found that DVA can be improved by various forms of training (Long & Riggs, 1991; Long & Rourke, 1989; Maeda, 1998; Maeda & Tsuruhara, 1998). Few studies have aimed to improve the dynamic visual function of older adults. One study (Liu, 2021), *Athlevision* (SPEESION, 2024), used DVA training software to train visual functions. This study compared younger people (65–76 years) and older people (77–88 years). The results showed that DVA, KVA and eye movement in the younger elderly adults aged 65–76 improved significantly after the 12-week dynamic visual acuity program.

While current approaches are designed to account for visual or cognitive or physical modalities or a combination of cognitive and physical modalities, no empirical studies combine all three modalities. By overlooking the DVA modality and the potential of synergizing vision, cognition and physical modalities, greater efficiency, simplicity and efficacy potentials are likely being missed.

1.3. Unique values of VR to health intervention

VR-based intervention tools offer a promising alternative that can combine multi-sensory affordances and modalities. Immersive VR (IVR) environments allow simultaneous modality stimulation and feedback, for example, from visual, auditory, tactile, motor and proprioceptive systems, thereby (1) providing a strong sensory immersion and a sense of presence and supporting natural sensorimotor contingencies for perception. (2) IVR is able to reproduce the sensory characteristics of the real world and provide the opportunity to sample cognitive functional integrity in an environment which is representative of everyday life.

These two characteristics make the unique affordances of IVR games available to health interventions. First, and most importantly, strong sensory immersion and a sense of presence might contribute toward greater cognitive improvement and stimulate neuroplasticity for older adults (Anderson-Hanley et al., 2012; Gamito et al., 2017; Huang, 2020; Isbely Montana et al., 2019; Shelstad et al., 2017; Teo et al., 2016). Immersive experiences can foster attention to mental representations of virtual spaces, enhancing brain activity linked to cognition (Kober et al., 2012), which might create an efficient platform for cognitive training, where older adult players can fully engage in the cognitive tasks of a game. VR has been shown to outperform traditional cognitive training, improving executive function and overall cognitive health in older adults (Anderson-Hanley et al., 2012; Pedroli et al., 2019). Secondly, IVR games could promote long-term engagement and the sustaining of older adults in health interventions since they can deliver better game experiences (Shelstad et al., 2017), higher levels of motivation, and positive emotions (Tan et al., 2015); players can more fully engage with VR than non-VR interventions (García-Betances et al., 2015; Laver et al., 2012). Third, IVR mimics the real environment, that is, IVR interventions do not happen in a vacuum or cold clinical space. Cognitive stimulation in VR can range from simple memory games to complex problem-solving scenarios that mimic real-world activities. Such stimulation can also liberate users from the limitations of the physical world, especially for older adults facing diminished independence, enabling their entire bodies to interact naturally and seamlessly with their surroundings, maximizing the benefits that older people get from being in touch with a virtual but near-real world (Appel et al., 2019). Fourth, older adults in "real life" might be put in dangerous situations due to their vulnerabilities and physical abilities, but they can be relatively safe in a VR environment (Bauer & Andringa, 2020).

1.4. The aim of the systematic review

The previous systematic reviews encompass a broad range of VR game designs, including both immersive setups (e.g., HMD-based) and non-immersive setups (e.g., Kinect, computer, and Wii), single cognitive modalities (i.e., sufficient and targeted cognitive stimulation but lack of physical stimulation, for example, sedentary activities involving controller operation), and single physical modalities (i.e., abundant physical stimulation but often lacking supplementary cognitive engagement beyond reactive responses to physical stimuli, for example, simply observing scenery while biking in VR). Although certain studies include designs that combine both cognitive and physical modalities, these are often mixed with other types of game design (e.g., a single VR cognitive/physical system) within systematic reviews. VR systems that exclusively target a combination of cognition and physical modalities have not been specifically investigated in the systematic review studies. In addition, no review has investigated design characteristics of dynamic visual modality with this kind of VR system. As a result, the design characteristics and effects of VR projects exclusively targeting combinations of cognitive and physical stimulation remain unspecified or unknown.

This systematic review aims to investigate the following two aspects: (1) Game design: the psychology-based design mechanisms of visual, cognitive, and physical modalities in immersive cognitive-physical VR games (IVR games) for older adults with and without mild cognitive impairment (MCI); additionally, other game design considerations are also investigated, for example, game difficulty. (2) The experimental design characteristics of IVR game-based intervention and its intervention effects on the cognitive and physical functions among older adults with and without MCI.

1.5. The contribution of the systematic review

The contributions of our study to the fields of HCI and aging research are shown below:

- This paper is the first of its kind in this specific field, offering a unique motivational perspective on multimodality in VR games for older adults. It highlights the scarcity of relevant research, particularly noting that only two studies combining DVA with other modalities are currently available.

- By identifying the potential synergistic impacts of various modalities in IVR games, our study provides new and broader perspectives for future research. This insight is crucial for developing more effective interventions that combine multiple sensory and cognitive elements.
- We systematically review the experimental design characteristics of IVR game interventions and their effects on cognitive and physical functions among older adults. This comprehensive analysis synthesizes existing research, demonstrating the potential benefits of such interventions and offering crucial insights for further studies in this realm.
- The findings of our review offer insights which can inform the design of more engaging and effective IVR experiences in both HCI and research regarding aging.

2. Method

Our study methodology adheres to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.

2.1. Search strategy

This systematic study covered the period from January 2018 to 31 March 2024 and involved five key databases: PubMed, IEEE Xplore, ACM Digital Library, Scopus, and Web of Science. The following Boolean string was used: ("Older Adults" OR "Seniors" OR "Elderly") AND ("Immersive virtual reality" OR "Immersive VR" OR "Virtual Reality" OR "VR") AND ("Exergaming" OR "Exergame" OR "Game" OR "Motion game") AND ("Cognitive" OR "Cognitive Stimulation" OR "Cognitive Stimulus" OR "Cognitive Enhancement" OR "Cognitive Training") AND ("Physical" OR "Exercise" OR "Motor").

2.2. Eligibility and exclusion criteria

Studies were included if they met the following criteria:

1. immersive VR games (i.e., use HMD) that simultaneously integrate cognitive exercises and physical movement stimuli;
2. the studies focused on systems specifically designed for or evaluated with healthy older adults or older adults with MCI, and the average age of participants is greater than or equal to 60 years older;
3. the studies involved IVR game training that comprised repeated engagement in the combination of cognitive and physical stimulations for at least 20 min;
4. the studies investigated the impact of training on one or more measures of cognitive, physical, or visual functions, and the eligible outcomes included using any validated measures, including computerized tests;
5. studies that report the results of a pretest and post-test from the same measures and outcomes for the training group or both in the training group and the control group;
6. the study reports the results of a pretest and post-test of the same measure outcomes for the training group only or both in the training group and the control group;

Exclusions (we excluded studies that did not meet the inclusion criteria):

1. studies using non-HMD VR setups (i.e., non-immersive VR) were excluded;
2. studies without evaluation and reported results related to cognitive, physical or visual functions, such as design-focused demonstration papers or theoretical research;
3. IVR games that involved a single cognitive modality only (i.e., sufficient and targeted cognitive stimulation but lack of physical stimulation, for example, sedentary activities involving controller operation) or single physical modalities only (i.e., abundant physical stimulation but lacking supplementary cognitive engagement beyond reactive responses to physical stimuli, for example, simply observing scenery while biking in VR);
4. participants with a current diagnosis of Alzheimer's disease, dementia, vascular dementia, stroke, head injury, depression, or other neurological disorders;
5. non-experimental publications, such as reviews, perspectives, meta-analyses, dissertations, abstracts, or opinions;
6. articles published in languages other than English.

2.3. Quality assessment

We used the Physiotherapy Evidence Database (PEDro) scale. This scale contains 11 items that evaluate various aspects of study design, conduct, and reporting. Each item is scored as either present (1 point) or absent (0 points). A score between 9 and 11 points indicates good methodological quality, a score between 6 and 8 indicates medium methodological quality, and a score of less than 6 points indicates low methodological quality.

2.4. Data extraction

All relevant data were combined in a single Excel table (Microsoft 365). For each study, the following basic information was retrieved: the year of publication, the country in which the study took place, and the participants' demographics. According to the purpose of this review and the key aspects that need to be considered generally when designing IVR games, the following two parts of data were extracted.

The first part focused on game design characteristics based on the perspective of multiple modalities, including:

1. game theme.

2. the design mechanisms of the visual, cognitive, and physical modalities.
   Regarding the visual modality, the definition of DVA refers to the ability to identify the details of visual targets when there are relative movements between subjects and objects. This includes two types of eye-movement: one is kinetic visual acuity (KVA, the sustained recognition of approaching and receding objects), the other is dynamic visual acuity (the sustained recognition of an object moving in the horizontal direction). Therefore, we classified the game's visual design into two types based on whether it incorporated visual stimuli with continuous movement or not. The first type, dynamic visual stimulation, involves visual stimuli that feature continuous movement, requiring the user to make rapid eye movements across a large field of view (Wood & Owsley, 2014) after the visual stimulus moves or appears horizontally. The second type, general visual stimulation, involves visual stimuli without continuous movement, where no rapid eye movements are required after the stimulus appears.
   Regarding the cognitive modality, according to traditional cognitive training design approaches (usually involving standardized cognitive psychological tasks or paradigms that optimize specific cognitive functions), we extracted the specific cognitive activation paradigm or task in the gameplay (if incorporated).
   Regarding the physical modality, according to current exergame designs and traditional physical training studies, the division of physical characteristics into the following three aspects can help us better understand the physical modality of IVR game designs: game posture (i.e., the game asked older participants to play in the sitting or standing postures), body part exercised (i.e., which parts of the body are exercised during gameplay, for example, upper body, lower body, full body), type of exercise (i.e., what type of exercise does the physical movement in IVR games belong to, e.g., aerobic, strength, balance training, Tai Chi, and walking).
3. **setting of game difficulty**: whether IVR games set up difficulty mechanisms? If so, how did these difficulties change during long-term IVR game-based intervention, for example, manual difficulty adjustment or dynamic difficulty adjustment.
4. **interactive mode**: how older participants interact with games during gameplay, and whether some complex operations are required.
5. **brand of HMD, controllers, and sensory devices used** (if applicable).

The second part is for experiment design characteristics and effectiveness, including:

(1) group settings; (2) duration of exposure in immersive VR environments; (3) cognitive and physical outcome measures; (4) intervention effectiveness for the main target functions.

