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The effects of a new immersive multidomain training on cognitive, dual-task and physical functions in older adults

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Abstract

The aim of this study was to assess the potential of multidomain training using Immersive and Interactive Wall Exergames (I2WE) to improve the cognitive and physical functions of older adults. This new generation of exergames offers specific advantageous characteristics (e.g., immersion, virtual cognitive solicitation, high physical stimulation, complex motor skills, multiple social interactions) that could make I2WE an enjoyable multidomain training medium for older adults. A pilot study was set up with 34 participants (M = 69.91 years old). It used the pre-tests – training (3 months, 2 one-hour sessions per week for the 2 groups) – post-tests method to compare: a) the cognitive and the Dual-Task (DT) effects (primary outcomes), b) the physical effects and perceived pleasure (secondary outcomes) between an experimental group following an I2WE program (n = 19) to an active control group performing a Walking and Muscle-Strengthening (WMS) program (n = 15). While visuospatial short-term memory was improved for both groups, only I2WE training enhanced visuospatial working memory, inhibition, and DT. All physical functions, except upper body strength, were enhanced for the 2 groups. The perceived pleasure was higher for the I2WE group than the WMS group. The results of this first study have important clinical implications, showing that I2WE can optimize strategies to improve older adults' physical and cognitive health. Virtual and immersive cognitive stimulation combined with varied physical activity (i.e., aerobic, muscle-strengthening, complex motor skills) appear to be major assets of these new exergames. Moreover, the high level of perceived pleasure to I2WE makes it a promising tool for engaging older adults in sustained multidomain practice.

Keywords: exergames, physical activity, healthy aging, cognition, cognitive-motor training, dual-task

1 Introduction

2 Cognitive-motor integrity and Dual-Task (DT) capacities are crucial for maintaining walking and
3 preventing falls [1], and thus, autonomy and quality of life of older adults. Despite this, as their
4 physical and cognitive functions decline [2] and even though novelty and change are beneficial to
5 maintain them, training with one modality (aerobic, muscle-strengthening) or usually combined
6 (aerobic and/or muscle-strengthening and/or balance and/or flexibility) are usually offered to them.
7 They improve cognitive functions [3,4], however, some researchers have pointed out [5] the necessity
8 to extend this field to other forms of physical activity (e.g., complex motor skills, open-ended
9 activities). An optimal combination that includes cognitive training based on enjoyable activities is
10 also essential to anchor participants in sustainable practice. Indeed, multidomain training that
11 combines different components (e.g., physical, motor, cognitive) can generate a synergistic effect,
12 increasing the efficiency of training in enhancing cognitive functions [6].

13 New technologies, like exergames, could offer efficient and enjoyable training support. However, their
14 effects on older adults' physical and cognitive functions are mixed and debated. Several studies have
15 shown that they can be effective [7], greater than physical programs alone [8–10], and even better than
16 programs combining physical and motor activities in improving mental flexibility [11], overall
17 cognitive level [12], and DT skills [13]. However, reviews and meta-analyses [8–10] highlight a great
18 deal of heterogeneity, which negatively impacts the conclusions. Moreover, some studies have failed
19 to demonstrate the superiority of exergames over conventional programs [14–16] or to be ineffective
20 [16,17]. In contrast, the development of a new generation of Immersive and Interactive Wall
21 Exergames (I2WE) could offer the support of an efficient combined training [18], maybe more than
22 training with one modality. However, due to their recent development, few studies have been
23 conducted (*Play Lü* [19], *ExerCube* [20], *Neo One* [18]). I2WE creates simultaneous multidomain
24 training, with complete physical stimulation (i.e., aerobic, muscle strengthening, and complex motor
25 skills) and virtual continuous cognitive solicitation. More specifically, the cognitive task is

1 incorporated into the physical task in accordance with the *Moving While Thinking* approach [21].

2 Thus, the 2 tasks are linked and interactive, which could benefit older adults' cognitive functions since

3 it can increase the synergistic effect of the combined training tenfold [22,23].

4 I2WE offers strong immersive capabilities that can increase session intensity [24], create lower

5 perceived exertion [19], generate better performance [25], and amplify the activity of brain regions

6 associated with executive functions [26]. Indeed, the cognitive stimulation of I2WE triggers greater

7 mental concentration than conventional physical training [20] and potentiates the effects on cognition.

8 These new exergames could generate higher physical intensity than their older counterparts (e.g., *Wii*)

9 or conventional physical activity. The large play area encourages energy expenditure, and participants

10 cannot use energy-saving strategies. They must unconsciously perform complex movements during

11 the sessions, using the whole body to achieve their goals (e.g., using the upper body to throw a ball,

12 moving quickly to reach targets, bending to retrieve a ball from the floor). A recent study on

13 adolescents using the *Play Lii* device [19] shows that it generates moderate to high intensity. *Neo One*

14 wall [18] also leads to moderate to high intensity on older adults, the levels of physical intensity

15 recommended by the ACSM [27] to generate benefits on cognitive functions [28,29].

16 Some I2WE can be played with up to 10 participants, naturally encouraging situations of cooperation

17 and/or opposition [19]. These activities hold promise for improving cognitive functions in older adults

18 [30]. Collective exergames also lead to higher intensity [19] and better results on improving functional

19 capacities in older adults [31] compared to exergames played alone. Thus, I2WE may be a promising

20 option with advantageous modalities to counter the limitations of conventional training and

21 simultaneously improve cognitive, dual-task, and physical functions in the elderly.

22 To our knowledge, the effects of I2WE compared to Walking and Muscle-Strengthening (WMS) on

23 cognitive, DT, and physical parameters is currently unknown, with no evidence describing which

24 exercise is superior to improve cognitive, DT, and physical functions. Therefore, this study aimed to

compare the effects of I2WE and WMS on a) cognitive functions and DT (primary outcomes) and b) physical parameters and perceived pleasure (secondary outcomes). We hypothesized that both groups would improve their cognitive, DT, and physical measures, whereas cognitive functions would enhanced in the I2WE group to a higher degree, consistent with Kraft's theory [6] of the synergistic effect of combined training.

