



HAL
open science

Factors for optimizing intervention programs for cognition in older adults: the value of exergames

Alexandra Perrot, Pauline Maillot

► To cite this version:

Alexandra Perrot, Pauline Maillot. Factors for optimizing intervention programs for cognition in older adults: the value of exergames. *npj Aging and Mechanisms of Disease*, 2023, 9 (1), pp.4. 10.1038/s41514-023-00103-7. hal-04055918

HAL Id: hal-04055918

<https://hal.science/hal-04055918v1>

Submitted on 3 Apr 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

PERSPECTIVE OPEN



Factors for optimizing intervention programs for cognition in older adults: the value of exergames

Alexandra Perrot^{1,2✉} and Pauline Maillot³

This review presents factors that could optimize the effectiveness of an intervention program on cognitive health in older adults. Combined, multi-dimensional and interactive programs appear to be relevant. On one hand, for the characteristics to be implemented in the physical dimension of a program, multimodal interventions stimulating the aerobic pathway and muscle strengthening during the solicitation of gross motor activities, seem to be interesting. On the other hand, regarding the cognitive dimension of a program, complex and variable cognitive stimuli appear to hold the greatest promise for generating cognitive benefits and the broadest transfers to untrained tasks. The field of video games also brings interesting enrichment through the gamification of situations and the feeling of immersion. However, some gray areas remain to be clarified, notably the ideal response dose, the balance between physical and cognitive solicitation and the programs' customization.

npj Aging (2023)9:4; <https://doi.org/10.1038/s41514-023-00103-7>

INTRODUCTION

With the representation of the elderly in the general population reaching unprecedented levels, it appears necessary to find solutions that will allow older adults to retain their autonomy as long as possible. Intervention programs that generate both physical and cognitive stimulation seem to provide interesting results. We might be tempted to propose simple and easy forms of stimulation to elderly people because of their physical and cognitive deficits. However, several results observed from interventional approaches suggest that enriching, complexifying and stimulating programs preserve or even improve cognitive functions in older adults. Exergames, which are video games that generate physical stimulation, could be a relevant tool for this objective¹. This review presents factors to optimize exergame intervention programs on the cognitive health of the elderly.

Recently, numerous studies have highlighted the relevance of interventions combining physical and cognitive stimulation. In 2013, Fissler et al. announced that such programs would induce multi-mechanism effects that could interact positively in a synergistic approach². This approach is encouraged in the clinical management of elderly persons to optimize their return home^{3,4}, mainly because cognitive level and brain health are determining factors in maintaining autonomy. In 2015, Erickson, Hillman and Kramer emphasized the need to understand the best way to combine cognitive training or intellectual activities with physical activity, in order to improve cognition and brain health. They then opened perspectives toward exergames⁵.

Currently, several authors report growing evidence that combined programs are superior to simple programs in older adults, with simultaneous interventions having a greater effect than sequential ones^{6–8}. The systematic review by Bruderer-Hofstetter et al. find 12 effective combined programs which improved specific aspects of physical activity and/or cognitive function. Five of these combined programs are superior to physical exercises and/or cognitive training alone⁶. Results of the meta-analysis of Zhu et al., including 20 interventional studies (2667 participants), show that the combined intervention

produces greater effects on overall effect size (0.22, $p < 0.01$) compared to physical exercise⁸. In the same line, Bamidis et al. argue that simultaneous physical and cognitive training should generate more benefits than simple training, especially when the program offers a socially challenging and attractive environment, like the case of exergames⁹. In 2020, Soltani et al. described exergames as a tool to combat sedentary lifestyles and deliver physical activity in a new way, through a safe, accessible and potentially home-based experience¹⁰. The American College of Sport Medicine even defines exergames as the future of physical activity¹¹. Exergames also address some of the barriers to practice (such as travel, weather, and fatigue). Older adults enjoy practicing exergames since they facilitate long-term investment in physical practice¹². In studies based on exergame intervention programs¹³, the feeling of safety, attraction and enjoyment of play is high, whereas the dropout rate is very low. However, much remains to be studied in order to provide the most effective and appropriate programs possible. To this end, recent literature suggests several characteristics that are worth to be considering.

General characteristics of the exercise program

Multimodality. To be more effective on cognition in older adults, combined multimodal programs offer very interesting benefits. Most of the time, these programs include a combination of aerobic physical activity and cognition (for a review¹⁴), although some articles highlight the relevance of other dimensions as well. In his review, Barnes states that to maximize benefits, it seems relevant in the future to offer exercises that engage learning, coordination, multiple muscle groups and continuous cognitive stimulation¹⁵. In a very complete multimodal approach, Montero-Odasso et al. present an intervention protocol (e.g., SYNERGIC TRIAL), combining up to four dimensions: aerobic activity, muscle strengthening, cognitive training and vitamin D intake¹⁶. Anderson-Hanley et al. also report the importance of more compelling, motivating multimodal interventions, that address the multiple deficits associated with a lack of stimulation and physical inactivity in older adults¹⁷. The value of group practice is also

¹Université Paris-Saclay, CIAMS, 91405 Orsay cedex, France. ²Université d'Orléans, CIAMS, 45067 Orléans, France. ³Université de Paris Cité, I3SP, F-75015 Paris, France. ✉email: alexandra.perrot@universite-paris-saclay.fr

highlighted in a meta-analysis⁸. Indeed, social engagement has previously been associated with neurogenesis and improved cognitive function¹⁸, as well as a more effective practice strategy with training partners¹⁹.

Simultaneity. Another important aspect is the simultaneity of programs. In 2013, Fissler et al. pointed out that several works combining cognitive training and physical activity showed no synergistic effect^{2,20–22}. For example, Legault et al. examine the effect of physical activity training intervention and/or cognitive training intervention in 73 community-dwelling persons, aged 70–85 years. They find no statistically significant differences in 4-months changes in composite scores of cognitive, executive, and episodic memory functions between the different groups²¹. A possible explanation is that the two program components were not simultaneous. Fissler indicates that simultaneity is an important component of the guided plasticity facilitation framework in order to observe interaction effects. The facilitation of cognitive plasticity induced by physical stimulation appears to be greatest during or immediately after exercise, in parallel with the increase of Brain-Derived Neurotrophic Factor (BDNF) levels, which slow down 1 h after exercise²³. Since the time window to obtain benefits from interaction effects appears to be quite small⁸, several reviews emphasize the need for simultaneity^{8,24–26}.