3. Results

3.1. Study selection and characteristics

As shown in Figure 1 of the process of study identification, a total of 504 papers were initially identified, with 327 remaining after removing duplicates. Following title and abstract screening, 223 papers were excluded, and 104 papers were further selected for full-text screening. After that and after screening for eligibility, 13 papers were ultimately included in our review studies and they were reported. Among them, one study (Basharat et al., 2023) included both healthy older adults and those with MCI which was classified as a study with older adult participants with MCI. Thus, 6 studies (Campo-Prieto et al., 2022; Du et al., 2024; Huang, 2020; Li, Salehzadeh Niksirat, et al., 2020; Liepa et al., 2022; Sakhare et al., 2022) used healthy older adults as participants, and 7 studies (Baldimtsi et al., 2023; Basharat et al., 2023; Kwan et al., 2021; Liao, Chen, et al., 2019; Liao, Tseng, et al., 2019; Thapa et al., 2020; Yang et al., 2022) used older adults with MCI as participants in this review study.

The study characteristics of the included studies are summarized in Figures 2–10. The samples composition of the 13 studies varied from 12 to 58 participants which were either divided between control group and intervention group, or intervention group only. The mean age of the participants ranged from 61.93 to 85.08 years. For some important information (e.g., posture during gameplay and game difficulty mechanism) that was not clearly stated in the three articles, we sent emails to ask the authors for missing details.

3.2. Quality assessment

Figure 2 reports levels of methodological quality for the studies that used, respectively, VR games for healthy older adults and older adults with MCI. The range of the quality assessment score was 4-9.

3.3. IVR game modality design characteristics for healthy older adults

We identified and categorized game design characteristics in the selected papers, as shown in Figure 3.

3.3.1. Game theme

Among the studies reviewed, two utilized commercially available games, specifically boxing in a virtual gym (Box VR (Campo-Prieto et al., 2022)) and VR Fruit Ninja (Huang, 2020). The remaining four studies (Du et al., 2024; Li, Salehzadeh Niksirat, et al., 2020; Liepa et al., 2022; Sakhare et al., 2022) employed customized games developed in laboratory settings. Three of these studies utilized cartoon-style graphics, while one study employed a neon aesthetic with electronica music themes (LightSword (Du et al., 2024)). Two studies adapted off-the-shelf commercial gameplay modes, integrating multitasking and cognitive-physical dual-task paradigms into Whack-a-Mole (VR Whack-a-Mole

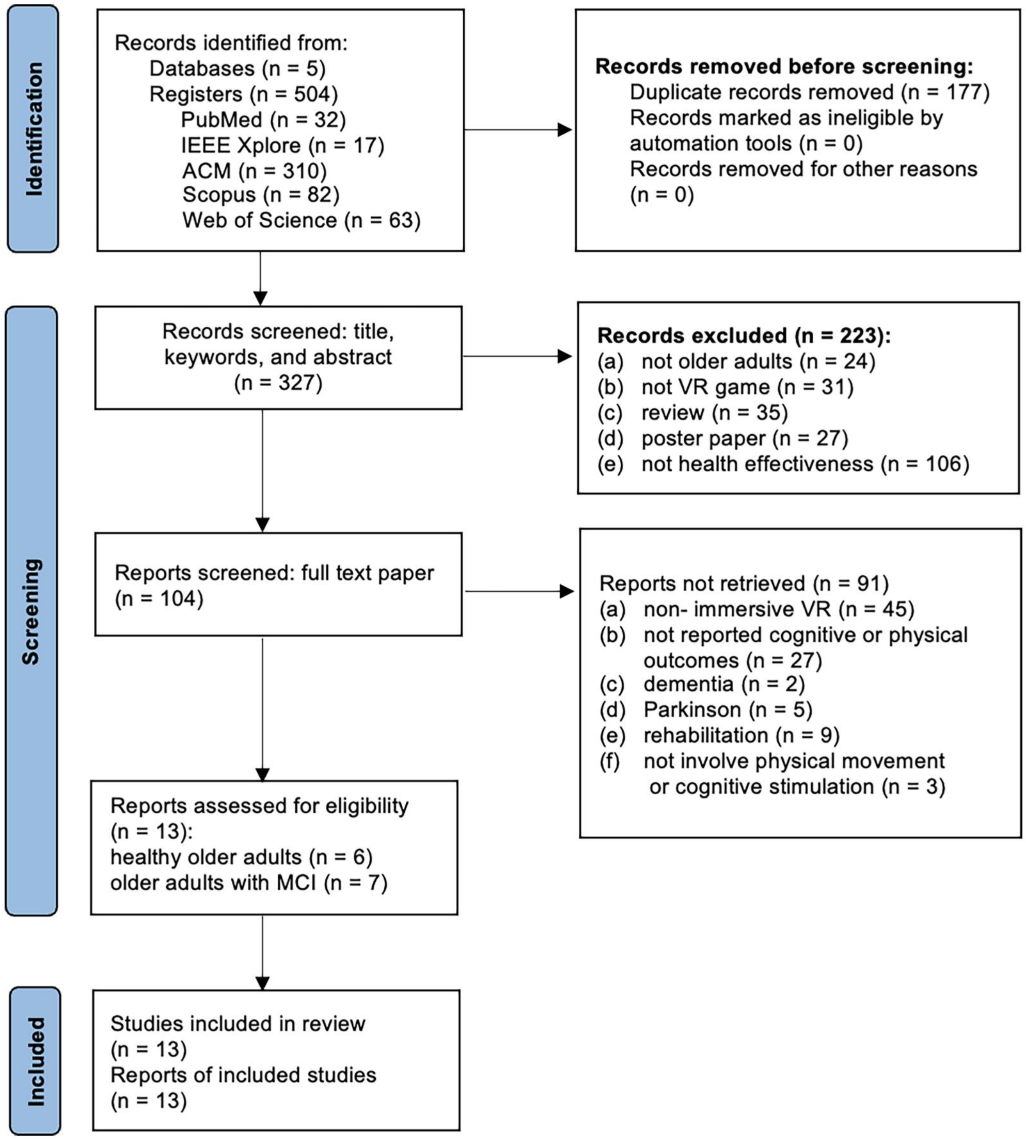


Figure 1. PRISMA diagram of study selection process.

(Li, Salehzadeh Niksirat, et al., 2020)), and incorporating the Stroop task into a rhythmic music game named Best Saber, requiring older adults to hit blocks (LightSword (Du et al., 2024)). One game (Falling diamonds (Liepa et al., 2022)) facilitated trunk movement for older participants using a balance board in both sitting and standing postures, while another involved cycling on a custom-built stationary exercise bike while completing cognitive tasks (Sakhare et al., 2022).

3.3.2. Game design mechanism of three modalities

3.3.2.1. Visual modality. Only 2 studies (Box VR (Campo-Prieto et al., 2022) and LightSword (Du et al., 2024)) incorporated dynamic visual stimulation (i.e., visual stimuli featuring continuous movement), however, these studies solely focused on KVA stimuli, and did not explore another type of dynamic visual acuity. In gameplay, this typically entails tasks where players are required to identify moving game stimuli objects approaching from a distance and simultaneously perceive and comprehend various features of the moving objects. For instance, identifying the direction of an arrow on a ball or discerning the color of blocks as they fly towards the player from a distance. Designs that respond to visual stimuli with continuous movement also require motion perception. Meanwhile, players need to synchronize visual information with hand movements to respond (e.g., hit a ball) accurately which also involves hand-eye coordination. Four studies (Huang, 2020; Li, Salehzadeh Niksirat, et al., 2020; Liepa et al., 2022; Sakhare et al., 2022) involved general visual stimuli (i.e., visual stimuli without continuous movement), this usually involves visual attention, including spatial attention, sustained attention, selective attention, and the allocation of attention. For example, in VR Fruit Ninja (Huang, 2020), fruits flew out from different directions and positions (spatial attention), and players needed to focus their attention (sustained attention) on the fruit moving on the screen in order to quickly judge and cut it (selective attention). Sometimes multiple fruits appear on the screen at the same time, and players need to effectively allocate their

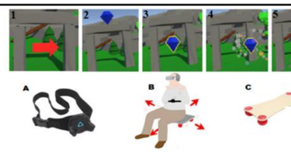
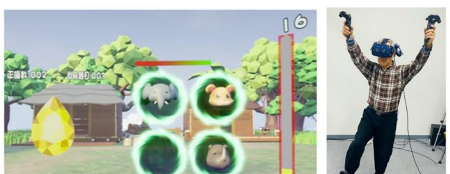
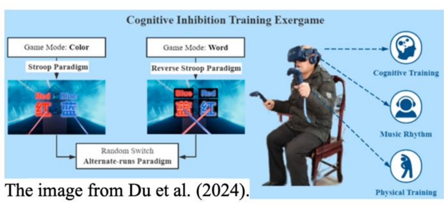
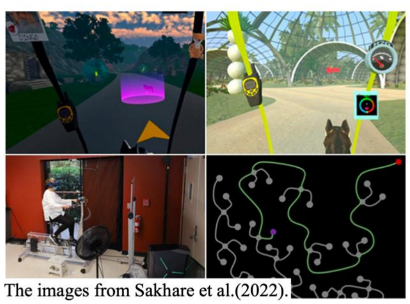
Study	Inclusion/ exclusion criteria[a]	Random allocation[b]	Concealed allocation[c]	Similarity of baseline characteristics[d]	Blind participant[e]	Blind therapists[f]	Blind assessors[g]	Key outcome[h]	Intention to treat[i]	Between-group comparisons[j]	Point estimates and variability[k]	Final score
Included studies of healthy older adults												
Liepa et al., 2022	√	√	√	N	N	-	-	√	√	√	√	7
Campo-Prieto et al., 2022	√	√	√	√	-	-	-	√	√	√	√	8
Huang, 2020	√	√	N	√	√	N	N	√	√	√	√	8
Li, Salehzadeh Niksirat, et al., 2020	√	√	-	-	-	-	-	√	√	√	√	6
Du et al., 2024	√	N	-	N	-	-	-	√	√	-	√	4
Sakhare et al., 2022	√	N	N	N	-	-	-	√	√	-	√	4
Included studies of older adults with MCI												
Liao, Tseng, et al., 2019	√	√	√	√	-	-	√	√	-	√	√	8
Liao, Chen, et al., 2019	√	√	√	√	-	-	√	√	√	√	√	9
Thapa et al., 2020	√	√	√	√	N	N	N	√	√	√	√	8
Yang et al., 2022	√	√	-	√	N	N	-	√	√	√	√	7
Kwan et al., 2021	√	√	N	√	-	-	√	√	√	√	√	8
Baldimtsi et al., 2023	√	√	√	N	N	N	-	√	√	√	√	7
Basharat et al., 2023	√	-	-	√	-	-	-	√	√	√	√	6

Notes: [a]Eligibility criteria were specified; [b]participants were randomly allocated to groups; [c]allocation to groups was concealed; [d]the groups were similar at baseline regarding the most important prognostic indicators; [e]participants were not aware of the group in which they were allocated (blinded); [f]staff that administered training was not aware (blind) of the group status (intervention or control); [g]assessors measuring at least one key outcome were not aware (blind) of the group status; [h]measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups; [i]all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least one key outcome were analyzed by "intention to treat"; [j]the results of between-group statistical comparisons are reported for at least one key outcome; [k]the study provides both point measures and measures of variability for at least one key outcome. "√" = 1 point, "-" = 0 points, N: no information or the study was not related to the question.
Abbreviations: PEDro, Physiotherapy Evidence Database.

