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Effects of computer-based cognitive training combined with physical training for older adults with cognitive impairment: A four-arm randomized controlled trial

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Abstract

Objective: Combined physical (PHY) and cognitive (COG) training in sequential (SEQ) and simultaneous (SIMUL) sessions may delay the progression of cognitive impairment. To date, no study has directly compared in older adults with cognitive impairment the effects of COG training, PHY training, SEQ motor-cognitive training and SIMUL motor-cognitve training on specific indices of cognitive performance and activities of daily living (ADL). The purpose of this study was to determine whether SEQ and SIMUL motor-cognitive training can improve treatment outcomes compared with PHY or COG training alone. We also aimed to compare the effects of SEQ versus SIMUL motor-cognitive training on cognitive functions and instrumental ADL (IADL) in older adults with cognitive impairment.

Methods: A cluster randomized controlled trial was conducted. Eighty older adults with cognitive impairment were randomly assigned to COG, PHY, SEQ or SIMUL training groups. The intervention consisted of 90-min training sessions, totaling 36 sessions. Outcome measures were the Montreal Cognitive Assessment, three subtests of the Wechsler Memory Scale (WMS) and the Lawton IADL scale.

Results: Significant interaction effects between group and time were found in WMS-spatial span ($p = 0.04$) and WMS-word lists ($p = 0.041$). For WMS-spatial span, the SIMUL group showed outperformed the COG ($p = 0.039$), PHY ($p = 0.010$) and SEQ groups ($p = 0.017$). For WMS-word lists, the SEQ group improve more than COG ($p = 0.013$), PHY ($p = 0.030$) and SIMUL ($p = 0.019$) groups. No significant differences were found in IADL performance among four groups ($p = 0.645$).

Conclusions: Our study showed SEQ and SIMUL motor-cognitive training led to more pronounced improvements in visuo-spatial working memory or verbal memory compared with isolated COG or PHY training for community-based older adults with cognitive impairment. For enhancing effects on IADL, we suggest the use of sensitive measurement tools and context-enriched cognitive training involving real-life task demands.

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Introduction

Populations in industrialized nations are rapidly aging, which may lead to impairment in cognitive function and increase the risk of developing diseases that cause dementia.[1] Cognitive impairment has a profound impact on an individual's daily life and well-being. There are no remedies for cognitive impairment in neurodegenerative diseases to date.[2] This concern has prompted research investigating interventions to alleviate the progression of cognitive impairment or improve cognitive function in neurodegenerative diseases at an early stage of cognitive impairment.

Computerized cognitive training is an intriguing, safe and cost-effective intervention that uses theoretically supported and structured activities to target multiple cognitive domains. Computerized cognitive training provides real-time performance feedback and adaptive adjustment, enhancing motivation and adherence in older adults compared with traditional cognitive training.[3] It has demonstrated significant and moderate effects in enhancing cognitive functions among older adults, both with and without cognitive impairment.[4,5] The mechanisms of computerized cognitive training are complex and include an improvement of functional brain activation patterns (e.g. an increase in functional connectivity of the hippocampus) that, in turn, contribute to an improvement of cognitive performance.[6]

To enhance the impact of cognitive training on cognitive performance in healthy older adults, recent studies have used a combination of physical training and cognitive training, known as motor-cognitive training.[7] This approach promotes neuroplasticity and ensures the stability of induced neuroplastic changes.[8] Two different modes of combination have been explored: sequential and simultaneous training.

Sequential motor-cognitive training involves consecutive performance of physical training and cognitive training, allowing participants to fully focus on both tasks. Previous research has demonstrated that sequentialmotor-cognitive training yields greater benefits in global cognition and visuospatial ability compared with physical training alone.[9,10]

Simultaneous motor-cognitive training, also known as dual-task training, involves engaging in both physical training and cognitive training simultaneously. This training mode emphasizes the combined abilities required for instrumental activities of daily living (IADL), such as talking on a mobile phone while walking or conversing with family while cooking.[11] Simultaneous motor-cognitive training aims to improve participants' functional ability.[12] Studies focusing on simultaneous motor-cognitive training have shown greater benefits in global cognition, working memory and executive function among older adults with cognitive impairment compared with passive control groups.[13–16]