In fact, simultaneity also places participants in dual-task situations, allowing older adults to transfer learning to new tasks^{24,27–30}. Even if most of the effects of age moderators were characteristic to a specific domain (e.g., expertise in typing will not help one drive a car better), transfers to other untrained tasks were more often observed during dual-task programs³¹. Older people can be taught to flexibly allocate their resources to different stimuli, which would generate broader benefits on high-level cognitive processes than with standard programs.

Interactivity. Interactivity between physical and cognitive stimulation is important to generate cognitive benefits in older adults^{32,33}. Interactivity produces cognitive benefits through a synergistic effect that magnifies benefits. To prevent age-related declines and to maintain brain health, continuous active interaction with the environment that engages cognitive, physical and sensory systems is necessary³⁴. The relevance of this interactivity also echoes the theory of Herold et al., which encourages further development of stimuli generating connections between physical, motor and cognitive demands³⁵. This theory argues for “moving while thinking” rather than “thinking while moving”. Incorporating cognitive tasks into motor acts, appears to be the most promising approach to improve cognitive reserve, rather than presenting them separately. The “embedded” cognitive task becomes a relevant prerequisite for the success of the cognitive-motor task. Moreover, this type of stimulation more closely resembles real-life situations. This proximity to real-life situations may generate greater adherence to the practice and, thus, greater benefits. Indeed, the benefits are moderated by participants’ expectations and the perceived importance of the program^{2,35}. Similar to dance or tai chi^{25,36,37}, exergames offer situations that naturally combine physical and interactive cognitive stimuli³⁵.

To summarize, programs combining physical and cognitive stimulation seem to be relevant to generate cognitive benefits in the elderly, particularly because of their multimodality. Moreover, they can be offered simultaneously and interactively, which seems to increase their effectiveness. It is now necessary to go into more detail about the characteristics of physical and cognitive stimulation.

Characteristics of physical stimulation

Physical multimodality. Although aerobic stimulation dominates much of the literature on the subject, it appears that it does not explain everything, and that multimodality is also relevant. A

growing body of work argues that resistance training programs may also be effective on cognition in older adults^{38–40}. Cassilhas et al. demonstrate that 24 weeks of either thrice-weekly resistance training improved memory performance and verbal concept formation among 62 community-dwelling senior men aged 65–75 years. Liu-Ambrose et al. demonstrate that an individualized home-based program of balance and strength significantly improves inhibition (Stroop test; $p < 0.05$) after 6 months among 74 seniors aged 70 years and older. Marston et al. investigate the effect of a 12-week of intense resistance training on cognitive function in 45 late middle-aged adults and observe an improvement in verbal memory ($p = 0.02$)⁴⁰. Resistance training is known to increase the level of Human Growth Hormone (HGH) and Insulin-like Growth Factor One (IGF-1), which have a positive effect on neuronal growth and performance^{31,41–43}. Therefore, it seems relevant to combine aerobic stimulation and muscle strengthening, as the HGH and IGF-1 hormones may help to enhance the effects of an aerobic program in older individuals. In addition, the recent meta-analysis by Marinus et al. argues in favor of strengthening programs or combined strengthening/aerobic programs to generate an increase in blood BDNF levels⁴⁴. The increase in the peripheral BDNF concentrations is significant after strength training ($Z = 2.21$, $p = 0.003$) and combined aerobic/strength training ($Z = 3.03$, $p = 0.002$) but not after aerobic exercise training ($Z = 0.82$, $p = 0.41$). Single exercise is not as beneficial as a multimodal program offering aerobic, muscle strengthening, balance and flexibility exercises¹⁵.

Several studies defend similar conclusions, advising solicitation of the aerobic pathway and muscular resistance, while also highlighting the value of adding situations requiring complex motor skills and coordination^{45,46}. Indeed, programs based on gross motor activities have shown interesting results on cognition^{47–49}. Berryman et al. reveal that gross motor activities lead to equivalent improvement in executive functions, compared to combined high intensity aerobic and strength training, in a cohort of healthy older adults⁴⁷. Gregoire et al. find that gross motor skills training leads to increased BDNF levels in healthy over 60 years old adults, significantly more than two aerobic/strength programs⁴⁸.

Based on several works^{50,51} and on the meta-analysis of Northey et al.⁵², Torre et al.⁵³ argue that such training is relevant to improve cognitive functions in the elderly and put forward the hypothesis of cognitive-motor dedifferentiation to partly explain these effects. This hypothesis states that the reduction with age of the number of specific neural networks subservient to a specific function result in stronger links between cognitive, sensory, and motor domains^{54,55}. Therefore, executive functions would be solicited, during complex motor situations, more in the elderly than in younger people. Consequently, it seems worthwhile to integrate this type of solicitation in order to increase cognitive benefits for the elderly.

If we summarize the most relevant characteristics to be implemented in the physical dimension of a program, it appears that multimodal interventions stimulating the aerobic pathway and the muscle strengthening, while soliciting gross motor activities, are the most interesting ones.

Characteristics of cognitive stimulation

Challenge. The literature highlights several interesting characteristics of the cognitive dimension of a program, such as the level of cognitive challenge of the task. In their meta-analysis, Gheysen et al. report that the cognitive challenge offered by the program is more important in observing significant effects on cognition than the number of sessions²⁵. Physical activity combined with cognitive challenge shows significantly greater cognitive improvement ($g = 0.160$; 95% CI 0.041–0.279, $p = 0.008$) and the effects are not moderated by session frequency and intervention length. Barcelos et al. point out that exergames with high cognitive demand generate greater effects than programs with low

cognitive demand tasks³². In particular, in their Aerobic and Cognitive Exercise Study (ACES), on 64 community based older adults, they found that exergames based on an effortful cognitive challenge (i.e., exer-score) produced greater cognitive benefits than exergames with relatively passive cognitive processing (i.e., exer-tour). Repeated measures ANOVAs conducted for each of the 3 measures of executive function reveal significant effect for Color trails after a single-bout ($p = 0.02$) and for Stroop test after 3 months of exercise ($p = 0.007$).