Figure 2. Evaluation of methodological quality of the included studies by PEDro scale.

Study	Type	Name, theme	Gameplay (mainly)	Visual modality (& whether incorporates visual stimuli featuring continuous movement)	Cognitive modality (& whether incorporates cognitive activation paradigm/task gameplay)	Physical modality: Postures	Physical modality: Body part	Physical modality: Type of exercise
Liepa et al., 2022	Customized	***Falling diamonds***, cartoon (diamond, tree and birds, etc.)	①Memorize and move the body according to the direction of the order in which multiple arrows appear. ②Ignore animated fox and bird.	**Visual working memory** (memorize the order of arrows), **visual attention distraction** (unexpected stimuli)	Working memory, attention; **Go/NO-GO Task**	Sitting & standing while moving trunk	Trunk movement through a balance board	Trunk balance exercise
Campo-Prieto et al., 2022	Commercial	***BOX VR***, a virtual gym	①Quick motor response is needed for boxing-based challenges. ②Arrows guide specific movements like uppercuts and crosses. ③Maneuver trunk, head, and limbs to evade obstacles.	**kinetic visual acuity** (balls flying from far to near; identify the direction of the ball's arrow), **visual attention** (the random appearance of unexpected stimuli), **motion perception** (perceive and understand the movement of objects, including speed and direction), **hand-eye coordination**	Attention; **Multitasking paradigm** and **Go/No-Go task**	Standing while moving	Full body	Multicomponent workout (aerobic, strength, and endurance combined with coordination, agility, and balance training); cardiovascular training; sensorimotor integration
Huang, 2020	Commercial	***VR Fruit Ninja***, (cartoon fruits)	①Hit fruits	**Multiple aspects of visual attention**	**Go/No-Go Task** (hit or not hit)	Standing while moving	Full body	Walk, raise arms
Li, Salehzadeh Niksirat, et al., 2020	Customized, adapted from Whac-A-Mole	***VR Whac-A-Mole***, cartoon farm (island, sea, wooden houses and plants, etc.)	①Walk left or right according to the shape. ②Raise hands and feet according to the animal's position to feed animals.	**Multiple aspects of visual attention**	Selective attention; **Multitasking paradigm**	Standing while moving	Full body	Walk, raise arms and kick legs
Du et al., 2024	Customized (a VR rhythm game), adapted from Beat saber	***LightSword***, neon feeling, electronica music theme	①Hit the block according to the corresponding stimulus	**kinetic visual acuity** (Blocks flying from far to near)	Inhibition control; **the Stroop paradigm** (white background identify the color) and **the reverse Stroop paradigm** (back background identify the word), **dual-task alternate-runs paradigm**	Sitting	Upper body	raise arms
Sakhare et al., 2022	Customized	***VR Cycling while navigating***, immersive storylines in an urban park, aviary, savannah, desert, and jungle)	①Participants cycled on a custom-built stationary exercise bike while finishing cognitive tasks (e.g., navigating, memorizing the route, ignoring distractors and collecting the items, etc.)	**Visual spatial**	Spatial memory (immediate recall and delayed recall), attention; **the cued route-learning paradigm, dual-task paradigm (attention)**	sitting while cycling	Lower body	Aerobic, cycling resistance

Figure 3. IVR game's modalities design characteristics of included studies in healthy older adults.

Name	Images	MDA or DDA	Game Difficulty during the intervention	Interactive Mode	Devices of HMD and others
Falling diamonds (Liepa et al., 2022)	 The image from Sakhare et al. (2022).	MDA	Difficulty changes in the cognitive stimulation: 33 levels in total, speed of objects and number of arrows gradually increased. • During the game, participant could reach the next level if it completed 70% of the given tasks.	Natural body Interaction without additional operations	HTC VIVE, HTC VIVE Tracker, TOGU® Balanza® Ballstep (mini balance board)
BOX VR (Campo-Prieto et al., 2022)	 The images from Campo-Prieto et al. (2022).	NA	NA	Natural body Interaction without additional operations	HTC VIVE ProTM, controllers
Fruit Ninja VR (Huang, 2020)	NA	MDA	• In the first two weeks: participants started with a moderate challenge level. • In the last two weeks, participants moved to the increased difficulty level. • Additionally, after each session, participants were asked to rate the difficulty of the game they just finished on a scale from 1 (very easy) to 9 (very difficult) as part of the manipulation check to ensure that the perceived difficulty was aligned with the intended adjustments.	Natural body Interaction without additional operations	Oculus Rift, controllers
VR Whac-A-Mole (Li, Salehzadeh Niksirat, et al., 2020)	 The images from Li, Salehzadeh Niksirat, et al. (2020).	MDA	• Five game difficulty levels in total (changes in, e.g., appearance time of animals and shapes, reaction time, the number of shapes). • Before starting each week of trials, participants were free to change the difficulty level, most increasing by one level each week.	Natural body Interaction without additional operations	HTC VIVE Pro, HTC VIVE Tracker,
LightSword (Du et al., 2024)	 The image from Du et al. (2024).	MDA	**Three customized progressively increasing game difficulty levels.** • In the Easy level, the proportion of inconsistent blocks was between 20% and 30%, the distance between neighboring blocks was more than 60cm, and the block flight time was more than 1.5 seconds; • In the Normal level, the proportions were at 30%-40%, distances at 50-60cm, and flight times at 1-1.5 seconds; • In the Hard level, the proportions were at 40%-50%, distances at 40-60cm, and flight times at 0.5-1 seconds; • Flight speed varied in range with the rhythm of the songs.	Natural body Interaction without additional operations	HTC VIVE Pro2, controllers
Cycling while navigating (Sakhare et al., 2022)	 The images from Sakhare et al.(2022).	MDA	• Difficulty changes in physical demands: aerobic exercise was prescribed using a linear periodized schedule, with cycling intensity levels increasing from 50% HR max at the onset of the intervention to 80% HR max at 12 weeks (intensity increased but duration decreased). • Periodization consisted of two 6-week phases, moderate and vigorous, with intensity levels increasing by 5% every two weeks within each phase. In the first 6 weeks, intensity levels increased from 50% to 60% HR max with a corresponding increase in volume from 120 to 150 minutes per week. In the last 6 weeks, intensity levels increased from 70% to 80% HR max with volumes decreasing from 120 to 75 minutes per week. • Heart rate was tracked using a Polar H7 chest strap monitor. • Difficulty changes in cognitive demands: the difficulty of the routes, defined by the number of decision points (intersections), progressively increased each week throughout the study.	Natural body Interaction without additional operations	HTC VIVE Pro, Heart rate (Polar H7 chest strap monitor), stationary exercise bike

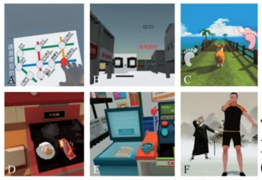
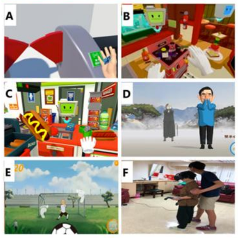
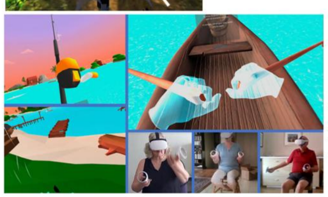
Abbreviations: MDA, Manual Difficulty Adjustment; DDA, Dynamic Difficulty Adjustment; N/A: not applicable.

Figure 4. IVR game's interactive design characteristics of included studies in healthy older adults.

Study	Type	Name, theme	Gameplay (mainly)	Visual modality (& whether incorporates visual stimuli featuring continuous movement)	Cognitive modality (& whether incorporates cognitive activation paradigm/task gameplay)	Physical modality		
						Postures	Body part	Type of exercise
Liao, Tseng, et al., 2019 Liao, Chen, et al., 2019	Customized & commercial (component)	Cartoon daily activities	①**Transportation**: take the MRT, find station, gather money and obtain tickets ②**Shopping**: looking for a store ③**Kitchen chef**: food preparation ④**Convenience store clerk**: handling finances. ①**Transportation** ②**Kitchen chef** ③**Convenience store clerk** ④**Tai Chi.** ⑤**Football** (running and stepping).	**Visual search/orientation, visuospatial** (search for targets quickly and accurately)	**Executive functions**: • **working memory** (memorize the dishes and steps), • **problem-solving** (thinking of solutions to overcome obstacles), • **spatial cognition** (understanding the layout of the store and navigating to find the items), • **attention** (searching for items in the store requires maintaining focused attention to avoid missing any items on the list.),	Standing	Full body	24-form Yang-style tai chi, resistance, balance, aerobic and functionally oriented tasks such as window cleaning, goldfish scooping, obstacle crossing, stair climbing and walking.
Thapa et al., 2020 Yang et al., 2022 Kwan et al., 2021	Customized (component)	Daily activities	①Juice making ②Crow shooting ③Find the fireworks number ④Memory object at the house	**Visual perception** (identifying flying black birds against the beachside background), **hand-eye coordination** (aiming and shooting accurately)	**Executive functions:** • **Working Memory/ Short-term memory** (e.g., remembering the recipe), • **spatial cognition** (understanding the layout of the virtual reality space and navigating), • **problem-solving** (figuring out where each object belongs based on memory and spatial cues).	Sitting	Hand movement	**Motor skills** (using the VR controller to manipulate objects, e.g., picking fruits), simple upper body exercises.
Baldimtsi et al., 2023	Customized (component)	Daily activities	①Orientation (N/A) ②Finding a bus stop (SMC) ③Reporting lost items (SMC) ④Finding a supermarket (SMC) ⑤Grocery shopping (SMC) ⑥Cooking (C) ⑦Finding a travel hotspot (SMC) ⑧Bird watching (SMC)	**visuospatial** (e.g., wayfinding)	• **spatial cognition** • **problem-solving** • attention • **memory** (recalling items while grocery shopping), • **calculation** (settling payment), • **processing speed** (flipping eggs when cooking), • **attention** (birth watching, findways, shopping)	Sitting	Lower body	Cycling resistance, aerobic, motor skills
Basharat et al., 2023	Customized	Forest, cycling while calculating, memory	①20 simple numerical calculations while cycling ②Answer a memory game using a remote control	**Visual memory/ attention** (memorize the number of animals that appeared in the forest)	• **Memory, calculation** (single-digit additions and subtractions)	Sitting	Lower body	Cycling resistance, aerobic, motor skills
Liao et al.,2019b	Customized (component)	***Seas the Day***, nature cartoon (mountain, sea and tree, etc.)	Tai chi, fishing, rowing, relax and unwind	**Visual attention** (keep track of leaves)	• Attention	Sitting	Upper body	Tai chi, stretch arms and row the boat

Note: a, the two studies used the same game in separate experiments.
Abbreviations: MRT, mass rapid transit. N/A: not applicable. SMC: simultaneous motor-cognitive training. C: cognitive training.