Methods

Population

Potential participants were contacted via mail, flyers, and call for participation in the Montreuil city (France) newspaper, and recruitment of participants was conducted between December 2021 and February 2022. A power analysis, using G*Power version 3.1.9.7, based on the primary statistical test planned for this study (2×2 within-between interaction ANOVA) revealed that a sample size of 34 participants was needed ($\alpha = .05$; power = .80; effect size: $\eta^2 = .06$). The dropout level was assumed to be 15 % so 40 community-dwelling older adults were recruited from Seine-Saint-Denis, France, volunteered to participate. All participants gave their written informed consent and were not compensated for their participation. The study was approved by the Polethis research ethics committee (CER-PS n°462). Participants met the following inclusion criteria: (a) be over 60 years old, (b) have a MMSE [32] score above 27, (c) engage in less than 2.5 hours of physical activity per week assessed by the QAPPA [33], (d) score 3 or higher on a subjective health scale (1= very poor to 5= very good), (e) be retired, (f) have no major pathology, (g) have normal or corrected vision and hearing, (h) have no difficulty bending or using their shoulders, (i) do not play video games or exergames, (j) present a medical certificate not contraindicating physical activity). They did not know in advance which group they would be included in.

Study design

This study was a single-center interventional study wherein participants were randomized into one of two groups (I2WE or WMS). The randomization was carried out in single-blind conditions: participants did not know their group in advance, and the researcher was not blinded. The allocation of participants between groups was done as the participants were included in the study according to 2 criteria: a) the equality in terms of age between the 2 groups and b) the availability of participants (randomization was not performed with a software). The pre- and post-tests were carried out just before the start and just after the end of the program, so there was a 13-week gap. The researcher who administered the tests had a bachelor's and a master's degree, specialized in physical activity for aging, and was trained to administer the tests.

The cognitive, dual-task, and physical tests took around 1h30 per participant. Cognitive tests were performed first, followed by physical tests. They were carried out in a quiet room. A break of about 3 minutes was observed between each test to manage the participant's mental fatigue and attention effect. In addition, the participant was regularly asked if they needed an extra break and if they felt ready to start another test. All participants took the tests in the same order, before and after the programs, to control the mental fatigue effect.

Outcomes

Primary outcome measures

The cognitive and DT battery

The French version [34] of **the Zoo Map Test** is from the Behavioural Assessment of the Dysexecutive Syndrome [35], a validated ecological test battery assessing planning ability [36]. To our knowledge, no test-retest coefficients are available for the population studied in this research. The participant indicated the route to take to visit a series of places on a map, avoiding making mistakes. In the *formulation of the plan* part, the participant organized their own travel. In the *execution of the plan*

part, they followed instructions. For each condition, the *total time* and the *sequence score* out of 8 points were collected for a total score out of 16 points.

The Spatial Span Test is a reliable and valid subtest of the Wechsler Memory Scale [37], with an acceptable internal consistency (Cronbach's $\alpha = .61$) [38] and test-retest reliability for 60 to 79 years old ranging from .52 to .65 [39]. In the first part, which assesses visuospatial short-term memory, the participant reproduces a sequence of cubes designated by the examiner in the same order. In the second, which assesses visuospatial working memory, the participant reproduces a sequence of movements in reverse order. The number of cubes increases progressively and determines the *spatial span* and the *backward spatial span*. For each level, the participant always performed 2 trials and scored 1 point for each successful trial. The test ended when 2 errors were made at the same level.

The Stroop Test [40] was used to assess inhibition. It has good reliability (.75 for Board 1, .82 for Boards 2 and 3 [41]) and validity [42]. Each board contained 100 items divided into 10 columns. Only the first 3 boards were kept: the *naming condition*, which contained colored rectangles, the *reading condition*, with color words appearing in black ink and the *interference condition*, which contained color words, appearing in a color different from their meaning. In all 3 conditions, the performance measure was the number of correct responses in 45 seconds. The interference score measure was calculated as follows: board 3 score/(mean of board 1 and 2 scores).

The Mental Rotation Test [43] assesses visuospatial abilities. This valid test displayed substantial internal consistency (KR-20 = .88) and a high test-retest reliability ($r = .83$) [43]. Twenty figures were presented as 2-dimensional visual images. A model was placed at the left end of the line, and 4 structures were located to the right of the model. The participant was asked to indicate which ones were the same figure as the model, taking rotation into account. The score was the number of correct items given in 6 minutes.

The Trail Making Test (TMT) [44] assesses cognitive flexibility, with high test-retest reliability for Part A ($r = .74$), part B ($r = .85$), and B-A ($r = .74$) [45]. Part A involves linking a series of increasing numbers from 1 to 25 by selecting the appropriate number. In part B, the participants connect 2 series of symbols in alternation: 1 of numbers and 1 of letters. This had to be done as quickly as possible without lifting the pen from the paper. If mistakes were made, the examiner informed the participant, who had to correct them. Following Corrigan and Hinkeldey's method [46], flexibility was highlighted specifically by analyzing the time difference in the result B-A, a purer measure of flexibility. Most recently, Sánchez-Cubillo and collaborators confirmed that B-A time minimizes the visuoperceptual and working memory demand of TMT A and TMT B, providing a pure indicator of task-switching [47].

Dual-Task Test (DT). The *single recall task* and *TUG in the dual task (TUG-dt)* tests were used to evaluate the DT. This test was designed for study purposes, so there were no data available to confirm its validity and/or reliability. For the *single recall task*, the examiner said 7 numbers aloud, at a rate of 1 number per second, which the participant repeated immediately after. For the *TUG-dt*, the participant had to simultaneously perform the single recall task and the TUG test (detailed below). Two scores were calculated: the difference between digits given in DT and Single Task (ST) and the difference between the time to complete the task in DT and ST.