Although these studies demonstrated beneficial effects of sequential or simultaneous combined training on cognitive abilities compared with a single-model training (cognitive or physical training alone),[9,10,13,17] some methodological concerns have prevented them from draw robust conclusions. For example, the training duration for the experimental group (i.e. sequential motor-cognitive training) was longer than that for the control groups (i.e. cognitive or physical training alone).[9,10] Many studies of simultaneous motor-cognitive training effects used control groups that did not receive an active intervention, such as physical or cognitive training, making it difficult to determine whether simultaneous motor-cognitive training per se or just specific training leads to better cognitive performance.[13] In addition, to the best of our knowledge, only one study has been identified that examined the effects of sequentially combining computer-based cognitive training with physical training on cognitive function in community-dwelling older adults.[18] The result showed that the benefit on global cognition and verbal memory was larger in the group that participated in sequential motor-cognitive training than that documented in the control group.[18]

The few systematic reviews that have compared simultaneous motor-cognitive training and sequential motor-cognitive training indicated that simultaneous motor-cognitive training may be more effective in improving cognitive function in older adults than sequential training.[10,13] However, the findings of these reviews need to be interpreted cautiously due to differences in training duration, frequency and the heterogeneous nature of the participant population.

Sequential motor-cognitive training offers the advantage of avoiding dual-task costs and prioritization effects when compared with simultaneous motor-cognitive training.[8] Dual-task costs refer to a decrease in performance in one or both tasks when performed simultaneously, influenced by task prioritization. On the other hand, simultaneous motor-cognitive training is closer to real-life situations and thus probably fosters a transfer to everyday environments and situations.[7]

To date, no clinical trial has directly compared sequential versus simultaneous motor-cognitive training using a computer-based combined training protocol in older adults with cognitive impairment. Such a study is needed to provide a head-to-head comparison and evaluate the potential differential benefits of these two training protocols on various aspects of cognitive abilities and daily functioning.

Based on the lack of studies that directly compared different types of motor-cognitive training, the current study aims (a) to determine whether combined physical and cognitive training using a computer-based cognitive training system, sequentially or simultaneously, can lead to enhanced therapy outcomes compared with physical training or cognitive training alone on cognitive functions and IADLs and (b) to compare the effects of sequential versus simultaneous motor-cognitive training on cognitive functions and IADLs in older adults with cognitive impairment. Given the findings of previous studies showing that motor-cognitive training is superior to improve cognitive functions and IDALs compared with physical training or cognitive training alone,[9,10,13,17] we hypothesize that comparable effects will occur in our cohort of older adults with cognitive impairment. In particular, we expect that our simultaneous and sequential motor-cognitive training protocol can induce greater changes in specific outcomes of cognitive performance and IADLs compared with physical training or cognitive training alone.

Methods

Participants

Participants were recruited from community facilities and adult day-care centers. Informed consent was obtained from all participants. The inclusion criteria were (a) age ≥55 years; (b) having self- or informant-reported cognitive complaints; (c) the ability to follow instructions (≥18 points on the Mini-Mental State Examination); (d) no difficulty with basic ADLs; (e) scores below 26 points on the Montreal Cognitive Assessment (MoCA), indicating cognitive impairment;[19] and (f) no clinically diagnosed dementia. Participants who reported other neurologic disorders or an unstable medical condition that prevented them from completing the training were excluded.

Study design and procedure

This study used cluster randomization due to practical reasons and to reduce possible contamination. A cluster was defined as a community facility or day-care center. A research assistant used a web-based research randomizer tool (freely available at http://www.randomizer.org/) to generate random tables based on the type of recruitment site (community facilities or adult day-care centers). The random tables were used to determine the group allocation for newly enrolled participants. An allocation ratio of 1:1:1:1 was used to randomly assign 20 clusters (115 participants, total) to four training modes: cognitive (COG), physical (PHY), sequential (SEQ) and simultaneous (SIMUL) trainings. The research assistant informed the therapists about the assigned groups for conducting the respective interventions. Over the course of the study, 35 participants dropped out, and 80 participants completed all the training sessions (Figure 1).

Interventions

The interventions for all groups contained two to three 90-min sessions per week on non-consecutive days, lasting a total of 12–18 weeks (36 training sessions in total). Each training group consisted of three to six participants. Each PHY and COG training session was led and supervised by a qualified therapist. As participants demonstrated gradual improvement throughout the practice sessions, the intensity of PHY training or the level of cognitive challenges was adjusted accordingly. Participants in each group received a different mode of training, as described below.