Figure 5. IVR game's modalities design characteristics of included studies in older adults with MCI.

Name	Images	MDA or DDA	Game Difficulty during the intervention	Interactive Mode	Devices of HMD and others
Liao, Tseng, et al., 2019	 The images from Liao, Tseng, et al. (2019).	NA	NA	Natural body Interaction without additional operations	HTC VIVE, controllers, the Kinect system (for capturing and tracking).
Liao, Chen, et al., 2019	 The images from Liao, Chen, et al. (2019).	NA	NA		
Thapa et al., 2020 Yang et al., 2022	 The image from Yang et al. (2022).	MDA	The VR game comprised three levels: easy, medium, and hard. These levels were set for participants based on their abilities, needs, and preferences. Throughout the 8-week training period, the difficulty levels were adjusted according to participants' progress and performance.	Using VR controllers to manipulate virtual objects	Oculus quest, controllers
Kwan et al., 2021	 The images from Kwan et al. (2021).	MDA	Difficulty changes in <u>cognitive demands</u>: e.g., more distractors, a higher complexity of items to be memorized, a shorter time for reaction. Each week featured tasks involving two levels of difficulty in terms of cognitive demands. Difficulty changes in <u>physical demands</u>: increase the effort of cycling by adjusting the cycling resistance.	Using VR controllers to manipulate virtual objects	HTC VIVE Focus Plus, controllers, cycling resistance (DeskCycle 2), wrist-worn heart rate sensor (Polar OH1)
Baldimtsi et al., 2023	 The image from Baldimtsi et al. (2023).	MDA	Physical (cycling): 20 min during the first 5 sessions (20 km/h) with a progressive increase in time up to 30 min and speed up to 30 km/h (mild to moderate intensity). Cognitive exercises while cycling: 20 simple numerical calculations (single-digit additions and subtractions); memory game (participants asked to remember the number of animals that appeared in the forest), max. Number of animals 5).	Remote control: set a ray cast from the VR controller, allowing each user to choose a response simply by pointing and pressing the ray at the button on the controller	The Oculus Go Head-Mounted display, controllers, cycle-ergometer (stationary seated bike type, Toorx, ChronoLine, BRX R 300)
Basharat et al., 2023	 The image from Basharat et al. (2023).	MDA	NA	Natural body Interaction without additional operations	Oculus Quest 2

Abbreviations: MDA, Manual Difficulty Adjustment; DDA, Dynamic Difficulty Adjustment; N/A: not applicable.

Figure 6. IVR game's interactive design characteristics of included studies in older adults with MCI.

Name	Group setting (number of participants & mean ± SD age)	Dosage of intervention	Cognitive outcome measures		Physical outcome measures	
			Domain	Tools	Domain	Tools
Falling diamonds (Liepa et al., 2022)	IVR (N=14, 71.67 ± 5.97) NIEG (N=15, 73.07 ± 6.31) PC (N=15, 72.43 ± 5.87)	9 weeks/ twice a week/ 20min	Divided attention Alertness Working memory Selective attention	• Take the visual and auditive tasks simultaneously • The evaluation of tonic alertness, phasic alertness and intrinsic alertness • Remember the order of color changes of dots • Judge horizontal striped square or vertical stripes	Trunk stability static balance gait speed leg strength	prone test SPPB-three positions: side-by side, semi-tandem, and full tandem balance. SPPB-a timed 4-meter walk performed twice at a self-selected pace SPPB-chair stand test
BOX VR (Campo-Prieto et al., 2022)	IVR (N=13, 85.08 ± 8.48) PC (N=11, 84.82 ± 8.10)	10 weeks/ three session/ 6 mins		NA	balance gait mobility lower limb handgrip strength	the Tinetti test TUG FTSTS measured with an analog hand dynamometer
Fruit Ninja VR (Huang, 2020)	IVR (N=16) NIEG (N=16) All participants (61.93 ±8.21)	4 weeks/ twice a week/ 20 mins	Inhibitory control Flexibility Working memory	the Stroop Test Trail Making Test Digit Span		NA
VR Whac-A-Mole (Li, Salehzadeh Niksirat, et al., 2020)	IVR (N=10, 73.8±7.35) PC (N=10, 72.4±7.75)	4 weeks/ three times a week/ 45mins	Working memory Reasoning Attention	Adaptive n-Back Task SPM Attention Network Task	Balance	One-leg Standing Balance Test
LightSword (Du et al., 2024)	IVR only (N=12, 72.4±7.75)	6 weeks/ once every two days/ 40-50 mins	Inhibition control	The Stroop task The Reversed Stroop task The Go/No-Go task		NA
Cycling while navigating (Sakhare et al., 2022)	IVR only (N=12, 64.7 ± 8.8)	12 weeks/ 3 times a week/ 25–50 minutes	Global cognition Cognitive flexibility Inhibition control Processing speed & attention Verbal memory Visual memory discrimination	MOCA TMT Eriksen Flanker Task Digit Symbol Substitution Test RAVLT MST		NA

Abbreviations: IVRG, immersive cognitive-physical VR game; NIEG, non-immersive exergame; PC, passive control; SPPB, the Short Physical Performance Battery; TUG, the Timed Up and Go test; FTSTS, the Five times sit-to-stand test; SPM, Raven's Standard Progressive Matrices; MOCA, Montreal-Cognitive Assessment; TMT, the D-KEFS Trail Making Test; RAVLT, the Rey Auditory Verbal Learning Test; MST, Mnemonic Similarity Task; N/A: not applicable.

Figure 7. Experimental design characteristics of included studies in healthy older adults.

Study & Group compare	Cognitive outcome measures	Physical outcome measures
Falling diamonds (Liepa et al., 2022) (IVR vs. NIEG vs. PC)	• Only the IVRG improved in selective attention control (p = 0.009) and selective attention speed (p = 0.033). For elective attention control, the effect size for IVRG vs. NIEG and IVRG vs. PC is 0.47 and 0.36 respectively; for selective attention speed, the effect size for IVRG vs. NIEG and IVRG vs. PC is 0.36 and 0.52 respectively.	• Significant improvements in the prone test and functional performance (SPPB) for all groups, the PC group (p = .005 and p = .034, respectively), the NIEG group (p = .001 and p = .004, respectively) and the IVR group (p = .001 and p = .014, respectively).
BOX VR (Campo-Prieto et al., 2022) (IVR vs. PC)	• NA	• The PC shows significantly worsened compared to the IVR: FTSTS test (lower limb), Tinetti test scores for balance, gait, and total score, and TUG test total score in the post-test. • At the same time, the IVR showed significant improvements in Tinetti scores for balance (p < 0.001), gait (p < 0.001), total score (p < 0.001) and handgrip (p < 0.001) in the post–pre-test. • Follow-up assessment: The PC shows significantly worsened compared to the IVR: Tinetti test scores for balance, gait, and total score.
Fruit Ninja VR (Huang, 2020) (IVR vs. NIEG)	• No acute effect • IVR led to more cognitive improvement than NIEG, in the Stroop Test (inhibition, p = 0.034) and the Trail Making Task (flexibility, p = 0.038). • For the backward Digit Span (working memory) (n = 30), the findings suggested that there was no significant difference between the IVR and NIEG.	NA
VR Whac-A-Mole (Li, Salehzadeh Niksirat, et al., 2020) (IVR vs. PC)	• Only IVR improved the number of 1-back (p<0.001) and 2-back trials (p<0.001) of working memory and the accuracy (p<0.05) in SPM (reasoning). • Both IVR (p<0.001) and PC (p<0.001) improved the response time in ANT test (attention).	• IVR increased (p<0.05) the one-leg balance time for open-eye condition, while PC is not increased.
LightSword (Du et al., 2024) (Only IVR)	• After the training of IVR, a significantly shorter reaction time was exhibited in the post assessment and maintained 6 months later (follow-up 6 months) for The Stroop task (p = 0.000, p = 0.003, respectively) and The Reverse Stroop task (inhibition) (p = 0.000, p = 0.012, respectively). • For Go/No-Go task, the discriminative index was significantly higher in the post-test (p = 0.003), but not in the follow-up test; the reaction time was significantly shorter in the post-test (p = 0.047) and follow-up test (p = 0.032).	NA
Cycling while navigating (Sakhare et al., 2022) (Only IVR)	• After the training of IVR, RT showed decreased of medium effect size (effect size = 0.42) in the TMT-B (flexibility) and Flanker (inhibitory control) (effect size is 0.54) • Visual memory discrimination related to pattern separation (the MST) lure discrimination index, showed large effect size improvement with scores (effect size is 0.43). • No differences in global cognition (MOCA), processing speed attention (the Digit Symbol Substitution Test) and verbal memory (RAVLT).	NA

Notes: If reported, effect size is presented. If measured, follow-up results are also presented.
Abbreviations: IVRG, immersive cognitive-physical VR game; PC, passive control; NIEG, non-immersive exergame; N/A: not applicable.

Figure 8. Effectiveness results of included studies in healthy older adults.

Study	Group setting (number of participants & mean ± SD age)	Dosage of intervention	Cognitive outcome measures		Physical outcome measures	
			Domain	Tools	Domain	Tools
Liao, Tseng, et al., 2019	IVR (N=18, 75.5±5.2) CG: traditional combined physical and cognitive training (N=16, 73.1 ± 6.8)	12 weeks/ three times a week/ 60 mins	Global cognition Executive function Verbal memory	MOCA EXIT-25 CVVLT	Functional status: activities of daily living	IADL
Liao, Chen, et al., 2019	IVR (N=18, 75.5±5.2) CG: traditional combined physical and cognitive training (N=16, 73.1 ± 6.8)	12 weeks/ three times a week/ 60 mins	Flexibility Inhibitory control	TMT SCWT	Gait	Single walking task, cognitive dual task, motor dual task
Thapa et al., 2020	IVR with educational program (N=33, 72.6 ± 5.4) CG: educational program only (N=33, 72.7 ± 5.6)	IVR: 8 weeks/ three times a week/ 60 mins CG: 8 weeks/ once a week/ 30-50 mins	Global cognition Flexibility Working memory	MMSE-DS TMT- A & B SDST	Gait Mobility Handgrip strength (non-dominant hand)	Gait speed test TUG A digital hand dynamometer
Yang et al., 2022	IVR (N=33, 72.5 ± 5) EG: warm up, aerobic, resistance, cool down (N=33, 67.9 ± 3.6) CG: education class (N=33, 72.6± 5.6)	IVR: 8 weeks/ three times a week/ 60 mins EG: 12 weeks/ twice a week/ 60 mins CG: 8 weeks/ once a week/ 30-50 mins	Global cognition Flexibility Working memory	MMSE-DS TMT- A & B SDST	Gait Mobility Handgrip strength (non-dominant hand)	Gait speed test TUG A digital hand dynamometer
Kwan et al., 2021	IVR (N=9, 73.0 ± 7.5) CG: motor (cycle on the ergometer) and cognitive training (on a tablet computer) sequentially (N=8, 77.5 ± 15.3)	8 weeks/ twice a week/ 30 mins	Global cognition	MOCA	Frailty Walking speed Muscle strength	FFP TUG grip strength
Baldimtsi et al., 2023	IVR (N=28, 66.07 ± 10.04) BG: cycling + calculations (N=11, 73.0 ± 8.54) PE: seated physical simple and complex exercise (N=24, 70.96 ± 7.95) MG: seated physical simple and complex exercise while counting (N=31, 70.39 ± 7.36) PC (N=28, 74.36 ± 7.04)	IVR & BG: 12 weeks/ 2-3 times a week/ 20-30 mins PE & MG: 12 weeks/ 2-3 times a week/ 45 mins	Global cognition Verbal memory Flexibility	MMSE RAVLT DGS-F TMT- B	NA	
Basharat et al., 2023	IVR (N=13, 68.46±1.34) Reading (N=14, 74.83±1.48)	6 weeks/ 3 times a week/ 15-20 mins	Perceptual processing	RT SIFI SJ TOJ	NA	