Secondary outcome measures

The physical battery

Physical tests were carried out in the following order: a) Chair stand, b) Chair-sit-and-reach, c) Handgrip, d) TUG Test, e) Back scratch, f) Seated Medicine Ball Throw, g) 6-minutes Walking Test. This order ensures that no two functions (e.g., strength, flexibility) and/or body parts (e.g., upper body, lower body) were required in succession. Five tests [i.e., chair-stand, chair-sit-and-reach, Timed Up and Go (*TUG*), Back scratch, 6-minutes Walking Test (*6WT*)], derived from the French version [48] of

the *Senior Fitness Test* [49] were used to assess respectively lower body strength, flexibility, dynamic balance, and endurance.

Chair-stand Test. The participant had to stand and sit up as many times as possible in 30 seconds. The arms were crossed on the chest, the feet always remained on the ground. The number of chair-stands was recorded.

Chair-sit-and-reach Test. Sitting on the edge of a chair, one leg straight, the other bent, the participant had to bring their hand as close as possible to the foot of the straight leg. The number of centimeters between the hand and the foot was measured. The values were negative if the fingers of the hand extended beyond the toes.

TUG Test. The participant had to get up from a chair, walk around a block located in front of them, 3 meters away, and sit down again as quickly as possible. The time to complete this course was recorded.

Back scratch Test. The participant had to bring their two hands as close together as possible (one hand reaching over the shoulder, palm against the back, the other reaching to the middle of the back, back of the hand against the back). The number of centimeters between both hands was measured. The values were negative if the fingers of the two hands crossed.

6WT. The participant was asked to walk as far as possible, in 30-meter round trips, for 6 minutes. The distance was recorded, as well as the heart rate, to determine the intensity of the effort.

Two upper-body strength tests (i.e., Handgrip test [50], Seated Medicine Ball Throw [51]) were added to complete the physical assessment.

Handgrip Test. The participant was standing and had to squeeze the dynamometer with maximum isometric effort, maintained for about 5 seconds. The force created, measured in kilograms, was recorded for both arms. The experimental protocol included a practice trial, followed by three attempts

for each side in alternation, with 30 seconds rest between them. The best of the three trials for each hand was considered for analysis.

Seated Medicine Ball Throw Test. Sitting in a chair, back against the back of the chair, feet flat on the floor, the subject had to throw a 3kg medicine ball as far as possible with both hands, starting from the chest. The distance between the subject and the medicine ball was recorded.

The questionnaires

The French version [52] of the **Physical Activity Enjoyment Scale** [53] with a scale from *absolutely disagree* (1) to *completely agree* (7) was used to evaluate the perceived pleasure. The score was between 7 and 70.

The feeling questionnaire. It was completed at the end of the program. It consisted of 4 questions in the form of a scale from 1 to 5 concerning (a) the difficulty of the sessions, (b) their physical and (c) cognitive developments, and (d) the desire to continue a program of this type.

Intervention

The 2 programs were implemented between February and May 2022 in a sports center in Montreuil (France). The workload was the same between groups: programs were composed of bi-weekly one-hour group sessions over 12 weeks (24 sessions) at a moderate intensity. The Heart Rate (HR) was measured during all sessions using the Polar Verity Sense heart rate monitor placed on the biceps and the perceived exertion using the modified Borg scale [54]. The Heart Rate Reserve (HRR), the difference between the Maximum Theoretical Heart Rate ($MTHR = 192 - 0.007 \times \text{age}^2$, [55]) and the RHR, is used to calculate exercise intensity. For all sessions, the mean intensity was calculated $[(\text{Average Heart Rate} - \text{RHR})/\text{HRR}] \times 100$. A sport therapist supervised the sessions, explaining and demonstrating the exercises, monitoring the participants' safety and correct posture, and encouraging and providing feedback to the participants. There were no activities to increase compliance.

The Immersive and Interactive Wall Exergames (I2WE) program was performed using the *Neo One* device described in Figure 1 and more detailed in this recent study [18]. This I2WE was chosen because of the variety and quality of the games offered, which are accessible to older people [18]. The sessions consisted of 10 minutes of warmup, 40 minutes of the main session using the *Neo One* device, and 10 minutes of cooldown with full body stretching exercises in groups of 4 participants (defined according to the availability of the participants, age, physical and cognitive capacities). The intensity of body workout was moderate (46.97% HHR). Five to 7 five-minutes games were selected from among 15 games [see Additional file 1 for a description of the games]. Various materials were used (e.g., basketball and handball balls, balloons, chairs, hoops, rhythm scales). The games were made more complex by selecting levels (easy, normal, hard) and by adding extra exercises to create cooperative and/or oppositional situations to the games where they were not initially implemented and to increase the physical and/or motor complexity [see Additional file 2].

In every other session, participants of the I2WE group played the *Break It Handball* game individually to measure their capacity to progress in *Neo One* games and to evaluate if they were improving in the training underlying their learning. For 2 minutes, the players had to throw the ball at different targets on the wall. They received immediate feedback on their scores.

The Walking and Muscle-Strengthening (WMS) program was held in groups of 5 to 8 participants (split according to the same criteria as the I2WE group) in the parks of the city of Montreuil, with flat and gradient courses that were used alternately. Participants spent 45 minutes walking and 15 minutes in muscle-strengthening exercises, during which they performed an average of 4881.59 steps (SD = 218.73), measured by standard pedometers. The intensity was 43.90% of the HRR (moderate intensity). The muscle-strengthening exercises were performed using either body weights or small equipment (e.g., balls, elastic bands, rhythm scales) or street furniture (e.g., benches, trees, steps). Approximately 3 to 5 exercises were performed, consisting of 2 to 3 sets of 10 to 20 repetitions.