Variability. Training on a variety of tasks rather than on a single type of task appears to bring global benefits and thus to improve transfers to untrained tasks². However, this variability should not concern only the number of tasks proposed but also the processes solicited by the tasks and stimuli⁵⁶. The more a training program is associated with a variety of combinations of processes involved, the greater the transfer effect observed^{57–59}. For example, Perrot et al. find that the scope of benefits of an action video game is broader than those from a cognitive training game. The digit symbol substitution test, the Corsi block test, the spatial relations test, and the number comparison test show significantly greater change in the action video game group, with a larger variability in required processes than in the cognitive training game with low variability⁵⁸. Moreover, challenging and variable tasks stimulate intrinsic motivation⁶⁰, which is conducive to long-term adherence; at the same time, it has been shown that the psychological state related to motivation facilitates brain plasticity^{61,62}.

This variability can also be reflected in the way cognitive tasks are performed in intervention programs. Indeed, Kramer et al. examined the efficacy of two different multiple-task training strategies (variable priority training and fixed priority training) for the acquisition, retention, and transfer of task coordination skills for both young and old adults. They also demonstrate that individuals trained in the variable priority condition display superior transfer to untrained tasks and better retention of time-sharing skills, over a 2-mo period, than do the individuals trained in the fixed priority condition⁶³. The fact that variable-priority training showed generalization of benefits to other tasks suggests that older adults may gain efficiency in a more general cognitive skill than the one being trained. The type of training would therefore generate different cognitive effects. This argument is also supported through the INTERACTIVE model⁶⁴, which states that training modalities (repetitive or strategic) modulate training-induced neural changes. A repetitive type of training would allow a decrease in activations and thus an increase in neural efficiency, whereas a strategic type of training would generate new activations and thus a compensation mechanism⁶⁵. The benefits of the type of training proposed depends on the level of reserve of the participants. Older people with a high brain reserve will benefit more from strategic training than those with a lower reserve, who will prefer a repetitive type of training. It appears important to take these parameters into account in order to propose the best suited programs possible.

To summarize the interesting features to implement in the cognitive dimension of a program, complex and variable cognitive stimuli seem to hold the greatest promise for generating cognitive benefits and the broadest transfers to untrained tasks. However, training modalities will have to take into account the characteristics of the participants and the objectives to be reached.

Specific characteristics of video games

Gamification. The video game and virtual environment can also be a factor in additional benefits^{17,33}. Video games are inherently entertaining while stimulating cognitive function^{66,67} and increasing social engagement, positive emotions, and generating synergistic effects on cognitive function and neuroplasticity. Anderson et al. investigate the impact of 3 months of cybercycling versus

traditional exercise on executive function and plasma BDNF, on 63 older adults. Results reveal significant benefits for the cybercycling group on executive function ($p = 0.002$) and on plasma BDNF ($p = 0.05$), compared with the traditional exercise group¹⁷. Few years later, the same author with his colleagues find that the cyberbike generated more benefits on 14 community-dwelling older adults meeting screening criteria for mild cognitive impairment, than a normal bike, and that these results cannot be explained by the level of adherence (identical between the two programs)³³. They argue that the screen generated additional benefits, through motivation and entertainment. The gameplay offered by most exergames (e.g., virtual environment, objectives, challenges, rules, biofeedback and immersion) contributes to these games' strong appeal⁶⁸. Adcock et al. discuss the benefits of gamification on training³⁴. The game generates an enriched environment and thus additional cognitive stimulation; in fact, this environment is further enriched because it is often new to older adults, who are less accustomed to such recreation. Moreover, some studies on the effects of environmental enrichment highlight the importance of novelty for cognition and brain health^{2,69,70}.

Variability. Another strength of video games lies in the situations proposed by most exergames, which correspond to open tasks⁶⁸ in which the environment varies, requiring higher executive functions⁷¹. In these types of situations, players are required to plan, make decisions and inhibit others in order to correctly interpret the stimuli generated by their movements and their displacements in the virtual environment⁷². Therefore, the stimuli offered by video games can improve these high-level cognitive functions⁶⁸ that are so important to autonomy in the elderly⁷³. Video game input is also interesting because it can generate transfers to untrained tasks, whereas several authors have pointed out that the benefits of cognitive training were mainly seen in trained tasks and only a few in other situations^{2,74–76}. For example, Ball et al. study evaluate whether 3 cognitive training interventions improve mental abilities and daily functioning in 2832 older, independent-living adults, aged 65–94 years. They demonstrate that cognitive intervention helps older adults to perform better on specific cognitive ability for which they are trained ($p < 0.001$ for all cognitive targeted ability) but no training effects on everyday functioning are detected at 2 years⁷⁶. This could be due to greater variability in video game situations compared to cognitive training tasks². Several authors also defend the hypothesis that new motor skills acquired during gameplay could generate transfers to other activities^{11,77}.

Immersion. Another interesting characteristic to set up and explore, which is specific to video games and exergames, concerns immersion in the game. Immersion depends on the immersiveness (isolation from the real environment), inclusiveness (number of sensory modalities proposed), and realism of the proposed virtual situation⁷⁸. The neuropsychological performance of older people increases more with virtual reality cognitive training than with a more traditional cognitive training program, suggesting that mental engagement in an immersive environment plays an important role in cognitive and especially executive improvements. Pedrolì et al. evaluate the efficacy of a novel Virtual Reality-based mixed training protocol for improving executive functions and spatial memory in patients with cognitive decline. The results show a significant improvement in executive functioning in the Virtual Reality group after the training period, compared to a classic rehabilitation protocol group⁷⁹.