Abbreviations: CG, the control group; EG, exercise intervention group; BG, bike group; PE, physical exercise group; MG, mixed group; MOCA, Montreal-Cognitive Assessment; EXIT-25, The Executive Interview 25; CVVLT, The Chinese version of the Verbal Learning Test; SCWT, Stroop Color and Word Test; IADL, the Lawton Instrumental Activities of Daily Living scale; TMT, Trail Making Test; MMSE-DS, the Korean version of the Mini-Mental State Examination-Dementia screening test; SDST, symbol digit substitution test; TUG, The 8-feet Up and Go test; FFP, the Fried Frailty Phenotype scale; MMSE, the Mini-Mental State Examination-Dementia screening test; RAVLT, the Rey Auditory Verbal Learning Test; DGS- F, the Digit Span Forward test; RT, the Response Time; SIFI, Sound induced flash illusion; SJ, Simultaneity Judgment; TOJ, Temporal Order Judgment task; N/A: not applicable.

Figure 9. Experimental design characteristics of included studies in older adults with MCI.

Game	Cognitive outcome measures & Group compare	Physical outcome measures
Liao, Tseng, et al., 2019	**IVR vs. CG: traditional combined physical and cognitive training** • Both groups showed improved executive function (EXIT-25; CG: $p = 0.001$, effect size=0.76; IVR: $p = 0.01$, effect size=0.65) and verbal immediate recall memory (CVVLT; CG: $p = 0.011$, effect size = 0.72; IVR: $p < 0.001$, effect size = 0.64). However, only the VR group showed significant improvements in global cognition (MoCA; $p < 0.001$, effect size=1.03), and CVVLT delayed recall ($p = 0.002$, effect size=0.89).	• Only the IVR group showed significant improvements in activities of daily living (IADL, $p < 0.001$) after the intervention.
Liao, Chen, et al., 2019	**IVR vs. CG: traditional combined physical and cognitive training** • Significant improvements in executive function (inhibition control) (SCWT) in both groups (IVR and CG). • The IVR group showed more improvements than the CG in the TMT-B.	• Significant improvements in single-task gait performance and motor dual-task gait performance in both groups (IVR and CG). • Only the IVR group showed improvements in cognitive dual-task gait performance and the DTC of cadence after training. • The IVR group showed more improvements than the CG in the cognitive DTC of cadence.
Thapa et al., 2020	**IVR vs. CG: educational program only** • TMT B time (flexibility) decreased significantly ($p = 0.03$) in IVR compared to the control group. • Small but not significant positive changes were observed in the global cognition function of MMSE and SDST.	• Gait speed ($p = 0.02$) and mobility (TUG) were significantly improved ($p = 0.03$) in the intervention group.
Yang et al., 2022	**IVR vs. exercise group vs. CG: educational class** • The MMSE score (Global cognition) significantly increased in both the IVR and exercise groups compared to baseline ($p < 0.05$). • Significant positive changes were observed in the TMT-A (flexibility) in the IVR ($p < 0.05$) in the post-test compared to baseline. • The SDST score at post-test was higher ($p < 0.05$) in the IVR than in the exercise group.	• The walking speed was significantly decreased ($p < 0.05$) in the control group, however, it was maintained and increased in IVR and exercise groups. • A significant increase ($p < 0.05$) in handgrip strength and TUG (Mobility) scores in both the exercise training and IVR groups in the post-intervention measurements.
Kwan et al., 2021	**IVR vs. CG: motor and cognitive training sequentially** • At post-test, the intervention group ($Z=-2.67$, $P=.01$) showed a significantly larger improvement in cognitive function than the control group ($Z=-1.19$, $P=.24$). • The within-group effect of global cognition function (MOCA) was significant in the IVR group ($P = 0.008$) but not in the control group.	• After the intervention, the reduction in physical frailty in the intervention group ($Z=-1.73$, $P=.08$) was similar to that in the control group ($Z=-1.89$, $P=.06$), the within-group effects in both groups were close to reaching statistical significance. • The improvement in walking speed (TUG test) in the within-group effect was significant in the control group ($P = 0.01$) but not in the intervention group.
Baldimtsi et al., 2023	**IVR vs. BG: cycling + calculations vs. PE: seated physical simple and complex exercise vs. MG: seated physical simple and complex exercise while counting vs. PC** • the IVR group showed significant improvements in general cognitive function (MMSE, $p = 0.006$) and memory (RAVLT, $p = 0.007$ and DGS-F, $p = 0.003$) compared to the bike group, which did not demonstrate such improvement. • The IVR group showed significantly better ($p = 0.016$) in execution function and flexibility (TMT-B) compared to the passive control group.	NA
Basharat et al., 2023	**IVR vs. Reading** • IVR exhibited higher accuracy scores on the SIFI task (acute effect) and faster response times on the audiovisual RT task (both chronic and acute effect). The significant improvements in perceptual processing in both the experimental and control groups suggest that these interventions may positively impact multisensory processing.	NA

Notes: If reported, effect size is presented. If measured, follow-up results are also presented.
Abbreviations: IVRG, immersive cognitive-physical VR game; PC, passive control; NIEG, non-immersive exergame; RT, the Response Time; SIFI, Sound induced flash illusion; SJ, Simultaneity Judgment; TOJ, Temporal Order Judgment task; N/A: not applicable.

Figure 10. Effectiveness results of included studies in older adults with MCI.

attention to track and cut multiple fruits at the same time. Similarly, VR whack-a-mole (Li, Salehzadeh Niksirat, et al., 2020) required similar skills and attention. One study (Liepa et al., 2022) explored visual working memory, which entailed the memorizing of sequences of the appearance of multiple stimuli. In all the studies reviewed, the strategy of directing visual attention toward unexpected stimuli (non-targets) was the most frequently utilized strategy, as evidenced in games such as Falling Diamonds (Liepa et al., 2022), BOX VR (Campo-Prieto et al., 2022), VR Fruit Ninja (Huang, 2020), and VR cycling (Sakhare et al., 2022), which asked player to ignore the unexpected stimuli.

3.3.2.2. Cognitive modality. Executive functions are the cognitive abilities most targeted by the design of IVR games, including inhibition control, attention and memory. The executive functions of cognitive modality cover five psychological paradigms: multitasking (Campo-Prieto et al., 2022; Li, Salehzadeh Niksirat, et al., 2020), Go/No-Go task (Campo-Prieto et al., 2022; Huang, 2020; Liepa et al., 2022), dual-task (Du et al., 2024; Sakhare et al., 2022), the Stroop task (Du et al., 2024) and a cued route-learning paradigm (Sakhare et al., 2022). The game designs featured in the reviewed papers typically combine one or two paradigms or they focus on a specific cognitive function. Five of the studies (Campo-Prieto et al., 2022; Du et al., 2024; Huang, 2020; Li, Salehzadeh Niksirat, et al., 2020; Liepa et al., 2022) emphasize dynamic, continuous multitasking, requiring players to frequently switch between multiple tasks. This necessitates attentional strategies to respond to unexpected stimuli and various physical responses. For instance, in VR Whac-A-Mole (Li, Salehzadeh Niksirat, et al., 2020), players must step to the right if the shape is a green triangle and to the left if the triangle is no green; this combines multitasking paradigm. Three of the studies (Campo-Prieto et al., 2022; Huang, 2020; Li, Salehzadeh Niksirat, et al., 2020) integrate multitasking with Go/No-Go tasks involving inhibition control, such as hitting fruit (go) and avoiding bombs (no-go) (Huang, 2020). One of the studies (Du et al., 2024) incorporated the Stroop paradigm (identifying the color and overcoming word interference), and its reverse paradigm (identifying the words and overcoming color interference) into a dual-task alternate-runs paradigm. Two studies specifically focus on working memory and spatial memory, respectively, for example, memorizing the order of arrows in Falling diamonds (Liepa et al., 2022), and immediate and delayed recall while cycling and navigating in VR (Sakhare et al., 2022).

3.3.2.3. Physical modality. Three studies (Campo-Prieto et al., 2022; Huang, 2020; Li, Salehzadeh Niksirat, et al., 2020) require older participants to stand while moving (walking) when playing the VR games, which simultaneously completes upper body movements, thus allowing them to move using the whole body. For example, in Box VR (Campo-Prieto et al., 2022), players stand and move their lower limbs and trunk while executing numerous fast and continuous punches and hits against moving stimuli, thereby exercising aerobic capacity, strength, and endurance. Three studies require older adults to sit while engaging in games, but two of the studies focus on exercising their upper bodies, for example, raising the arms as far as possible (Du et al., 2024). One remaining study (Sakhare et al., 2022) let older participants cycle on a custom-built stationary exercise bike while navigating in an immersive VR environment, thus it is primarily aerobic training for the lower limbs. Only one study (Liepa et al., 2022) asked older participants to play in both sitting and standing postures, both of which involved moving the trunk through a balance board and, therefore, it primarily targeted balance training in older adults.