COG group. We used a computerized cognitive training program, BrainHQ (Posit Science Inc., San Francisco, CA, USA), which is supported by research demonstrating its effectiveness for improving cognitive function.[20,21] The content of BrainHQ involved attention, visual recognition and spatial ability, memory and processing speed. To facilitate generalization of cognitive ability to functional performance, we also designed a PowerPoint (Microsoft, Redmond, WA, USA) presentation with content derived from BrainHQ and incorporating the functional elements. For example, the calculation task was designed to provide a grocery catalog for summing the costs of discounted items. The therapists led the group and encouraged participants to perform the tasks. We selected one to three different Brain HQ tasks and one PowerPoint task for the participants in one session.[21] Each training session was divided into multiple parts: warm-up (10 min), COG training (30 min), break (10 min), COG training (30 min) and cool-down (10 min).

PHY group. This group participated in a multicomponent exercise program including aerobic training, resistance training and balance training. The training sessions were led

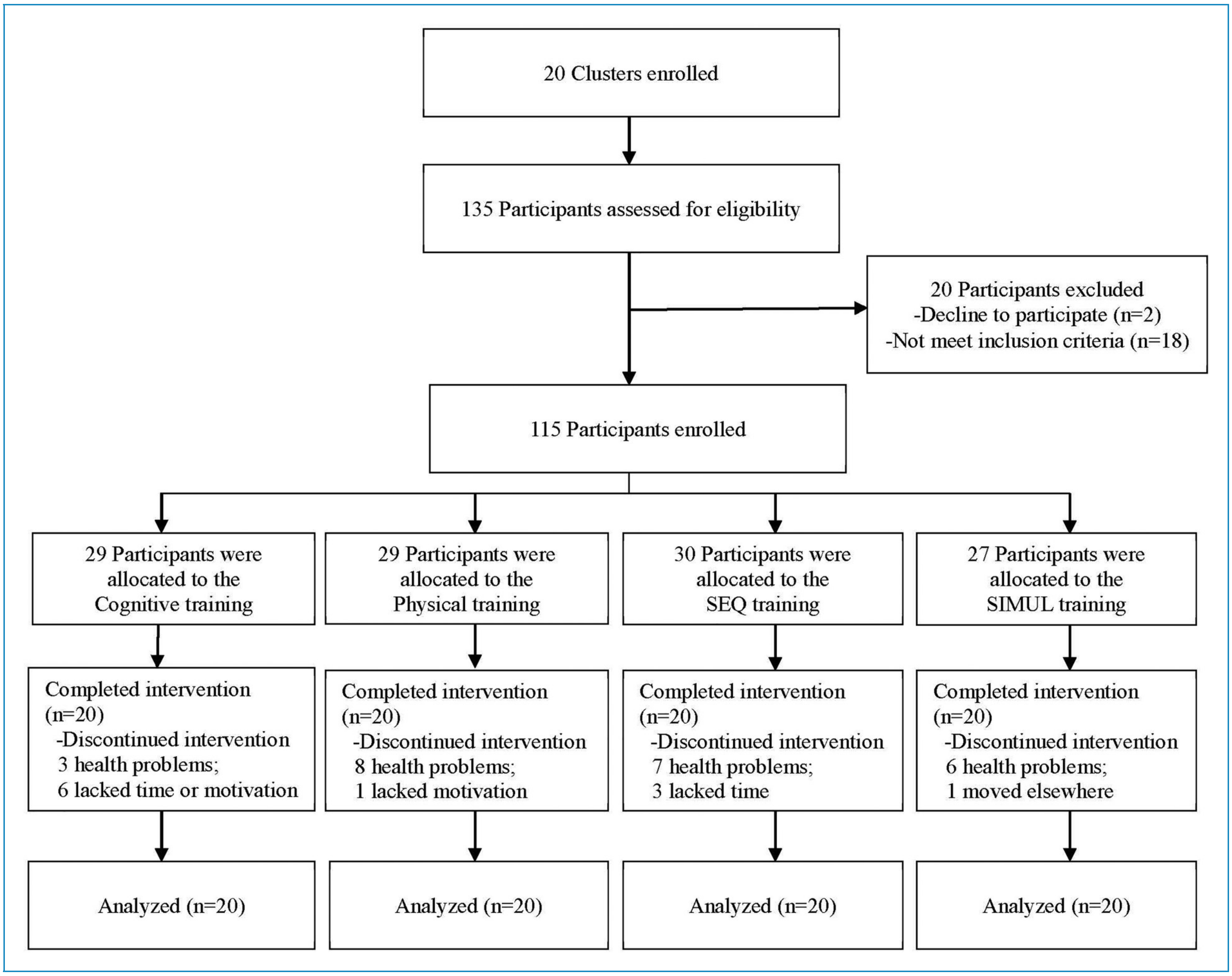

Figure 1. Flowchart of participant disposition throughout the study. SEQ: sequential training; SIMUL: simultaneous training.

by a therapist and divided into two sessions. In the first session, the participants engaged in aerobic exercise, such as stepping and walking. The target heart rate of the aerobic exercise was 65%–85% of the maximal heart rate.[22] The maximum heart rate was calculated using the formula: $208 - 0.7 \times \text{age}$. Heart rate measurements were obtained from a sports watch that participants wore at a specific time during the intervention. The exercise intensity was progressed to training at 75–85% of the maximal heart rate during the final 4 weeks as the participants improve their performance throughout practice. The participants implemented balance training and muscle strengthening in the second session. Participants initially started the muscle strength training with lower resistance levels, specifically at 40%–50% of their 1 repetition maximum. The weights selected were adjusted to allow the participants to complete 8–12 repetitions per set, and they were able to perform two to three sets. As the participants demonstrated progress, the therapist made further adjustments to the resistance level, ranging from 60% to 75% of their 1 repetition maximum. Based on Fragala et al.'s[23] suggestions that resistance level should progress from low to moderate, we used a Borg rating of perceived exertion score ranging from 9 to 14 as an indication of reaching the desired resistance level.