Data analysis

The analyses were performed using JASP software. Before completing any inferential statistical tests, all relevant assumptions were checked, and if they were met, statistical analysis was allowed to proceed. Measures of variance used were Standard Deviation (SD). The equivalent of I2WE and WMS groups before the program was checked using a *t*-test. For cognitive, DT, and physical tests, repeated ANOVA measures were used to test the interaction between pre-test and post-test x training group (I2WE, WMS) and were completed by 95% Confidence Intervals for mean difference (between pre- and post-tests or between I2WE and WMS). All statistical analyses with a *p*-value < .05 were considered significant. A Bonferroni Post Hoc test was realized if a significant interaction was found. Only the *p*-values from the Post Hoc tests were Bonferroni-corrected. Effect Sizes were calculated to study the power of the results: Eta-Squared for ANOVA and Cohen's *d* for *t* test. To test the reliability of results, Reliable Change Indexes (RCIs) were calculated according to the method presented in Duff's work [56]. The calculation was as follows:

$$RCI = \frac{T_2 - T_1}{\sqrt{(2S_{21}(1 - r_{12}))}}$$

T_1 = mean score at pre-test, T_2 = mean score at post-test, S_1 = standard deviation at pre-test, r_{12} = correlation between T_1 and T_2 . Calculation of the RCI results in a z-score, which needs to be compared with a normal distribution table to be interpreted. Within the existing literature, a z-score of +1.645 or -1.645 would be considered a "reliable change". Correlation analysis was also performed using Spearman correlation, and the potential difference in perceived pleasure between the two groups was tested with a *t*-test.

Results

Participants

The study workflow is shown in Figure 2. 34 participants (26 women) completed the study, and there were no significant differences between the 2 groups in age, years of education, BMI, Resting Heart

Rate (RHR), subjective health, MMSE, QAPPA scores (Table 1) and between all pre-test (Additional file 3 and 4).

Effects of the programs

Primary outcome

Cognitive and DT assessments

The results obtained in the pre- and post-tests for cognitive functions, DT, and the results on simple time and time*group interaction effects from ANOVA are given in Table 2, the results on Post-Hoc Tests are given in Additional file 5, and those of RCI in Additional file 6.

Spatial Span test. Both groups significantly improved their *spatial span*: there was a significant time effect ($p = .02$), with no time*group interaction or group effect ($p = .44$). Post Hoc Comparison for time effect was significant ($p = .02$, $d = .43$). For the *backward spatial span*, only participants in the I2WE group improved their score. There was a significant time ($p < .001$) and a time*group interaction ($p = .01$) effect, with no group effect. Post Hoc analysis revealed a significant difference between pre- and post-tests for the I2WE group ($p < .001$, $d = 1.04$) and none for the other comparisons.

Stroop Test. The I2WE group improved its *interference score* and *words in board 3* after the program, while the WMS group did not, confirmed by the significant score*group interaction for the interference score ($p = .01$), with no simple time or group effect. Post Hoc analysis indicated a significant difference between the pre- and post-test for the I2WE group ($p = .05$, $d = .50$) and none for the WMS group. For the *words in board 3*, there was also a score*group interaction ($p = .03$). Post Hoc analysis showed a significant difference between pre- and post-tests for the I2WE group ($p = .05$, $d = .33$).

Dual-Task Test. The I2WE group improved its time on DT compared to ST after the program, while the WMS group did not. There was a significant time effect ($p = .01$) and a significant score*group interaction ($p = .04$) with no group effect. Post Hoc analysis revealed a significant difference between pre- and post-tests for the I2WE group ($p = .01$, $d = 1.02$) and none for the other comparisons.

TMT. The score*group interaction effect was nearly significant ($p = .06$), but Post Hoc analysis revealed no significant differences.

For all cognitive tests, RCI values indicated that changes were unreliable (none RCIs were between $-\infty$ and -1.645 or between ∞ and 1.645).

Secondary Outcomes

Physical assessment

The results of the pre- and post-tests for physical abilities and the results on simple time effects from ANOVA are given in Table 3 and those of RCI in Additional file 7. Seven measures had a time effect ($p < .01$ or $p < .001$) but no group effect or time*group interaction effect.

For all physical tests, RCI values indicated that changes were unreliable (none RCIs were between $-\infty$ and -1.645 or between ∞ and 1.645).

Evolution of Break It Handball performance

The I2WE group improved their scores, with a significant time effect ($F(11,66) = 7.27$, $p < .001$, $\eta^2 = 0.55$). Post Hoc analysis indicated a significant difference between score 1 and score 9 ($p = .04$), scores 1 and 10 ($p = .01$), 1 and 11 ($p < .001$), and 1 and 12 ($p < .001$) as indicated in Additional file 8.

The link between the evolution of DT performance and Break It Handball performance.

The evolution score of the game performance (score 12–score 1) score was calculated to test the correlation with the change in cognitive test scores (post-test–pre-test). The change in the percentage of time spent in DT versus ST was positively correlated with the change in game performance ($r = .56$, $p = .01$). There were no other correlations with changes in cognitive tests.

Compliance

Compliance was 91.01% (415 sessions out of 456) for the I2WE program versus 85.28% (307 sessions out of 360) for the WMS program. *Perceived pleasure* was significantly higher ($t(32) = 2.34$, $p = .03$, $d = 0.81$) for the I2WE group who scored 63.74 ± 6.04 to 59.57 ± 4.82 for the WMS group. All participants wanted to continue their respective programs. For the I2WE group, 10.53% had a moderate, 36.84% a strong, and 52.63% a very strong desire to continue. For the WMS group, 33.33% had a moderate and 66.67% a strong desire. For physical evolution, 84.21% of the participants in the I2WE group (21.05% very positive) and 93.33% in the WMS group (6.67% neutral) felt a positive change. For cognitive evolution, 78.95% of the I2WE group (21.05% neutral) compared to 20% (80% neutral) of the WMS group felt a positive change. As shown in Table 4, there were no significant differences between effort intensities of the WMS and I2WE groups.

Discussion

This study aimed to compare the cognitive, dual-task, and physical effects of an Immersive and Interactive Wall Exergames program (I2WE) to a Walking and Muscle-Strengthening (WMS) in healthy but inactive older adults.