3.3.3. Game difficulty

As shown in Figure 4, five out of six mentioned (Du et al., 2024; Huang, 2020; Li, Salehzadeh Niksirat, et al., 2020; Liepa et al., 2022; Sakhare et al., 2022) the design of the difficulty mechanism, but all of them detailed gradual manual difficulty changes, and none dealt with dynamic difficulty changes. These game difficulty mechanisms generally had the following characteristics during long-term IVR game-based intervention training: (1) Progressive challenge levels: for example, in Falling Diamonds (Liepa et al., 2022), participants faced a total of 33 levels, where the speed of objects and the number of arrows gradually increased. Advancement to the next level was possible upon completing 70% of the tasks given. (2) Weekly Adjustments: over the training period, participants experienced transitions in difficulty levels in each of one, two, or more weeks. For example, the challenge level was moderate for the first two weeks, then increased in the last two weeks (Campo-Prieto et al., 2022). (3) Customized elements/factors of game difficulty change based on the game design mechanism. For example, in the game of LightSword (Du et al., 2024) which incorporated the Stroop task, one of the differences in each difficulty level (easy, normal, and hard levels) was the proportion of inconsistent blocks. In the two studies (Box VR (Campo-Prieto et al., 2022) and LightSword (Du et al., 2024)) that incorporated dynamic visual stimulation featuring continuous movement, the factors involved in the difficulty change include the duration and speed of the movement. One study (Sakhare et al., 2022) set up different game difficulty changes for cognitive and physical modalities separately, i.e., cycling while navigating in VR. Here the game difficulty factor of the physical channel is measured by the maximum heart rate during cycling, and the game difficulty factor of the cognitive channel is the navigation route difficulty, defined by the number of decision points (intersections).

3.3.4. Gameplay interactions, HMD and sensor devices

As shown in Figure 4, 6 studies employ natural body interaction without the use of additional controllers, except in one study (Sakhare et al., 2022). In this study, older participants are required to utilize handlebar brakes to respond to cognitive stimulation while navigating on a bicycle. Two studies asked older participants to use a balance board (Liepa et al., 2022) and a stationary exercise bike (Sakhare et al., 2022) during gameplay, respectively, while the remaining four studies used HMD controllers.

3.4. IVR game's modalities design characteristics for older adults with MCI

3.4.1. Game theme

As shown in Figure 5, all seven studies used customized games. Most of the topics of these studies (5/7) (Kwan et al., 2021; Liao, Chen, et al., 2019; Liao, Tseng, et al., 2019; Thapa et al., 2020; Yang et al., 2022) focused on the daily activities of cartoon-style environment settings. The entire training content in the VR game systems consisted of a series of daily tasks or activities, for example, taking transportation (including buying tickets), shopping (looking for a store/supermarket), and food preparation, and so on, older players had to complete these components sequentially. In addition to daily task-based component games, one study (Basharat et al., 2023) also used component games consisting of rowing, Tai Chi, fishing, and so on. One study (Baldimtsi et al., 2023) incorporated cycling while calculating or memorizing in a VR forest environment.

3.4.2. Game design mechanism of three modalities

3.4.2.1. Visual modality. No studies have incorporated continuous dynamic stimuli in the design of a visual modality. Visual modalities in studies using older adults with MCI all involve general visual stimulation only. Among the 5 studies (Kwan et al., 2021; Liao, Chen, et al., 2019; Liao, Tseng, et al., 2019; Thapa et al., 2020; Yang et al., 2022) that use daily activities as the design content, visuospatial and visual search are the most commonly integrated visual functions. They require finding the target quickly and accurately, such as finding stores when shopping, wayfinding and positioning within the games. One study asked players to memorize the number of animals that appeared in the forest (Baldimtsi et al., 2023); this involves visual working memory. In "Seas the Day" (Basharat et al., 2023), where players perform a Tai Chi game, they need to use their arms to keep tracking the floating trajectory of leaves, which involves visual attention.

3.4.2.2. Cognitive modality. Although daily task-based components of IVR games did not incorporate specialized cognitive activation paradigms, they all involved some high executive functions (Kwan et al., 2021; Liao, Chen, et al., 2019; Liao, Tseng, et al., 2019; Thapa et al., 2020; Yang et al., 2022). For example, memorizing the dishes and steps (working memory), thinking of solutions to overcome obstacles (problem-solving), settling payments (calculation), understanding the layout of the store and navigating to find the items (spatial cognition). Searching for items in the store requires maintaining focused attention to avoid missing any items on the list (attention).

3.4.2.3. Physical modality. Two studies (Liao, Chen, et al., 2019; Liao, Tseng, et al., 2019) asked older participants to stand while playing VR games. They involved full-body exercise by performing 24 Form Yang-style Tai chi, resistance, balance, aerobic, and functionally oriented tasks such as window cleaning, goldfish scooping, obstacle crossing, stair climbing, and walking. Five studies required older participants to play in a sitting position, two (Baldimtsi et al., 2023; Kwan et al., 2021) of which mainly involved lower-body exercises using cycling resistance and aerobics; at the same time, they were asked to complete cognitive tasks by manipulating VR controllers which required motor skills; two of the studies (Thapa et al., 2020; Yang et al., 2022) focused on exercising the upper body, such as simple hand movement and motor skills by using the VR controller to manipulate objects, for example, picking fruits. One study stretching arms and rowing your boat (Basharat et al., 2023).

3.4.3. Game difficulty

As shown in Figure 6, of the 7 studies, 4 studies (Baldimtsi et al., 2023; Kwan et al., 2021; Thapa et al., 2020; Yang et al., 2022) mentioned the design of the game difficulty mechanism. In two of the studies, difficulty changes for both cognitive and physical modalities separately, ref. Kwan et al. (2021) and Baldimtsi et al. (2023). In the study presented by Kwan et al. (2021), the training system required the participants to travel in the virtual world of the game by cycling on an ergometer while simultaneously participating in cognitively demanding daily living tasks. Here, the difficulty changes in cognitive demands were mainly in the form of distractors, higher complexity of items to be memorized and shorter times for reaction. Changes in physical demand were in the form of increased effort required in cycling by adjusting the cycling resistance. In the study of Baldimtsi et al. (2023) participants cycled while calculating 20 simple numerals tasks and memorizing the number of animals that appeared. Regarding the physical demands, the work load was 20 min in total for the first 5 sessions (20 km/h) with a progressive increase in time up to 30 min, and speed up to 30 km/h (mild to moderate intensity). Regarding the cognitive demands, changes included the number of animals, and single-digit addition and subtraction calculations. The remaining two studies (Thapa et al., 2020; Yang et al., 2022) used the same VR game, which comprised three levels: easy, medium, and hard. These levels were set for participants based on their abilities, needs, and preferences. Throughout the 8-week training period, the difficulty levels were adjusted according to the respective participants' progress and performance.

3.4.4. Gameplay interactions, HMD and sensor devices

As shown in Figure 6, two studies utilized cycling equipment, including the DeskCycle 2 cycling resistance device with the Polar OH1 wrist-worn heart rate monitor (Kwan et al., 2021), and the Toorx Chrono Line cycle-ergometer (Baldimtsi et al., 2023), respectively.

3.5. Experimental design characteristics and effects observed in healthy older adults

3.5.1. Experimental design characteristics

All studies, except two (Du et al., 2024; Sakhare et al., 2022), set up one (3 out of 5 studies) or two (1 out of 5 studies) control groups, two of which compared immersive cognition-physical VR games with non-immersive exergames (Huang, 2020; Liepa et al., 2022): immersive VR falling diamonds & non-immersive falling diamonds (on the flat screen of the laptop), immersive VR Fruit Ninja & non-immersive Fruit Ninja (Fruit Ninja Kinect). The other 2 studies used passive control groups for comparison (non-treatment group) (Campo-Prieto et al., 2022; Li, Salehzadeh Niksirat, et al., 2020). Two studies conducted follow-up assessments for 1-month (Campo-Prieto et al., 2022) and 6-months (Du et al., 2024) respectively. Training interventions lasted an average of 8 weeks (ranging from 4 weeks to 12 weeks), with 4 studies reaching or exceeding 6 weeks (Campo-Prieto et al., 2022; Du et al., 2024; Liepa et al., 2022; Sakhare et al., 2022). Training sessions occurred 2–3 times per week. Most (4 out of 6) (Campo-Prieto et al., 2022; Du et al., 2024; Li, Salehzadeh Niksirat, et al., 2020; Sakhare et al., 2022) intervention sessions took place three times a week. The duration of each training session varied from 40 min per week up to 160 min per week, with individual sessions lasting between 6 and 50 min.

No studies included visual outcome measures. All studies, except one (Campo-Prieto et al., 2022), reported cognitive outcome measures, while three reported physical outcome measures (Campo-Prieto et al., 2022; Li, Salehzadeh Niksirat, et al., 2020; Liepa et al., 2022); two of these studies reported both cognitive and physical outcome measures (Li, Salehzadeh Niksirat, et al., 2020; Liepa et al., 2022). Different domains of executive function (inhibition control, working memory, and cognitive flexibility/ switching) were most frequently investigated ($n = 5$) (Du et al., 2024; Huang, 2020; Li, Salehzadeh Niksirat, et al., 2020; Liepa et al., 2022; Sakhare et al., 2022), and were measured using multiple tests or a single test targeting a specific function, which were validated through measures such as The Stroop Task, Digital Span and the Trail Making Test. Three of these studies which assessed executive functions also recorded additional cognitive domains: attention, global cognition and reasoning. Physical assessments include balance, gait, lower body strength, mobility, handgrip strength, and trunk stability. Balance was included in all three studies measuring physical function. Balance measures included the Short Physical Performance Battery test (SPPB), the Tinetti test, and OLSBT. For more detailed information on outcome measures, see Figure 7.

3.5.2. Cognitive effects

For the two studies (Huang, 2020; Liepa et al., 2022) that compared immersive exergames (i.e., IVR) with non-immersive exergames, the improvement favoring IVR was observed in selective attention control and selective attention speed, inhibition control and flexibility respectively; however, there was no improvement in working memory for IVR in either study. Two studies included only the IVR group (Du et al., 2024; Sakhare et al., 2022). Du et al. (2024) found significant within-group improvement in inhibition control; this improvement was still maintained after 6 months. In addition to inhibitory control, the improvement of flexibility and visual memory discrimination was observed in the study of Sakhare et al. (2022). The study (Li, Salehzadeh Niksirat, et al., 2020) that used comparison with a passive control group observed improved working memory capacity and reasoning accuracy only in the IVR group, however, the response time for the attention task decreased in all groups.

3.5.3. Physical effects

In three studies that report physical outcome measures, all of which included a passive control group as a comparison, Campo-Prieto et al. (2022) noted that the IVR group showed significantly better results than the passive control (PC) group in the lower limb using the Five Times Sit-to-Stand test (FTSTS), the Tinetti test for balance and gait, and the timed up and go (TUG) test for mobility, but no handgrip strength test was used. The difference in Tinetti test scores persisted at the one-month follow-up assessment later. Li, Salehzadeh Niksirat, et al. (2020), also reported that the one-leg balance ability under the eyes-open condition was improved in IVR conditions. However, the study Liepa et al. (2022) with three groups, namely, an IVR group, a non-immersive exergame group and a passive control group, improvements were shown in the prone test and SPPB test in all groups with no difference between them. All results are summarized in Figure 8.