[24] During each 45-min training session, the participants first performed 5 min of warm-up, followed by 35 min of exercise and ended with 5 min of cool-down.

SEQ group. The participants performed physical training for 45 min, followed by 45 min of computerized cognitive training. The principles of physical training and computerized cognitive training are described in the PHY and COG groups, respectively. The physical training and computerized cognitive training individually included 5 min of warm-up, followed by 35 min of training and ended with 5 min of cool-down.

SIMUL group. The participants performed computerized cognitive tasks and physical training simultaneously, for example, practicing math calculations while stepping in place and memorizing the position of an object on the screen while strengthening muscles with a Thera-Band. One 90-min training session was divided into two 45-min dual-task programs. For each 45-min program, the

Table 1. Demographic and clinical data at baseline.

Variables	SEQ ($n = 20$)	SIMUL ($n = 20$)	COG ($n = 20$)	PHY ($n = 20$)	p
Demographic and clinical parameters					
Female, n (%)	16 (80)	16 (80)	15 (75)	17 (85)	0.89
Age, years	76.21 (8.62)	81.53 (7.01)	76.36 (9.76)	77.07 (9.28)	0.18
Education, years	9.45 (4.67)	6.90 (3.11)	8.45 (5.07)	6.80 (4.36)	0.17
MMSE	23.95 (4.76)	20.75 (4.10)	22.35 (4.98)	23.75 (4.06)	0.10
Outcome measures					
MoCA	18.7 (5.46)	14.35 (5.01)	17.05 (5.92)	18.25 (5.41)	0.06
WMS-FR	8.9 (3.81)	8.05 (2.33)	8.6 (1.96)	8.2 (3.3)	0.79
WMS-SS	7.93 (3.2)	5.5 (2.04)	8.05 (3.87)	8.2 (2.88)	0.02
WMS-WL	7.9 (3.19)	6.43 (2.6)	8.3 (3.57)	8.35 (3.39)	0.20
Lawton IADL scale	23.4 (7.38)	21.3 (5.86)	25.05 (4.71)	23.45 (9.63)	0.43

Notes: The data are presented as the mean (standard deviations), unless indicated otherwise.
COG: cognitive training; FR: facial recognition; IADL: instrumental activities of daily living; MMSE: Mini-Mental State Examination; MoCA: Montreal Cognitive Assessment; PHY: physical training; SEQ: sequential training; SIMUL: simultaneous training; SS: spatial span; WL: word lists; WMS: Wechsler Memory Scale.

therapists explained the rules of the cognitive task and the way to perform the exercise in the first 10 min, followed by 35 min of dual-task training of the cognitive and physical elements.