Montana et al. also confirm with a systematic review on 16 studies that virtual reality-based training increases neural plasticity⁸⁰, which improves cognitive function. Therefore, an exergame in a virtual environment will generate more cognitive improvement than an exergame with low immersion. In 2020, Huang proposes to combine an exergame and an immersive virtual environment, for a greater effect on brain health, in

General stimulation	Physical stimulation	Cognitive stimulation	Video Game stimulation
<ul style="list-style-type: none"> • Multimodality • Simultaneity • Interactivity 	<ul style="list-style-type: none"> • Physical multimodality 	<ul style="list-style-type: none"> • Challenge • Variability 	<ul style="list-style-type: none"> • Gamification • Variability • Immersion

Fig. 1 Overview of the characteristics of the stimulation programs. List of important characteristics, divided into four areas.

particular by arousing the feeling of presence, which, in turn, increases cognitive performance in inhibition and flexibility⁸¹. Immersive technologies, which allow players to isolate themselves from the real world and to explore a virtual environment, generate a spatial presence experience⁸². This sense of presence is when, during a video game and/or in a virtual environment situation, players feel as if they are somewhere other than where they actually physically are⁸³. And it has already been shown that spatial presence in an immersive environment generates an increase in the activity of brain regions associated with cognitive functions, and particularly executive functions⁸⁴. It seems important to increase the immersive aspect of exergames to create a strong sense of presence, which could serve as a new strategy in preventing cognitive decline.

In 2021, Temprado's article echoed several of the characteristics highlighted so far, namely interactivity, immersion, novelty, attractiveness and challenge, and considers them to be the essential content of an exergame program to generate interesting transfers to both cognitive functions and daily activities⁴⁶. The author also emphasizes the importance of proposing natural and spontaneous actions in an emotional context adapted to daily life (e.g., catching, hitting, intercepting moving objects, coordinating several limbs simultaneously and controlling balance).

To summarize, Fig. 1 shows all the characteristics discussed in this review that seem to offer the most efficient stimulation to the elderly.

Limitations and gray areas

Although several studies observe a beneficial effect of exergame programs on the cognition of older adults, that exceeds the benefits of simple programs (e.g., cognitive training, video games or physical activity) (for review¹⁴), the conclusions are not unanimous^{85,86} and the results remain quite heterogeneous. For example, Ordnung et al. investigate the effects of an exergame training over 6 weeks on cognitive, motor, and sensory functions in 30 healthy old participants, randomly assigned to either an exergame training group or a control group without training. Results indicate that even though exergames might improve gaming performance, behavioral assessment was probably not sensitive enough to capture exergaming-induced improvements⁸⁵. The systematic review by Gallou-Guyot et al.¹³, conducted on 18 reviews even reports that exergames do not outperform the effects of more traditional combined programs on cognitive functions. One review finds exergame interventions effective on cognitive functions. Two reviews find that exergames interventions are equivalent compared to fall prevention programs, single task training and active and inactive controls. One reason that may explain this inconsistency is the variety of exergames that can generate different effects based on their physical and cognitive demands^{87–92}. Indeed, metabolic and/or cognitive demands may be low, very basic or general in certain exergames, but highly developed and specific in others. Therefore, they can trigger different mechanisms. Three categories of exergames are identified as effectively generating differences in cognitive and physical stimulation¹⁴, namely (i) dance and step video games, (ii) commercial home consoles, and (iii) virtual ergometers. Each category has both positive and negative points.

On the one hand, home consoles (e.g., Nintendo, Kinect) provide a wide variety of games, and thus varied forms of physical and cognitive stimulation⁸⁹, whereas dance ergometers and exergames have more restricted variety and possible stimulation^{93,94}. On the other hand, the intensity of practice is easier to control with the latter exergames, making them simpler to use in programs and to determine their effect^{17,32}. Thus, there is the versatility of possible combinations of physical stimuli (endurance, strength, flexibility and motor skills) and cognitive stimuli (type of games offered and cognitive functions most solicited), which makes comparisons between studies difficult. It seems necessary to clarify the physical effort generated (intensity and type) and the cognitive demand (amplitude and functions required).

To create an optimal multimodal program for the cognitive health of the elderly, much work remains to be done to clarify not only the content but also the intensities, durations and frequencies^{8,14,95–98}. Indeed, as highlighted by Erickson, Hillman & Kramer⁵, and by Gheysen et al.²⁵, a considerable knowledge gap persists to understand how to get the best benefits from these enriched combined stimulations, with the dose-response relationship remaining a gray area that needs to be addressed, especially in terms of the intensities of the cognitive and physical stimulations offered simultaneously. In their meta-analysis, Zhu et al.⁸ state that stimuli that are demanding in physical intensity and cognitive demand could also have negative effects on older adults, generating cognitive fatigue⁹⁹ excessive stress and less engagement in the activity¹⁰⁰. They also find that high frequency of practice does not produce the best effects on cognition. Interventions scheduled five or more times per week showed less effectiveness than those conducted fewer than five times. These findings echo other meta-analyses conducted on cognitive training programs^{101,102} and video games⁶⁷. Thus, it appears that a “maximum dosage” exists and that future work is needed to best adjust the frequency of practice, without risking an overdose. The beneficial effects of combined programs do not appear to depend on the length of the program, or on the number, the frequency or the duration of sessions^{25,103}. More emphasis should be placed on the qualitative aspects of combined exercise and cognition programs (type of exercises), rather than on their quantitative aspects (i.e., duration and intensity)^{49,53}.

At the same time, imbalances between physical and cognitive stimulation could have important consequences. It is possible that excessively high physical demand prevents older people from performing cognitive exercises and thus from benefiting from the synergistic effects. Conversely, cognitive exercises that are too demanding could limit physical investment and not reach sufficient intensity. Combourieu et al. evaluate the impact of different aerobic and cognitive training intervention programs and observed that the group that performed simultaneous aerobic and cognitive training had a significantly lower intensity of effort than the group that performed aerobic activity alone (respectively 32% and 47%, $p < 0.05$)¹⁰⁴. It would therefore be relevant to explore how to achieve this right balance, related here to simultaneity, but also to compare it with very closely spaced sequential programs that could prove a suitable way to avoid the domination of one type of stimulation over another.

Several studies also emphasize the need to develop individualized exergame programs for each practitioner^{11,105}. Commercially available exergames are of value because they are technically very well designed and therefore attractive and entertaining. However, they are less adaptive and specific. It is important to propose situations that are best suited to the participants' objectives and/or abilities. The next challenges will be to propose games that are as attractive as the commercial ones, especially in terms of flow, while being fully customizable.