3.6. Experimental design characteristics and effects observed in older adults with MCI

3.6.1. Experimental design characteristics

All studies set up at least one control group. Three studies (Kwan et al., 2021; Liao, Chen, et al., 2019; Liao, Tseng, et al., 2019) compared IVR groups with traditional combined physical and cognitive training, including simultaneous or sequential tasks. One study (Yang et al., 2022) used traditional physical training (warm-ups, aerobic resistance, and cool-downs) as a comparison. One five-group study (Baldimtsi et al., 2023) compared IVR with a bike group (cycling while calculating), a physical exercise group (seated physical simple and complex exercise), a mixed group (seated physical simple and complex exercise while counting), and a passive control group. Other content for the control group also included education classes (Thapa et al., 2020; Yang et al., 2022) or reading (Basharat et al., 2023). For IVR training, interventions ranged from 6 weeks to 12 weeks; one study lasted 6 weeks (Basharat et al., 2023), 3 studies lasted 8 weeks (Kwan et al., 2021; Thapa et al., 2020; Yang et al., 2022) and 3 studies (Baldimtsi et al., 2023; Liao, Chen, et al., 2019; Liao, Tseng, et al., 2019) lasted 12 weeks. Most (5 out of 7) intervention sessions occurred three times a week, one study asked older participants to play twice a week, and one occurred twice or three times a week. Training durations ranged from 40 minutes per week up to 180 minutes per week, with individual sessions lasting between 15 and 60 minutes. Four studies required older participants to engage in 60-minute sessions three times a week, while two studies recommended 30-minute sessions twice (or two to three times) a week.

No studies included visual outcome measures. All studies, except two (Baldimtsi et al., 2023; Basharat et al., 2023), reported both cognitive and physical outcome measures. Two studies reported cognitive outcome measures only. In the cognitive outcomes evaluations, global cognition was measured by the Montreal Cognitive Assessment (MoCA) and the Mini-Mental State Examination (MMSE), with the latter being the most frequently applied (5 out of 7 studies). Executive functions were also frequently investigated and included assessments of brief executive control function, inhibitory control, cognitive flexibility, and verbal memory. These functions were measured using the Executive Interview 25, Stroop Color and Word Test, Trail Making Test (TMT), Chinese version of the Verbal Learning Test, Rey Auditory Verbal Learning Test, and Digit Span Forward test. Additionally, one study (referred to as Basharat et al. (2023)) measured perceptual processing and included four types of audio-visual judgment tasks. Domains of physical outcome were investigated including the functional status of daily activities measured by the Instrumental Activities of Daily Living scale (IADL), gait performance - tested in the condition of a single task, cognitive dual task and motor dual task, walking speed and mobility measured by the 8-feet Up and Go test (TUG), and grip strength tested by a digital hand dynamometer. For more detailed information on outcome measures, see Figure 9.

3.6.2. Cognitive effects

Five studies (Kwan et al., 2021; Liao, Chen, et al., 2019; Liao, Tseng, et al., 2019; Thapa et al., 2020; Yang et al., 2022) used daily activities as training content. One study measured effects on global cognition (the most commonly investigated). Four studies showed (Baldimtsi et al., 2023; Kwan et al., 2021; Liao, Tseng, et al., 2019; Yang et al., 2022) a significant improvement in the IVR group for global cognition in the post-test compared to the baseline or control groups. One study showed that only the IVR group improved significantly compared to traditional combined physical and cognitive training. Another study Thapa et al. (2020), also observed a small but not significant positive change in the global cognition function for MMSE. Regarding the effects on executive functions (5 studies) (Baldimtsi et al., 2023; Liao, Chen, et al., 2019; Liao, Tseng, et al., 2019; Thapa et al., 2020; Yang et al., 2022), significant improvements in a brief executive control function, verbal memory (immediate recall), inhibition control were observed in both the IVR and control groups (i.e., the traditional combined physical and cognitive training group). Of the 4 studies that measured flexibility (Baldimtsi et al., 2023; Liao, Chen, et al., 2019; Thapa et al., 2020; Yang et al., 2022), 3 studies (Baldimtsi et al., 2023; Liao, Chen, et al., 2019; Thapa et al., 2020) found that IVR significantly improved flexibility compared to the control groups. One study Baldimtsi et al. (2023) found significant positive changes in the post-test compared to the baseline.

3.6.3. Physical effects

For gait performance (Liao, Chen, et al., 2019; Thapa et al., 2020; Yang et al., 2022), significant positive changes in gait speed and mobility were observed in the IVR group (Thapa et al., 2020; Yang et al., 2022). Study Liao, Chen, et al. (2019) found significant improvements in single-task gait performance and motor dual-task gait performance in both groups but only the IVR group showed improvements in cognitive dual-task gait performance and the dual-task cost of cadence after training. In the three studies that measured handgrip strength (Kwan et al., 2021; Thapa et al., 2020; Yang et al., 2022), only one study Yang et al. (2022) observed a significant improvement in handgrip strength in the IVR group, but this positive change was also observed in the exercise control group. A study that measured the functional status of daily activities found that, compared with traditional combined physical and cognitive training, only the IVR group significantly improved IADL after intervention which focused mainly on daily activities as training content. All observed results are summarized in Figure 10.

4. Discussion

In this systematic review, we comprehensively evaluated IVR games designed for both healthy older adults and those with MCI. Thirteen studies in total were identified. Our focus encompassed an in-depth exploration of the design mechanisms, encompassing multimodal aspects and game difficulty settings, experimental design, and the effects of these IVR games on cognitive and physical enhancement. Our findings revealed a rich diversity in game designs, reflecting a broad spectrum of features across visual, cognitive, and physical modalities. Additionally, we identified consistent principles in game difficulty design, alongside varying effects observed in cognitive and physical improvement.

In the following subsections, we delve deeper into our findings to present the significance of this systematic work to future studies from the following perspectives: game design considerations for the synergizing modalities of DVA, cognitive and physical (Section 4.1), the differences in the game design considerations for healthy older adults and those with MCI (Section 4.2), settings of game difficulty and gameplay interaction (Section 4.3), the cognitive and physical benefits of IVR game interventions (Section 4.4) and the synergistic impacts of DVA and physical modalities on cognitive interventions (Section 4.5). We also present the limitations of this systematic review (Section 4.6).

4.1. Game design considerations for synergizing modalities

In this subsection, we discuss implications and potential considerations for incorporating DVA into cognitive and physical combinations when designing IVR games for older adults in the context of findings from this and other studies.

Among all the IVR games included in this study, only two that were designed for healthy older adults were integrated with dynamic visual stimulation (KVA only), namely Box VR (Campo-Prieto et al., 2022) and LightSword (Du et al., 2024). Compared to other IVR games that did not involve dynamic visual stimulation, Box VR appears to demonstrate better potential for improving physical function, exhibiting more improvements in physical function also in follow-up assessments. LightSword shows positive effects in inhibition control in the pre-post assessment, and this improvement is still maintained after a 6-month follow-up. It seems that synergizing modalities has the potential for better intervention effects. However, the limited number of studies involving DVA makes it challenging to fully grasp how multimodal interventions affect cognitive and physical functions in older adults. Furthermore, the comparative advantages of these DVA-inclusive interventions over those lacking dynamic visual stimulation remain insufficiently explored.

This may be supported by other studies. For the impact of dynamic visual stimulation on cognition, studies indicate (Lockhofen & Mulert, 2021; Park et al., 2023) that dynamic visual stimulation leads to stronger activity in the frontal and parietal regions of the brain, which are associated with attention, visual motion tracking, and executive functions. As evidenced via the dynamic scene tracking, older adults require faster information processing and reaction speeds while also stimulating more attention and spatial perception, which also helps train visual perception and motor coordination abilities (Davids et al., 2005). For the impact of dynamic visual stimulation on physical functions, dynamic visual stimulation may lead to more physical activity and bodily freedom for older adults. A study investigating the acceptability of the multisensory VR games combined with dynamic visual acuity for older adults (Li et al., 2024) mentioned the synergistic value of the multiple modality combinations incorporating visual, cognitive and physical affordances. This study was not included in our review because it did not evaluate the effects of the intervention. The study found that the addition of dynamic visual acuity stimulation (KVA and DVA) enhanced adaptability, achieved a wider range of physical movements, and adapted well to older adults with different exercise habits and physical abilities. In terms of the impact on gaming experience, dynamic visual stimulation increases visual attractiveness and challenge, leading to fast-paced actions that may enhance immersion and engagement. The increased game challenge could stimulate players' motivation, thereby increasing the enjoyment and sustainability of the game.

However, as these studies were not intended for strict comparison and only a limited number of studies were available, further research is needed to make more precise comparisons. On the other hand, dynamic visual stimulation may increase the complexity and difficulty of games which older adults may find too fast-moving or fast-paced and visually uncomfortable, leading to dizziness or discomfort. Future research could explore how dynamic visual stimulation affects cognitive and physical modalities in older adults, while considering individual differences and inclusivity in game design. Evaluating both cognitive burden and fatigue during gameplay practice can provide insights into the optimization of immersive interventions. Optimizing multimodal game designs that integrate dynamic visual acuity, cognitive and physical modalities has potential to maximize benefits and minimize negative impacts.

4.2. Differences in game design characteristics for older adults with and without MCI

In this review, we found the differences in the design of IVR games for older adults with and without MCI. Overall, for healthy older adults, the gameplay and design mechanisms across the three modalities were more diversified, whereas for older adults with MCI, the game types were narrower, focusing on simulating daily life activities, training in advanced executive functions, and suitable physical activities.

None of the studies for older adults with MCI included continuous dynamic visual stimulation but rather general visual stimulation only. These games typically integrated visual functions such as visual localization and search, requiring quick and accurate target identification such as finding stores while shopping or locating objects in the game. Although IVR games based on daily tasks did not integrate specialized cognitive activation paradigms, they all involved some advanced executive functions such as memory, problem-solving, calculation, spatial cognition, and attention. The emphases on practicality and cognitive load in the design of IVR games for older adults with MCI may be attributed to several factors. Firstly, older adults with MCI typically had lower scores in Instrumental Activities of Daily Living. By simulating activities from daily life in a VR environment, such as shopping or cooking, the training effects may be more readily transferable to real-life situations, helping participants maintain or improve relevant daily life skills and independence. Secondly, daily activities are often accompanied by specific and familiar contexts and environments, which help them identify with the learned information and the VR environment context. The cognitive loads of tasks related to daily life are more suitable to activate brain neurons than abstract cognitive exercises. Third, cognitive interventions with daily activity themes are more likely to interest these participants.