Outcome measures

All of the outcome assessments were conducted before and immediately after training by assessors who were blinded to the treatment allocation. Previous research showed that the combined training led to improvements in general cognitive function, spatial abilities and verbal memory among healthy older adults,[9] suggesting that these cognitive domains are relatively malleable by this type of training. Thus, the current study focused on the assessment of these cognitive domains.

The MoCA, with a total score of 30, was used to evaluate general cognitive function. The MoCA has been commonly used to detect cognitive changes and is a valid tool to evaluate the global cognitive function in the older adults with cognitive impairment.[25]

We used the facial recognition (FR), word lists (WL) and spatial span (SS) subtests of the Wechsler Memory Scale (WMS) to measure memory.[26] For the FR test, the participants were asked to look at 24 pictures of faces one by one and then identify the faces. The WL test asked the participants to memorize and respond to word pairs read out by the instructor. In the SS test, the instructor pointed to the positioned blocks in turn, and then the participants touched the blocks in the same or in reverse order. The reliability and validity of WMS have been established in community-dwelling adults and is valid to assess cognitive improvements after training.[27]

The Lawton scale assessed the performance of IADLs, including using a telephone, shopping, food preparation, housekeeping, laundry, mode of transportation, responsibility for one's own medication and ability to handle finances, with a higher score indicating more independence in IADL.[28] It is a valid and reliable tool for use in the older adults and is commonly used to assess older adults with cognitive impairment.[29]

Data analysis

The sample size was calculated, based on the previous studies[30–32] of global cognitive measures, including MMSE and MoCA, and resulted in a Cohen's d effect size of 0.45–0.63. To achieve a power of 0.8 and a two-sided type I error of 0.05 using G* Power software, 20–48 participants had to be recruited. Taking into account the effect of clustering, the sample size would be increased. Given an assumed intra-cluster correlation coefficient of 0.05 and 20 clusters, the inflation factor of 1.95 was

Table 2. Statistical analysis on COG functions and IADL performance.

Assessment	Mean difference (95% CI) from baseline in all subjects				p value mixed ANOVA			ES
	SEQ ($n=20$)	SIMUL ($n=20$)	COG ($n=20$)	PHY ($n=20$)	Group	Time	Group × time interaction	(η^2)
MoCA	0.75 (−0.73, 2.23)	0.72 (−0.62, 2.06)	1.65 (0.1, 3.2)	0.85 (−0.7, 2.4)	0.051	0.006	0.761	0.015
WMS-FR	0.85 (−0.08, 1.78)	0.15 (−1.39, 1.69)	1.70 (0.38, 3.02)	0.10 (−1.08, 1.28)	0.345	0.023	0.212	0.057
WMS-SS	0.12 (−1.39, 1.63)	2.20 (1.26, 3.14)	0.75 (−0.48, 1.98)	−0.05 (−1.33, 1.23)	0.190	0.014	0.040	0.103
WMS-WL	1.45 (0.57, 2.33)	0.04 (−0.89, 0.96)	−0.05 (−0.75, 0.65)	0.15 (−0.8, 1.1)	0.122	0.060	0.041	0.102
IADL scale	0.05 (−1.21, 1.31)	1.3 (−1.61, 4.21)	0.85 (0.1, 1.6)	1.7 (−0.57, 3.97)	0.395	0.043	0.645	0.021

ANOVA: analysis of variance; CI: confidence interval; COG: cognitive training; ES: effect size; FR: facial recognition; IADL scale: Lawton instrumental activities of daily living scale; MoCA: Montreal Cognitive Assessment; *n*: number of participants; PHY: physical training; SEQ: sequential training; SIMUL: simultaneous training; SS: spatial span; WL: word lists; WMS: Wechsler Memory Scale.

calculated for the sample size.[33] The required sample size was increased from 39 to 94 participants.