The effects of programs differ on cognitive and DT capacities, with an advantage for the I2WE group with small to medium effects. Two of the 4 executive functions tested (i.e., visuospatial working memory, inhibition) and DT capacity were enhanced only for the I2WE group. The increase of mental flexibility specific to I2WE group participants was also nearly significant ($p = .06$), and visuospatial

1 short-term memory improved for participants in both groups. However, these improvements were not
2 confirmed by RCIs.

3 Since physical activity, moderate-intensity aerobic, and muscle strengthening were the only same
4 stimulation between the 2 groups, their similar improvement in visuospatial short-term memory could
5 be the consequence. Indeed, physical activity enhances cognitive functions [4] and memory [57]. The
6 benefits of aerobic programs on improving cardiorespiratory health are already known, allowing for
7 better cognitive efficiency [58–60] thanks to better oxygenation of the central nervous system and
8 increased neurogenesis through neurotrophic growth factors. Erickson and his collaborators [57]
9 showed a 2% increase in hippocampal volume and BDNF levels, associated with improvement in
10 spatial memory performance after an aerobic program. Thus, changes in visuospatial short-term
11 memory in both groups may have been driven by aerobic physical activity. Several researchers have
12 emphasized that the aerobic effect is more important for executive functions [4], whereas here, only
13 visuospatial short-term memory was improved for both groups. It may have been sensitive more
14 quickly, and the programs may not have been long/high frequency enough to improve the other
15 functions, whereas these 2 are fundamental to have an effect on executive efficiency [61]. In addition,
16 the strength training that all participants received could also mediate the positive changes in
17 visuospatial short-term memory [62,63]. Cassilhas and collaborators [64] found an increase in IGF-1
18 related to resistance training coinciding with improved cognition.

19 Except for one function, the benefits of aerobic physical activity combined with muscle-strengthening
20 did not explain the superior cognitive variation of the I2WE group in inhibition, visuospatial working
21 memory, and DT. Other multidimensional mechanisms (i.e., complex physical training, rich cognitive
22 training, combined training, cooperative and oppositional activity) inherent to the characteristics of
23 I2WE (see Figure 3) could have been responsible.

24 I2WE are complex physical training that solicited coordination, dynamic balance as well as flexibility
25 through large freedom of movement triggered different structural adaptations linked to distinct

cognitive functions [65]. Already in 2003, Colcombe and Kramer [4] stated that programs combining endurance, muscle strengthening, flexibility, and balance were the most effective for improving executive functions. The richness of physical stimulation and motor complexity could produce greater cognitive benefits [4,5] and encourage transfer effects [21].

In addition to complex physical stimulation, I2WE provide rich cognitive solicitation. Fissler and colleagues [66] stipulated that "*novelty interventions*", including video games that were novel and optimally calibrated in difficulty, combined with high variability of the training task stimulated broad processes. These benefits could be increased by the addition of physical stimulation [66], generating effects on non-specific cognitive skills such as those found in this study. Indeed, the I2WE games solicited diverse cognitive processes, with more than 15 games associated with different gameplay. For example, players were required to retain information to be as efficiently as possible (short-term and working memory), to combine a motor and a cognitive task (DT), to ignore certain details to focus on critical information (inhibition), all while analyzing multiple visuospatial stimuli (visuospatial functions), to switch quickly from one information to another (mental flexibility) as well as to plan their action and strategies (planning). However, these last 3 functions were not improved while these are usually sensitive to training using video games [3] and exergames [10]. Cognitive enrichment could be dependent on the specificity of the video game [3], which implies that these 3 functions were not engaged intensively and/or frequently enough by I2WE. In 2008, Basak and collaborators [67] did not obtain the same increases in visuospatial skills using a strategy game as Green and Bavelier [68] did with action video games. Thus, the characteristics of the games could be directly related to the types of processes that were modified [69]. The transfer was not as general as claimed by Fissler and collaborators' theory [66]. This could explain the discordance in the ability of exergames to improve cognitive functions. Given low levels of evidence from meta-analysis, studies on exergames should focus on an accurate description of the games used and on their specific cognitive stimulation. In addition to cognitive stimulation, the strong immersive capabilities of I2WE provided an adequate training environment. The combination of exergames and immersive virtual environments could

1 increase the efficiency of training on brain health [70]. Immersion could amplify the activity of brain
2 regions associated with executive functions [26] and create higher mental focus than a conventional
3 physical activity session [20]. Furthermore, I2WE is an alternative to head-mounted virtual reality,
4 which can negatively affect older adults, including nausea, dizziness, and malaise [71]. These could be
5 particularly dangerous for older persons, who have a greater propensity for falls and loss of balance.
6 No negative events, including those related to cybersickness, occurred during the program despite
7 repeated exposure to the immersive wall, and the User Experience is positive [18]. This mixed reality
8 offered by the I2WE represent a compromise to increase the efficiency of multidomain training
9 without generating negative events.

10 I2WE offered a physical and cognitive combination through the DT. Several studies have shown that
11 DT performance could be improved when stimulated and strengthened by the transfer of learning to
12 new tasks [72]. In the present study, DT skills were enhanced in the I2WE group, with a high size
13 effect, and were correlated to improved game performance. Thus, it is enhanced by the I2WE practice
14 and necessary to perform in the games. They generated positive effects even when the tasks used in
15 the test differed from the training situations, so-called “*learning to learn*” [73]. These DT abilities are
16 crucial to the quality of life of older adults, especially to maintain walking and preventing falls [1].
17 Combined training created by I2WE could have a synergistic effect and be more efficient in improving
18 cognitive functions in older adults [6]. Indeed, physical activity could “facilitate” neuroplasticity,
19 reflected by both groups' improvement in visuospatial short-term memory. The additional cognitive
20 stimulation of the I2WE group may have “guided” these effects [66], resulting in enhancement in
21 other cognitive processes, such as executive functions and DT. An additional advantage is that the
22 cognitive task was embedded simultaneously with the motor task and could be more promising to
23 increase the cognitive reserve [21,66]. This *Moving While Thinking* approach prevented older adults
24 from using adaptive strategies to prioritize one task over another (posture first phenomenon). They
25 often protect their motor function at the expense of the cognitive task when a situation involves a

1 threat to balance [74], which could affect the intensity of physical and/or motor stimulation. With
2 I2WE, participants were forced to engage in a motor task to perform the cognitive task and vice versa.