By contrast with designing for the MCI demographic, IVR games designed for healthy older adults lean towards customization and more diverse multimodal design mechanisms. These games incorporate dynamic visual stimulation in the visual modality and utilize a variety of cognitive activation paradigms in the cognitive modality, for example, multitasking, Go/No-Go tasks, and Stroop tasks. These different cognitive tasks may target specific cognitive functions in older adults, thereby improving their overall cognitive function. In the physical modality, compared to older adults with MCI, healthy older adults are more often required to play in a standing position, engage in more full-body exercises, and participate in more diverse workouts. Future research could further explore the long-term effects of different physical design mechanisms on the cognitive and physical functions of older adults, given that the effects of different physical training tasks on older adults' cardiovascular function, muscle strength, and balance also vary. Additionally, more attention should be paid to individual differences and personalized interventions, as healthy older adults and those with MCI may respond differently to different types of cognitive and physical training.

4.3. Game design considerations for game difficulty and interaction

Game difficulty settings are essential considerations in game design. They impact the gaming experience and intervention effects for older adults. Appropriate game difficulty settings can enhance the efficacy of the challenge of a game by increasing player engagement and promote improvements in cognitive and physical functions. All studies included in this review employed gradual manual difficulty adjustments, however, the lack of dynamic difficulty adjustment is a notable omission. The absence of dynamic difficulty adjustments may well mean the games potential to promote improvements cannot be realized. Incorporating dynamic difficulty adjustments into VR games for older adults could address this issue by adapting the game's challenge level in real time based on each player's performance and other contextual factors. This dynamic adaptation could help maintain optimal levels of challenge, keeping the gameplay engaging and enjoyable for older adults while ensuring that it remains within their capabilities. Future research could explore the impact of dynamic difficulty adjustments on older adults' gaming experience and intervention outcomes to further optimize the design of VR games for this population.

Most studies utilized natural body interaction as the primary mode of gameplay interaction; this can better simulate daily activities and enhance the physical activity levels of older adults. While natural body interaction can enhance the gaming experience for older adults, in certain situations the use of VR controllers may provide more precise game control and increase the diversity in gameplay. Therefore, future research could further compare the impact of different gameplay interaction modes on the gaming experience and intervention effects for older adults. By exploring the advantages and disadvantages of both natural body interaction and VR controllers, researchers can better tailor gaming interventions to suit the needs and preferences of older adults, ultimately maximizing the effectiveness of such interventions in promoting cognitive and physical health.

4.4. Intervention effects of IVR games on cognitive and physical functions

Overall, the findings from our review underscore the cognitive and physical benefits of IVR game interventions for both healthy older adults and those with MCI.

We found that out of the 13 studies analyzed, 11 (5 targeting healthy older adults and 6 targeting older adults with MCI) reported significant benefits from IVR game interventions compared to control groups in terms of executive function (Baldimtsi et al., 2023; Du et al., 2024; Huang, 2020; Liao, Chen, et al., 2019; Sakhare et al., 2022; Thapa et al., 2020), working memory (Basharat et al., 2023; Huang, 2020; Li, Salehzadeh Niksirat, et al., 2020; Liao, Tseng, et al., 2019; Liepa et al., 2022; Sakhare et al., 2022), and global cognition (Baldimtsi et al., 2023; Kwan et al., 2021; Liao, Tseng, et al., 2019; Sakhare et al., 2022; Thapa et al., 2020; Yang et al., 2022). Of eight studies that assessed executive function, 6 reported significant improvements compared to control groups in older adults with and without MCI. These 6 studies covered aspects of inhibitory control and flexibility in healthy older adults, and flexibility in older adults with MCI. Among them, three studies (Du et al., 2024; Huang, 2020; Sakhare et al., 2022) found a positive effect from IVR games on inhibitory control in healthy older adults, with one study reporting sustained benefits even after a 6-month follow-up; two studies found a positive effect on cognitive flexibility in healthy older adults (Huang, 2020; Sakhare et al., 2022); 3 studies found a positive effect on cognitive flexibility in older adults with MCI (Baldimtsi et al., 2023; Liao, Chen, et al., 2019; Thapa et al., 2020), while only one study measured inhibitory control but did not find a positive effect from IVR games on older adults with MCI. Notably, two studies comparing immersive exergames (i.e., IVR) with non-immersive exergames found that only the IVR groups showed significant improvement in selective attention control and selective attention speed, inhibition control, and flexibility. This implies that, by contrast with non-immersive exergames (with other intervention contents being the same as the IVR), immersive VR game interventions yielded superior cognitive benefits for healthy older adults, highlighting the distinct values in inhibition control and attention provided by immersive virtual reality environments (Huang, 2020; Liepa et al., 2022).

We found inconsistent results in working memory, attention and global cognition. Regarding working memory, including visual and verbal aspects, three of six studies indicate statistically significant improvement compared to their control groups (Basharat et al., 2023; Li, Salehzadeh Niksirat, et al., 2020; Liao, Tseng, et al., 2019) but not in the other three studies (Huang, 2020; Liepa et al., 2022; Sakhare et al., 2022). Regarding global cognition (Baldimtsi et al., 2023; Kwan et al., 2021; Liao, Tseng, et al., 2019; Sakhare et al., 2022; Thapa et al., 2020; Yang et al., 2022), three of six studies indicate statistically significant improvement compared to their control groups in older adults with MCI (Baldimtsi et al., 2023; Kwan et al., 2021; Liao, Tseng, et al., 2019) but not in the other three studies (Sakhare et al., 2022; Thapa et al., 2020; Yang et al., 2022). No study showed positive results for healthy older adults. Regarding attention, one study found only the IVR game group improved selective attention, while another study did not find any positive results. The results should be conservatively interpreted due to the small number of studies.

Potential physical improvements for IVR interventions were found in balance for healthy older adults and in gait performance and also in mobility for older adults with MCI. In seven studies that assessed physical functions (three studies for healthy older adults, four studies for older adults with MCI), three reported significant improvements compared to control groups in both healthy older adults and older adults with MCI. For healthy older adults, two studies showed significant improvement in balance and gait, respectively compared to the passive control group. However, findings from studies with multiple groups revealed comparable improvements in functional performance across all intervention groups including IVR and non-immersive exergame groups, suggesting that the immersive nature of the intervention may not confer additional benefits beyond those of non-immersive exergames in certain physical domains. This is a different situation to the cognitive domains mentioned above, suggesting that the advantages of the IVR environment for intervention effects are likely to be different in cognitive and physical domains. Future research needs to explore the differences between IVR and non-immersive games in improving cognitive and physical function. This will help determine which type of intervention is most effective and in what situations IVR intervention may be more advantageous.

The divergent outcomes observed between older adults with and without MCI underscore the importance of personalizing game interventions based on individual cognitive profiles and needs. Tailoring interventions to target specific cognitive deficits and physical limitations could maximize their effectiveness and relevance for each participant.

The limitations of the existing studies mainly include small sample sizes and heterogeneity of research design. Furthermore, the quality of studies is not high (e.g., no blinding was conducted). Future studies can expand the sample size and strengthen the consistency of research design to verify the long-term effects of IVR games on improving cognitive and physical function in older adults. In addition, future research needs to strengthen interdisciplinary applications in the fields of game design (cognitive science, and human-computer interaction) so as to design VR games that are more suitable for the characteristics of the elderly and more effective for long-term intervention. It is also possible to further explore the effects of different types of game design, dynamic difficulty adjustment, and the effects of different game interaction methods on the cognitive and physical functions of the elderly, as well as optimize the methods and strategies for IVR game intervention.

4.5. The synergistic impacts of DVA and physical modalities on cognitive interventions

One area of interest is whether the combination of DVA training and physical exercise yields compounds cognitive benefits beyond those achieved through either intervention alone. Although we found limited sample sizes in DVA integration studies, we believe that the synergistic impacts of DVA and physical modalities within cognitive interventions offer an intriguing avenue for enhancing the efficacy of therapeutic approaches for older adults, according to findings from prevous and our studies.

First, findings from studies (Lockhofen & Mulert, 2021; Park et al., 2023) indicate that DVA training can stimulate cognitive functions such as attention, executive control, and visual processing by engaging brain regions associated with motion tracking and reaction speed. Physical exercise is also well-established for enhancing executive functions and memory through neuroplasticity and increased blood flow to the brain (Colcombe & Kramer, 2003). Given these independent benefits, it is plausible that integrating DVA stimulation with physical exercise could amplify cognitive improvements, particularly in older adults, by creating a more immersive and mentally demanding environment that challenges both visual and motor coordination.

Second, our findings also found games like Box VR and LightSword provide tentative support for the hypothesis of a synergistic impact. The results show that tasks requiring both dynamic visual processing and physical responses can significantly enhance cognitive functions, such as attention and executive control. These games that involve tracking moving stimuli not only engage visual perception but also necessitate hand-eye coordination, thereby fostering cognitive engagement. This dual-tasking scenario could be hypothesized to potentially amplify the cognitive gains observed in isolated interventions. However, due to the limited sample size of DVA-integrated studies, it is challenging to discern whether the observed improvements arise primarily from the cognitive demands imposed by dynamic visual stimuli, from physical activity, or from their interaction. Future research should aim to isolate these variables and investigate the extent to which DVA and physical modalities, when combined, enhance cognitive functions compared to their separate implementation. This would help clarify whether DVA plays a unique and essential role in generating compounded intervention effects that optimize training outcomes for older adults. Additionally, understanding how these elements interact could inform the design of more effective interventions that integrate both visual and physical modalities to maximize cognitive benefits for older adults.

4.6. Limitation

Firstly, the few studies incorporating DVA identified in this review limit the broader understanding and interpretation of multimodal synergistic impacts for cognitive and physical interventions in older adults. Second, the generalizability of the findings may be limited due to variations in study methodologies, interventions, and outcome measures across the included studies. Third, methodological limitations within individual studies, such as small sample sizes, lack of control groups, and potential biases, also pose challenges to the reliability of the synthesized evidence.

5. Conclusion

This paper presents a review study investigating the game design mechanisms and experimental design characteristics of VR games and their intervention effects on cognitive and physical functions. This is motivated by the significant and synergistic impacts of integrating DVA, cognitive, and physical modalities to assist older adults. Although we found only two studies incorporating dynamic visual stimulation, the potential positive synergistic impacts of multimodality on cognitive and physical benefits for older adults were identified, suggesting that multimodal approaches may lead to more effective interventions. This study also revealed the diversity of VR game designs for healthy older adults, and examined the differences between older adults with MCI. We identified consistent principles in game difficulty design, and we observed varying effects in cognitive and physical improvements. This study fills the gap in current review articles that lack an understanding of multi-modality VR game design and empirical research examination. This study also provides valuable insights for future studies on designing more effective and age-appropriate IVR games for older adults through a comprehensive understanding of game design characteristics. Future studies could verify the effects of whether VR games combining three modalities has stronger health benefits than those with single or two modalities. To comprehensively understand the benefits of multimodal synergy, future studies could also explore various aspects of multimodal VR games, such as collecting the physiological and cognitive-behavioral data of users (Li, Anguera, et al., 2020) investigating the underlying neural processes and personalized experiences of these games (Bowman, 2019), and examining their applications and intervention effects in rehabilitation (Elor et al., 2018a; 2018b).

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