This part underscores that future works are necessary to clarify and to control the impact of many parameters on the effectiveness of exergames on cognitive aging. In a more general approach to the optimal program for cognition in the elderly, understanding the interactions between factors that may affect the expression of benefits is only at its beginning at present. Factors contributing to program effectiveness still require further investigation. It also seems important to further investigate how combined programs optimize the maintenance of autonomy at home and/or the return home after institutionalization. Even if the improvement of the cognitive and physical functions contributes to sustaining independence, additional work needs to be done on the transfers generated by the combined programs on activities of daily living.

Received: 4 July 2022; Accepted: 15 March 2023;

Published online: 29 March 2023

REFERENCES

- Maillot, P., Perrot, A. & Hartley, A. Effects of interactive physical-activity video-game training on physical and cognitive function in older adults. *Psychol. Aging* **27**, 589–600 (2012).
- Fissler, P., Küster, O., Schlee, W. & Kolassa, I.-T. Novelty interventions to enhance broad cognitive abilities and prevent dementia: synergistic approaches for the facilitation of positive plastic change. *Prog. Brain Res.* **207**, 403–434 (2013).
- Pichierri, G., Murer, K. & de Bruin, E. D. A cognitive-motor intervention using a dance video game to enhance foot placement accuracy and gait under dual task conditions in older adults: a randomized controlled trial. *BMC Geriatr.* **12**, 74 (2012).
- Segev-Jacobovskii, O. et al. The interplay between gait, falls and cognition: can cognitive therapy reduce fall risk. *Exp. Rev. Neurother.* **11**, 1057–1075 (2011).
- Erickson, K., Hillman, C. & Kramer, A. Physical activity, brain, and cognition. *Curr. Opin. Behav. Sci.* **4**, 27–32 (2015).
- Bruderer-Hofstetter, M., Rausch-Osthoff, A. K., Meichtry, A., Münzer, T. & Niedermann, K. Effective multicomponent interventions in comparison to active control and no interventions on physical capacity, cognitive function and instrumental activities of daily living in elderly people with and without mild impaired cognition - A systematic review and network meta-analysis. *Ageing Res. Rev.* **45**, 1–14 (2018).
- Karssemeijer, E. et al. The quest for synergy between physical exercise and cognitive stimulation via exergaming in people with dementia: a randomized controlled trial. *Alzheimers Res. Ther.* **11**, 3 (2019).
- Zhu, X., Yin, S., Lang, M., He, R. & Li, J. The more the better? A meta-analysis on effects of combined cognitive and physical intervention on cognition in healthy older adults. *Ageing Res. Rev.* **31**, 67–79 (2016).
- Bamidis, P. D. et al. A review of physical and cognitive interventions in aging. *Neurosci. Biobehav. Rev.* **44**, 206–220 (2014).
- Soltani, P., Figueiredo, P. & Vilas-Boas, J. P. Does exergaming drive future physical activity and sport intentions. *J. Health Psychol.* **12**, 2173–2185 (2021).
- Benzing, V. & Schmidt, M. Exergaming for Children and Adolescents: Strengths, Weaknesses, Opportunities and Threats. *J. Clin. Med.* **7**, 422 (2018).
- Moholdt, T., Weie, S., Chorianopoulos, K., Wang, A. I. & Hagen, K. Exergaming can be an innovative way of enjoyable high-intensity interval training. *BMJ Open Sport Exerc. Med.* **3**, e000258 (2017).
- Gallou-Guyot, M., Mandigout, S., Bherer, L. & Perrochon, A. Effects of exergames and cognitive-motor dual-task training on cognitive, physical and dual-task functions in cognitively healthy older adults: An overview. *Ageing Res. Rev.* **63**, 101135 (2020).
- Stojan, R. & Voelcker-Rehage, C. A Systematic Review on the Cognitive Benefits and Neurophysiological Correlates of Exergaming in Healthy Older Adults. *J. Clin. Med.* **8**, 734 (2019).
- Barnes, J. N. Exercise, cognitive function, and aging. *Adv. Physiol. Educ.* **39**, 55–62 (2015).
- Montero-Odasso, M. et al. SYNERGIC TRIAL (SYNchronizing Exercises, Remedies in Gait and Cognition) a multi-Centre randomized controlled double blind trial to improve gait and cognition in mild cognitive impairment. *BMC Geriatr.* **18**, 93 (2018).
- Anderson-Hanley, C. et al. Exergaming and older adult cognition: a cluster randomized clinical trial. *Am. J. Prev. Med.* **42**, 109–119 (2012).
- Amieva, H. et al. What aspects of social network are protective for dementia? Not the quantity but the quality of social interactions is protective up to 15 years later. *Psychosom. Med.* **72**, 905–911 (2010).
- Rebok, G. W., Carlson, M. C. & Langbaum, J. B. Training and maintaining memory abilities in healthy older adults: traditional and novel approaches. *J. Gerontol. B Psychol. Sci. Soc. Sci.* **62**, 53–61 (2007).
- Barnes, D. E. et al. The Mental Activity and eXercise (MAX) trial: a randomized controlled trial to enhance cognitive function in older adults. *JAMA Inter. Med.* **173**, 797–804 (2013).
- Legault, C. et al. Study Group Designing clinical trials for assessing the effects of cognitive training and physical activity interventions on cognitive outcomes: the Seniors Health and Activity Research Program Pilot (SHARP-P) study, a randomized controlled trial. *BMC Geriatr.* **11**, 27 (2011).
- Shatil, E. Does combined cognitive training and physical activity training enhance cognitive abilities more than either alone? A four-condition randomized controlled trial among healthy older adults. *Front. Aging Neurosci.* **5**, 8 (2013).
- Knaepen, K., Goekint, M., Heyman, E. M. & Meeusen, R. Neuroplasticity – exercise induced response of peripheral brain-derived neurotrophic factor: a systematic review of experimental studies in human subjects. *Sports Med.* **40**, 765–801 (2010).
- Bherer, L. et al. Synergistic effects of cognitive training and physical exercise on dual-task performance in older adults. *J. Gerontol. B Psychol. Sci. Soc. Sci.* **76**, 1533–1541 (2021).
- Gheysen, F. et al. Physical activity to improve cognition in older adults: can physical activity programs enriched with cognitive challenges enhance the effects? A systematic review and meta-analysis. *Inter. J. Behav. Nutr. Phys. Act* **15**, 63 (2018).
- Tait, J. L., Duckham, R. L., Milte, C. M., Main, L. C. & Daly, R. M. Influence of Sequential vs. Simultaneous Dual-Task Exercise Training on Cognitive Function in Older Adults. *Front. Aging Neurosci.* **9**, 368 (2017).
- Anguera, J. A. et al. Video game training enhances cognitive control in older adults. *Nature* **501**, 97–101 (2013).
- Bherer, L. et al. Training effects on dual-task performance: are there age-related differences in plasticity of attentional control. *Psychol. Aging* **20**, 695–709 (2005).
- Bherer, L. et al. Transfer effects in task-set cost and dual-task cost after dual-task training in older and younger adults: further evidence for cognitive plasticity in attentional control in late adulthood. *Exp. Aging Res.* **34**, 188–219 (2008).
- Li, K. Z. et al. Benefits of cognitive dual-task training on balance performance in healthy older adults. *J. Gerontol. A Bio. Sci. Med. Sci.* **65**, 1344–1352 (2010).
- Colcombe, S. J., Kramer, A. F., McAuley, E., Erickson, K. I. & Scaif, P. Neurocognitive aging and cardiovascular fitness: recent findings and future directions. *J. Mol. Neurosci.* **24**, 9–14 (2004).
- Barcelos, N. et al. Aerobic and Cognitive Exercise (ACE) Pilot Study for Older Adults: Executive Function Improves with Cognitive Challenge While Exergaming. *J. Inter. Neuropsychol. Soc.* **21**, 768–779 (2015).
- Anderson-Hanley, C. et al. The Aerobic and Cognitive Exercise Study (ACES) for Community-Dwelling Older Adults With or At-Risk for Mild Cognitive Impairment (MCI): Neuropsychological, Neurobiological and Neuroimaging Outcomes of a Randomized Clinical Trial. *Front. Aging Neurosci.* **10**, 76 (2018).
- Adcock, M. et al. A usability study of a multicomponent video game-based training for older adults. *Eur. Rev. Aging Phys. Act.* **17**, 3 (2020).
- Herold, F., Hamacher, D., Schega, L. & Müller, N. G. Thinking while moving or moving while thinking—Concepts of motor—cognitive training for cognitive performance enhancement. *Front. Aging Neurosci.* **10**, 228 (2018).
- Predovan, D., Julien, A., Esmail, A. & Bherer, L. Effects of Dancing on Cognition in Healthy Older Adults: a Systematic Review. *J. Cogn. Enhanc.* **3**, 161–167 (2019).
- Vranceanu, T. et al. Dance your stress away: comparing the effect of dance/movement training to aerobic exercise training on the cortisol awakening response in healthy older adults. *Stress* **22**, 687–695 (2019).
- Cassilhas, R. C. et al. The impact of resistance exercise on the cognitive function of the elderly. *Med. Sci. Sports Exerc.* **39**, 1401–1407 (2007).
- Liu-Ambrose, T. et al. Otago home-based strength and balance retraining improves executive functioning in older fallers: a randomized controlled trial. *J. Am. Geriatr. Soc.* **56**, 1821–1830 (2008).
- Marston, K. J. et al. Resistance training enhances delayed memory in healthy middle-aged and older adults: A randomised controlled trial. *J. Sci. Med. Sport* **22**, 1226–1231 (2019).