3 The original characteristics of this new type of exclusively collective exergames created a social bond
4 between players, thanks to cooperative and oppositional situations. Participants must communicate,
5 develop strategies, and plan together to perform in the games, creating important cognitive
6 engagement.

7 Thanks to its specific characteristics, this new generation of exergames generated cognitive benefits
8 superior to those of conventional physical activity programs. It can be applied for prevention, as was
9 done in this study, and could also be used in rehabilitation, re-education environments (e.g., hospitals),
10 and care facilities (e.g., residences) for older adults.

11 At the physical level, almost all capacities benefited from the programs, with no differences in
12 evolution between the 2 groups. Like conventional exergames [8,75] and physical activity, I2WE
13 improved multiple physical functions. Thus, they are an interesting successor to the insufficient first
14 generation of exergames, some of which did not solicit physical capacities sufficiently to lead to
15 improvements [76,77]. As Janhunen and collaborators [78] reported, exergames have the same
16 physical effect as physical activity. I2WE involve complex motor skills, which could have led to
17 greater improvements in physical function or higher intensity than a conventional program.
18 Nevertheless, the intensity was the desired one (i.e., moderate), and an intensity too high could have
19 negative effects, such as the impossibility of adequately performing the physical task and the cognitive
20 task.

21 Only upper body strength was unchanged for both groups, which may have been due to the lack of
22 solicitation: ball throws for the I2WE group and swinging movements of the arms during walking for
23 the WMS group. Still, as 82.21% of the participants felt, this new exergame improved a wide range of
24 physical functions, like conventional physical training. This is positive for maintaining the daily

functioning and quality of life of older adults since muscle strength and physical performance are predictive of decline in daily living activities [79].

I2WE training is effective in improving the participants' performance in the games, as they showed a significant increase in the *Break It Handball* game. These encouraging results are accompanied by a very high level of compliance and the desire of all participants, very strong for 52.63%, to continue their program. This may have been due to the perceived pleasure provided by I2WE. While a preliminary study [18] had already shown that these games created a high level of perceived pleasure (60.71/70), these results were confirmed here with an even higher score of perceived pleasure evaluated by the same questionnaire and significantly higher than the WMS group. The collective [80] and the playful aspect of video games were fun factors. In line with the findings of Graves and collaborators [81] showing that the Wii generated more pleasure than conventional physical activity, I2WE are enjoyable and promising alternatives for training.

The main limitation of this study concerned the small number of comparative groups, which made it difficult to determine the specific benefits of I2WE multidimensional characteristics. Moreover, to our knowledge, no studies have evaluated the effects of this type of program on older adults. The results obtained were compared with those in the literature on physical activity, cognitive, exergames, and combined training, but not specifically with I2WE. This limited the extent to which the results could be compared to the literature. Furthermore, it would have been interesting to perform retention tests to determine whether this new type of exergame could extend the benefits to a greater extent and/or for a longer time than a conventional program. Sustained effects after the programs need further research, as they play a key role in the context of clinical relevance. Finally, the lack of a passive control group did not counteract the practice effects of the tests. Nevertheless, validated and reliable tests commonly used in this population were selected, and there was a long delay between pre- and post-tests. In addition, differences between pre and post-tests were evaluated with mean comparison tests and interpreted by effect sizes, confidence intervals, and RCIs. However, the results of inferential tests and

1 RCI were contradictory. On the one hand, inferential statistics and effect sizes can overestimate
2 results, notably due to measurement error and/or practice effects. On the other hand, RCIs can be
3 criticized, mainly because they do not consider the practice effects, test reliability, and variability of
4 results in post-tests. Therefore, the results of this study must be interpreted with caution. More
5 research is needed to determine what constitutes real change. Should change be assessed using
6 inferential statistics or RCI? In any case, improvements were noted in this study, particularly about the
7 dual task, which represents a real-life ability and could be a "true" change, as Duff and colleagues [56]
8 indicated.

9 This study is the first to show the effects of this new generation of exergames on the cognitive and
10 physical health of older adults, although the reliability of the results has yet to be confirmed by further
11 studies. I2WE produced benefits across a wide range of physical functions comparable to a
12 conventional physical activity program and superior in DT, visuospatial working memory, and
13 inhibition with small to medium effects. It suggests that I2WE has advantageous characteristics
14 representing a solution to introduce the practice of regular physical activity into the lives of initially
15 inactive older adults while stimulating their cognitive functions.

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2 **Sources of Funding**

3 No funding was received for this study.

4 **Competing interests**

5 The authors declare no competing interests.

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Figure Legends

Fig. 1. Legend text: *Neo One* device is equipped with a projector system and wall-mounted infrared sensors and is played without a head-mounted display or other equipment. Games are selected via a remote touch screen connected to a computer. Speakers are used to play the music.

Fig. 2. Legend text: I2WE: Immersive and interactive wall exergames; WMS: walking and strengthening.

Fig. 3. No legend text.

Tables

Table 1. Means of variables for I2WE and WMS groups

	I2WE (n = 19)		WMS (n = 15)		t	p
	M	SD	M	SD		
Age (years)	69.63	5.31	70.27	5.82	-0.33	.74
Years of education	12.89	3.91	13.87	3.72	-0.73	.47
BMI (m ² /kg)	25.09	3.67	26.40	4.12	-0.91	.37
Self-rated health (score)	3.68	0.58	3.40	0.63	1.36	.18
RHR (bpm)	59.31	3.92	59.33	6.04	-0.01	.99
HRR (bpm)	98.56	6.54	97.88	7.36	0.28	.78
MMSE (score)	28.95	1.08	28.80	1.01	0.41	.69
Physical activity (MET/week)	287.37	171.56	238.67	225.95	1.37	.18

Abbreviations: BMI = Body Mass Index; HRR = Heart Rate Reserve; I2WE = Immersive and Interactive Wall Exergames; M = Mean; METS = Metabolic Equivalent of Task; MMSE = Mini-Mental State Examination; RHR: Resting Heart Rate; SD = Standard Deviation; WMS = Walking and Muscle-Strengthening.