41. Carro, E., Trejo, J. L., Busiguina, S. & Torres-Aleman, I. Circulating insulin-like growth factor I mediates the protective effects of physical exercise against brain insults of different etiology and anatomy. *J. Neurosci.* **21**, 5678–5684 (2001).
42. Cotman, C. W. & Berchtold, N. C. Exercise: a behavioral intervention to enhance brain health and plasticity. *Trends Neurosci.* **25**, 295–30 (2002).
43. Godfrey, R. J., Madgwick, Z. & Whyte, G. P. The exercise-induced growth hormone response in athletes. *Sports Med.* **33**, 599–613 (2003).
44. Marinus, N. et al. The Impact of Different Types of Exercise Training on Peripheral Blood Brain-Derived Neurotrophic Factor Concentrations in Older Adults: A Meta-Analysis. *Sports Med.* **49**, 1529–1546 (2019).
45. Hötting, K. & Röder, B. Beneficial effects of physical exercise on neuroplasticity and cognition. *Neurosci. Biobehav. Rev.* **37**, 2243–2257 (2013).
46. Temprado, J. J. Can Exergames Be Improved to Better Enhance Behavioral Adaptability in Older Adults? An Ecological Dynamics Perspective. *Front. Aging Neurosci.* **13**, 670166 (2021).
47. Berryman, N. et al. Multiple roads lead to Rome: combined high-intensity aerobic and strength training vs. gross motor activities leads to equivalent improvement in executive functions in a cohort of healthy older adults. *Age* **36**, 9710 (2014).
48. Grégoire, C. A. et al. Gross Motor Skills Training Leads to Increased Brain-Derived Neurotrophic Factor Levels in Healthy Older Adults: A Pilot Study. *Front. Physiol.* **10**, 410 (2019).
49. Pesce, C. Shifting the focus from quantitative to qualitative exercise characteristics in exercise and cognition research. *J. Sport Exer. Psycho.* **34**, 766–786 (2012).
50. Niemann, C., Godde, B. & Voelcker-Rehage, C. Not only cardiovascular, but also coordinative exercise increases hippocampal volume in older adults. *Front. Aging Neurosci.* **6**, 170 (2014).
51. Voelcker-Rehage, C., Godde, B. & Staudinger, U. M. Cardiovascular and coordination training differentially improve cognitive performance and neural processing in older adults. *Front. Hum. Neurosci.* **5**, 26 (2011).
52. Northey, J. M., Cherbuin, N., Pumpa, K. L., Smees, D. J. & Rattray, B. Exercise interventions for cognitive function in adults older than 50: a systematic review with meta-analysis. *Br. J. Sports Med.* **52**, 154–160 (2018).
53. Torre, M. M., Langeard, A., Hugues, N., Laurin, J. & Temprado, J. J. Comparison of Three Physical-Cognitive Training Programs in Healthy Older Adults: A Study Protocol for a Monocentric Randomized Trial. *Brain Sci.* **11**, 66 (2021).
54. Schäfer, S., Huxhold, O. & Lindenberger, U. Healthy mind in healthy body? A review of sensorimotor–cognitive interdependencies in old age. *Eur. Rev. Aging Phys. Act.* **3**, 45–54 (2006).
55. Sleimen-Malkoun, R., Temprado, J. J. & Berton, E. Age-related dedifferentiation of cognitive and motor slowing: insight from the comparison of Hick-Hyman and Fitts' laws. *Front. Aging Neurosci.* **5**, 62 (2013).
56. Thorell, L. B., Lindqvist, S., Bergman Nutley, S., Bohlin, G. & Klingberg, T. Training and transfer effects of executive functions in preschool children. *Dev. Sci.* **12**, 106–113 (2009).
57. Green, C. S. & Bavelier, D. Exercising Your Brain: A Review of Human Brain Plasticity and Training-Induced Learning. *Psychol. Aging* **23**, 692–701 (2008).
58. Perrot, A., Maillot, P. & Hartley, A. Cognitive Training Game Versus Action videogame: Effects on Cognitive Functions in Older Adults. *Games Health J.* **8**, 35–40 (2019).
59. Stuss, D. T. et al. Cognitive rehabilitation in the elderly: A randomized trial to evaluate a new protocol. *J. Inter. Neuropsychol. Soc.* **13**, 120–131 (2007).
60. Ryan, R. M. & Deci, E. L. Self-determination theory and the facilitation of intrinsic motivation, social development, and well-being. *Am. Psychol.* **55**, 68–78 (2000).
61. Bao, S., Chan, V. T. & Merzenich, M. M. Cortical remodelling induced by activity of ventral tegmental dopamine neurons. *Nature* **412**, 79–83 (2001).
62. Kang, M. J. et al. The wick in the candle of learning: epistemic curiosity activates reward circuitry and enhances memory. *Psychol. Sci.* **20**, 963–973 (2009).
63. Kramer, et al. Training for executive control: task coordination strategies and aging. In: Gopher D. and Koriat A., (eds.), *Atten.Perform. XVII*. (MIT Press, Cambridge, MA, 1999)
64. Belleville, S. & Boller, B. Comprendre le stade compensatoire de la maladie d'Alzheimer et agir pour promouvoir la cognition et la plasticité cérébrale. *Can. J. Exp. Psychol.* **70**, 288–294 (2016).
65. Boller, B. & Belleville, S. Capacités de réserve et entraînement cognitif dans le vieillissement: similarité des effets protecteurs sur la cognition et le cerveau. *Rev. Neuropsychol.* **4**, 245–252 (2016).
66. Powers, K. L., Brooks, P. J., Aldrich, N. J., Palladino, M. A. & Alfieri, L. Effects of videogame play on information processing: a meta-analytic investigation. *Psychon. Bul Rev.* **20**, 1055–1079 (2013).
67. Toril, P., Reales, J. M. & Ballesteros, S. Video game training enhances cognition of older adults: a meta-analytic study. *Psychol. Aging* **29**, 706–716 (2014).
68. Monteiro-Junior, R. S., Vaghetti, C. A., Nascimento, O. J., Laks, J. & Deslandes, A. C. Exergames: neuroplastic hypothesis about cognitive improvement and biological effects on physical function of institutionalized older persons. *Neural Rege Res.* **11**, 201–204 (2016).
69. Angevaren, M. et al. Intensity, but not duration, of physical activities is related to cognitive function. *Eur. J. Cardiovasc. Prev. Rehab.* **14**, 825–830 (2007).
70. Raichlen, D. A. & Alexander, G. E. Adaptive Capacity: An Evolutionary Neuroscience Model Linking Exercise, Cognition, and Brain Health. *Trends Neurosci.* **40**, 408–421 (2017).
71. Taddei, F., Bultrini, A., Spinelli, D. & Di Russo, F. Neural correlates of attentional and executive processing in middle-age fencers. *Med. Sci. Sports Exerc.* **44**, 1057–1066 (2012).
72. Maguire, E. A. et al. Knowing where and getting there: a human navigation network. *Science* **80**, 921–924 (1998).
73. González-Colaço Harmand, M. et al. Cognitive decline after entering a nursing home: a 22-year follow-up study of institutionalized and noninstitutionalized elderly people. *J. Am. Med. Dir. Asso.* **15**, 504–508 (2014).
74. Hampstead, B. M. et al. Mnemonic strategy training improves memory for object location associations in both healthy elderly and patients with amnesic mild cognitive impairment: a randomized, singleblind study. *Neuropsychol* **26**, 385–399 (2012).
75. Mahncke, H. W. et al. Memory enhancement in healthy older adults using a brain plasticity-based training program: a randomized, controlled study. *Proc. Natl Acad. Sci USA* **103**, 12523–12528 (2006).
76. Ball, K. et al. Effects of cognitive training interventions with older adults: a randomized controlled trial. *JAMA* **288**, 2271–2281 (2002).
77. Staiano, A. E. & Calvert, S. L. Exergames for Physical Education Courses: Physical, Social, and Cognitive Benefits. *Child Dev. Perspect.* **5**, 93–98 (2011).
78. Slater, M. & Wilbur, S. A Framework for Immersive Virtual Environments (FIVE): Speculations on the Role of Presence in Virtual Environments. *Presence Teleoperators Virt. Environ.* **6**, 603–616 (1997).
79. Pedroli, E., et al. *Beyond Cognitive Rehabilitation: Immersive but Noninvasive Treatment for Elderly*. In: Cipresso P., Serino S., Villani D. (eds) *Pervasive Computing Paradigms for Mental Health*. MindCare 2019. Lecture Notes of the Institute for Computer Sciences, Social Informatics and Telecommunications Engineering, 288. (Springer, Cham, 2019).
80. Montana, J. I., Tuena, C., Serino, S., Cipresso, P. & Riva, G. Neurorehabilitation of Spatial Memory Using Virtual Environments: A Systematic Review. *J. Clin. Med.* **8**, 1516 (2019).
81. Huang, K. T. Exergaming Executive Functions: An Immersive Virtual Reality-Based Cognitive Training for Adults Aged 50 and Older. *Cyberpsychol. Behav. Social Netw.* **23**, 143–149 (2020).
82. Iachini, T. et al. The experience of virtual reality: are individual differences in mental imagery associated with sense of presence. *Cogn. Process* **20**, 291–298 (2019).
83. Sheridan, T. Musings on Telepresence and Virtual Presence. *Presence: Teleoperators Virt. Environ.* **1**, 120–126 (1992).
84. Kober, S. E., Kurzmann, J. & Neuper, C. Cortical correlate of spatial presence in 2D and 3D interactive virtual reality: an EEG study. *Int. J. Psychophysiol.: Offic. J. Int. Organization Psychophysiol.* **83**, 365–374 (2012).
85. Ordnung, M., Hoff, M., Kaminski, E., Villringer, A. & Ragert, P. No Overt Effects of a 6-Week Exergame Training on Sensorimotor and Cognitive Function in Older Adults: A Preliminary Investigation. *Front. Hum. Neurosci.* **11**, 160 (2017).
86. Sala, G., Tatlidil, K. S. & Gobet, F. Still no evidence that exergames improve cognitive ability: A commentary on Stanmore et al. (2017). *Neurosci. Biobehav. Rev.* **123**, 352–353 (2021).
87. Canabrava, K., Faria, F. R., Lima, J., Guedes, D. P. & Amorim, P. Energy Expenditure and Intensity of Active Video Games in Children and Adolescents. *Res. Q Exer. Sport* **89**, 47–56 (2018).
88. Graves, L. E. et al. The physiological cost and enjoyment of Wii Fit in adolescents, young adults, and older adults. *J. Phy. Act Health* **7**, 393–401 (2010).
89. Lyons, E. et al. Energy expenditure and enjoyment during video game play: differences by game type. *Med. Sci. Sports Exerc.* **43**, 1987–1993 (2011).
90. Miyachi, M., Yamamoto, K., Ohkawara, K. & Tanaka, S. METs in adults while 9 playing active video games: A metabolic chamber study. *Med. Sci. Sports Exerc.* **42**, 1149–1153 (2010).
91. O'Donovan, C. et al. Energy expended playing Xbox Kinect™ and Wii™ games: a preliminary study comparing single and multiplayer modes. *Physiotherapy* **98**, 224–229 (2012).
92. Taylor, L. M. et al. Activity and energy expenditure in older people playing active video games. *Arch. Phy. Med. Rehabil.* **93**, 2281–2286 (2012).
93. Sell, K., Lillie, T. & Taylor, J. Energy expenditure during physically interactive video game playing in male college students with different playing experience. *J. Am. Coll. Health* **56**, 505–511 (2008).
94. Tan, B., Aziz, A. R., Chua, K. & Teh, K. C. Aerobic demands of the dance simulation game. *Int. J. Sports Med.* **23**, 125–129 (2002).