Table 2. Scores on cognitive and dual-task tests

	I2WE		WMS		Mean difference	95% CI for Mean Difference*		ANOVA			
	Pre-test	Post-test	Pre-test	Post-test				Main effect	Interaction effect		
	M (SD)	M (SD)	M (SD)	M (SD)		Lower	Upper	p	η²	p	η²
Zoo Map Test											
Plan formulation											
Total time (s)	214.10 (127.02)	205.13 (144.61)	202.34 (122.55)	196.01 (139.77)	-2.64	-86.83	81.56	.71	.00	.95	.00
Sequence score (n)	3.42 (3.27)	3.52 (8.19)	4.20 (3.49)	5.07 (3.28)	-0.76	-3.37	1.85	.45	.01	.56	.00
Plan execution											
Total time (s)	84.42 (51.07)	81.17 (28.30)	70.98 (38.86)	71.76 (41.90)	-4.02	-31.99	29.94	.86	.00	.77	.00
Sequence score (n)	7.10 (2.23)	6.89 (2.02)	7.67 (0.82)	7.73 (0.46)	-0.28	-1.04	0.49	.70	.00	.47	.00
Total score (n)	10.53 (4.41)	10.42 (3.79)	11.87 (3.58)	12.80 (3.34)	-1.04	-3.56	1.48	.51	.00	.41	.00
Spatial Span test											
Spatial span (n)	6.05 (1.18)	6.68 (1.12)	6.07 (0.88)	6.40 (1.06)	0.30	-0.48	1.08	.02	.05	.44	.00
Backward spatial span (n)	4.53 (1.58)	6.26 (1.66)	4.60 (2.03)	5.00 (1.36)	1.34	0.33	2.34	<.001	.09	.01	.04
Stroop test											
Board 1 (n)	68.79 (19.93)	68.58 (15.84)	63.60 (15.00)	65.80 (15.90)	-2.41	-11.22	6.40	.65	.00	.58	.00
Board 2 (n)	96.58 (26.04)	99.26 (19.99)	99.00 (18.78)	98.67 (18.09)	3.02	-5.41	11.45	.57	.00	.47	.00
Board 3 (n)	37.05 (16.09)	41.42 (14.18)	33.87 (10.53)	32.73 (12.37)	5.66	0.73	10.59	.17	.00	.03	.01
Interference score (n)	0.43 (0.13)	0.49 (0.11)	0.42 (0.09)	0.39 (0.11)	0.08	0.02	0.14	.28	.00	.01	.03
Mental Rotation test											
Score (n)	12.95 (4.43)	14.42 (5.39)	12.07 (5.19)	12.87 (4.94)	0.67	-2.44	3.79	.15	.01	.66	.00
Trail Making Test											
Time A (s)	36.12 (22.03)	35.93 (16.35)	37.94 (13.83)	40.72 (18.86)	-2.97	-12.54	6.60	.59	.00	.53	.00
Times B (s)	106.14 (87.75)	77.96 (38.83)	103.13 (72.68)	109.97 (70.09)	-35.02	-72.70	2.65	.26	.01	.07	.02
Time B-A (s)	70.02 (69.27)	42.03 (31.54)	65.19 (61.37)	69.25 (60.73)	-32.06	-65.93	1.82	.16	.01	.06	.02
Dual Task test											
TUG-dt (n) DT-ST	-0.79 (0.92)	-1.05 (1.22)	-0.93 (1.22)	-1.33 (1.17)	0.14	-0.96	1.23	0.23	.02	.80	.00
TUG-dt (time) DT - ST	2.80 (2.57)	1.17 (1.16)	1.71 (0.93)	1.44 (0.73)	-1.36	-2.71	-0.01	0.01	.08	0.04	.04

Bold values are significant. *95% CI for the mean difference in evolution (post-test – pre-test) between the two groups (I2WE, WMS).

Abbreviations: CI = Confidence Interval; Interaction effect = time*group effect; I2WE = Immersive and Interactive Wall Exergames; Main effect = time effect; M = Mean; n = numbers; SD = Standard Deviation; s = seconds; TUG-dt = Timed Up and Go Dual Task; WMS = Walking and Muscle Strengthening.