95. Desjardins-Crépeau, L. et al. Effects of combined physical and cognitive training on fitness and neuropsychological outcomes in healthy older adults. *Clin. Inter. Aging* **11**, 1287–1299 (2016).
96. Kueider, A. M., Parisi, J. M., Gross, A. L. & Rebok, G. W. Computerized cognitive training with older adults: a systematic review. *PLoS ONE* **7**, e40588 (2012).
97. Young, J., Angevaren, M., Rusted, J. & Tabet, N. Aerobic exercise to improve cognitive function in older people without known cognitive impairment. *Coch. Library* **4**, 1–141 (2015).
98. Hillman, C. H., Erickson, K. I. & Kramer, A. F. Be smart, exercise your heart: exercise effects on brain and cognition. *Nat. Rev. Neurosci.* **9**, 58–65 (2008).
99. Holtzer, R., Shuman, M., Mahoney, J. R., Lipton, R. & Verghese, J. Cognitive fatigue defined in the context of attention networks. *Neuropsychol. Dev. Cogn. B, Aging Neuropsychol. Cogn.* **18**, 108–128 (2011).
100. Fiatarone Singh, M. A. et al. The Study of Mental and Resistance Training (SMART) study—resistance training and/or cognitive training in mild cognitive impairment: a randomized, double-blind, double-blind controlled trial. *J. Am. Med. Dir. Asso.* **15**, 873–880 (2014).
101. Au, J. et al. Improving fluid intelligence with training on working memory: a meta-analysis. *Psychon. Bull. Rev.* **22**, 366–377 (2015).
102. Li, H. et al. Cognitive intervention for persons with mild cognitive impairment: A meta-analysis. *Ageing Res. Rev.* **10**, 285–296 (2011).
103. Colcombe, S. & Kramer, A. F. Fitness effects on the cognitive function of older adults: a meta-analytic study. *Psychol. Sci.* **14**, 125–130 (2003).
104. Combourieu, L., Perrot, A., Bloch, F., Belleville, S. & Kemoun, G. Effects of simultaneous aerobic and cognitive training on executive functions, cardiovascular fitness and functional abilities in older adults with mild cognitive impairment. *Ment. Health Phys. Act* **15**, 78–87 (2018).
105. Mishra, J., Anguera, J. A. & Gazzaley, A. Video Games for Neuro-Cognitive Optimization. *Neuron* **90**, 214–218 (2016).

AUTHOR CONTRIBUTIONS

Both authors meet all four criteria: (1) Substantial contributions to the conception or design of the work or the acquisition, analysis or interpretation of the data, (2) Drafting the work or revising it critically for important intellectual content, (3) Final

approval of the completed version, (4) Accountability for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Correspondence and requests for materials should be addressed to Alexandra Perrot.

Reprints and permission information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2023