Table 3. Scores on physical tests

	I2WE					WMS				ANOVA	
	<i>Pre-test</i>	<i>Post-test</i>	<i>Mean</i>	<i>95% CI for Mean</i>		<i>Pre-test</i>	<i>Post-test</i>	<i>Mean</i>	<i>95% CI for Mean</i>		<i>Time effect</i>
	M (SD)	M (SD)	<i>difference</i>	<i>Difference</i>		M (SD)	M (SD)	<i>difference</i>	<i>Difference</i>		<i>p</i> η^2
Chair stand (number)	11.32 (2.43)	13.21 (3.15)	-1.89	-3.46	-0.33	10.20 (2.68)	11.13 (2.20)	-0.93	-2.70	0.83	<.01 .06
Handgrip left (kg)	24.21 (8.19)	25.63 (7.31)	-1.42	-3.27	0.44	22.95 (5.07)	23.25 (5.01)	-0.30	-2.39	1.79	.09 .00
Handgrip right (kg)	23.49 (7.85)	24.19 (7.63)	-0.70	-2.52	1.18	20.64 (3.77)	20.79 (4.11)	-0.15	-2.19	1.90	.39 .00
Chair-sit-and-reach left (cm)	3.10 (11.35)	-2.63 (8.19)	5.74	2.36	9.12	-1.67 (8.63)	-4.60 (10.51)	2.93	-0.87	11.38	<.001 .05
Chair-sit-and-reach right (cm)	3.95 (11.06)	-1.26 (9.24)	5.21	2.46	7.96	-1.36 (8.84)	-4.64 (10.35)	3.29	0.08	6.49	<.001 .04
Timed up and go (s)	5.84 (1.70)	5.44 (1.72)	0.41	-0.05	0.87	5.78 (0.97)	5.39 (0.85)	0.39	-0.13	0.91	<.01 .02
Back scratch right (cm)	7.68 (12.20)	4.00 (9.76)	3.68	-0.29	7.66	7.00 (13.57)	3.20 (11.57)	3.80	-0.67	8.27	<.001 .03
Back scratch left (cm)	13.13 (13.26)	8.68 (11.54)	4.58	1.70	7.46	10.13 (13.21)	8.27 (13.44)	1.87	-1.37	5.10	<.001 .02
Seated Medicine Ball Throw (cm)	261.84 (67.47)	272.32 (65.60)	-10.47	-26.07	5.12	239.27 (41.75)	239.00 (43.48)	0.27	-17.29	17.82	.23 .00
6WT Distance (m)	551.45 (111.17)	588.16 (128.80)	-36.71	-76.86	3.44	525.00 (91.72)	559.00 (88.01)	-34.00	-79.19	11.19	<.01 .03
6WT Intensity (% HRR)	0.52 (0.14)	0.53 (0.15)	-0.01	-0.09	0.06	0.48 (0.14)	0.51 (0.14)	-0.03	-0.12	0.15	.29 .01

Bold values are significant.

Abbreviations: CI = Confidence Interval; HRR = Heart Rate Reserve; I2WE = Immersive and Interactive Wall Exergames; M = Mean; SD = Standard Deviation; WMS = Walking and Muscle-Strengthening; 6WT = 6-minutes Walking Test.

Table 4. Objective and subjective intensities

	I2WE		WMS		t	p
	M	SD	M	SD		
Mean HR (bpm)	105.42	14.13	102.08	13.02	.71	.48
Peak HR (bpm)	127.21	16.94	125.33	16.20	.33	.75
Mean intensity (% HRR)	46.97	12.55	43.90	11.32	.74	.46
Peak intensity (% HRR)	69.01	15.16	67.83	14.60	.23	.82
Mean modified Borg (number)	4.75	0.89	4.59	0.69	.58	.57

Abbreviations: HR = Heart Rate; HRR = Heart Rate Reserve; I2WE = Immersive and Interactive Wall Exergames; M = Mean; SD = Standard Deviation; WMS = Walking and Muscle-Strengthening

Figure 1. *Neo One device*



Figure 2. Study workflow

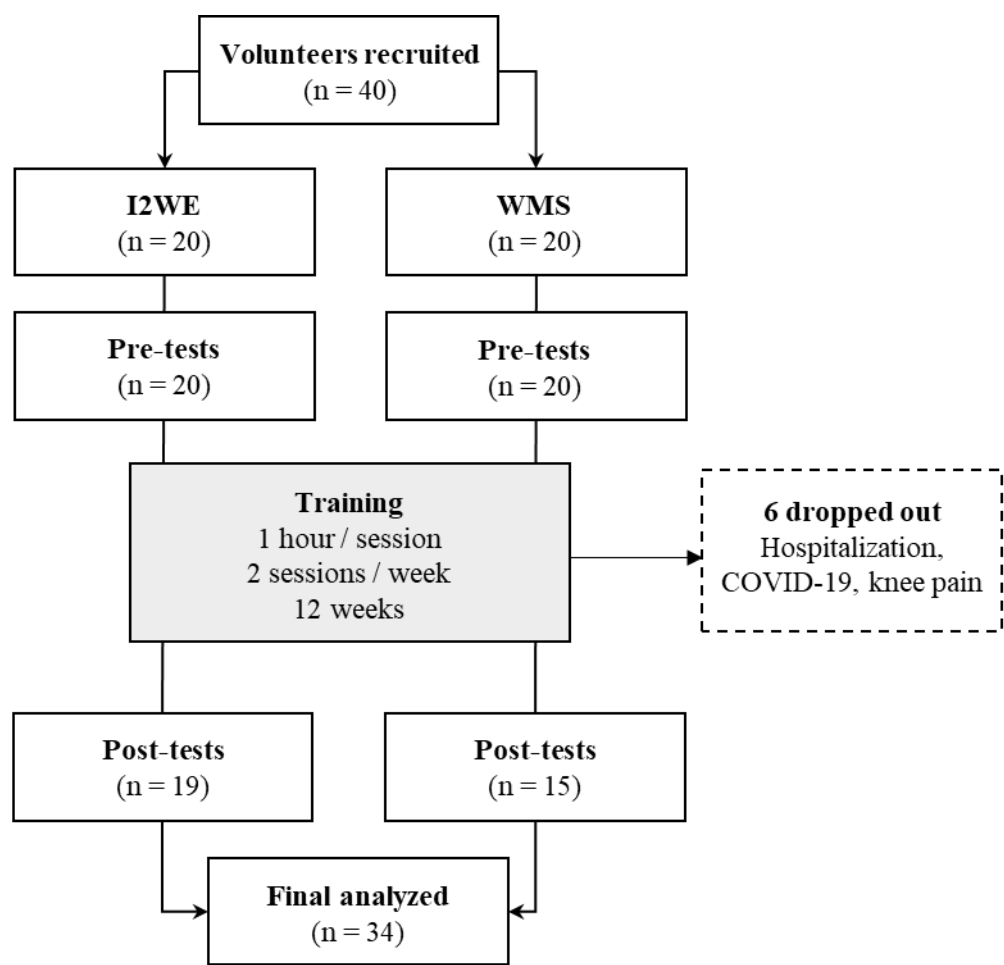


Figure 3. Multidimensional mechanisms from I2WE to explain cognitive improvement