Baseline variables among the groups were compared with χ^2 and one-way analysis of variance (ANOVA). Mixed ANOVA was applied on the outcome measures to compare the training effects for the four groups, where the within-subject factor was the time (before and after interventions) and the between-subject factor was the four intervention groups. Post hoc comparisons were conducted using the Tukey method, which effectively controls for the issue of multiple comparisons. The effect size η^2 was calculated to determine the magnitude of interaction and main effects. Effect sizes (η^2) greater than 0.138 are classified as large effects, η^2 values between 0.138 and 0.059 are considered moderate effects, and η^2 values between 0.01 and 0.059 are regarded as small effects.[34] We used the paired *t*-test to determine the difference on change scores within groups between baseline and post-intervention. The significant statistical level was set at 0.05 for all statistical tests. We used the Cohen's *d* as the effect size to represent the magnitude of changes from baseline to post-intervention. Effect size (Cohen's *d*) values of 0.2 are commonly interpreted as small effects, values of 0.5 are considered moderate effects and values of 0.8 are considered large effects. Missing data were replaced at random with the group means.[35] Data were analyzed with PASW Statistics 18.0 software (IBM Corp., Armonk, NY, USA).

Results

Demographic and clinical data at baseline

The demographic and clinical data at baseline are listed in Table 1. No statistically significant differences were found for the demographic and clinical data at baseline among the four groups, except for the SIMUL group, which exhibited significantly lower scores on the WMS-SS (Table 1).

Effects of training sessions on cognitive function

For the MoCA and WMS-FR, no statistically significant interaction effects between group and time were found. Significant interaction effects between group and time were found for the WMS-SS and WMS-WL (Table 2). For the WMS-SS, the Tukey's post hoc analysis indicated that the SIMUL group had a significantly better outcome than the COG ($p = 0.039$; Cohen's $d = 0.68$), PHY ($p = 0.010$; Cohen's $d = 0.86$) and SEQ groups ($p = 0.017$; Cohen's $d = 0.79$). Tukey's post hoc analysis showed that the SEQ group had a significantly better outcome for the WMS-WL than the COG ($p = 0.013$; Cohen's $d = 0.82$), PHY ($p = 0.030$; Cohen's $d = 0.71$) and SIMUL ($p = 0.019$; Cohen's $d = 0.77$) groups.

Significant main effects of time were found in all outcomes except the WMS-WL ($p = 0.06$) (Table 2). The SIMUL group had a significant improvement in the WMS-SS ($t = 4.88$, $p < 0.01$, Cohen's $d = 0.9$) from pre-intervention to post-intervention. The COG group showed a better performance in the MOCA ($t = 2.23$, $p = 0.04$, Cohen's $d = 0.5$) and in the WMS-FR ($t = 2.69$, $p = 0.02$, Cohen's $d = 0.6$) from pre-intervention to post-intervention. No significant main effects of group were found in the cognitive outcomes.

Effects of training sessions on IADL

No significant interaction effects between group and time and main effects of group were found in IADL outcomes. Significant main effects of time were found in IADL outcomes (Table 2). The COG group demonstrated improvements in the IADL ($t = 2.38$, $p = 0.028$, Cohen's $d = 0.53$) from pre-intervention to post-intervention.

Adherence and adverse events

The average completion adherence for all training sessions was 87% (range, 78%–100%). No significant adverse events were documented, suggesting that the training is safe and welltolerated among older adults with cognitive impairment.

Discussion

To the best of our knowledge, this is the first study to use a parallel four-arm cluster randomized controlled trial in older adults with cognitive impairment to directly compare the effects of SIMUL and SEQ motor-cognitive training with PHY training and COG training alone. For the MoCA and WMS-FR, no significant differences were found among the four training modes. Statistically significant interaction effects between group and time were found for the WMS-SS and WMS-WL, for which SIMUL and SEQ motor-cognitive training showed larger gains compared with the single mode, respectively. Compared with the other three groups, the SIMUL group showed superior improvements in WMS-SS performance. The SEQ group demonstrated a greater improvement in WMS-WL performance than the other three groups. No significant differences among training modes were found for IADL performance.

For the MoCA and WMS-FR, no statistically significant interaction effects between group and time were found. However, the COG group had significant improvements post-intervention in general cognitive function and visual recognition, whereas the other interventions did not show significant differences. These findings suggest that cognitive interventions incorporating multiple activities targeting various cognitive domains might have an impact on increasing cognitive reserve for developing diverse cognitive abilities for people with cognitive impairments.[36] This could be attributed to the fact that the computerized cognitive training program is multidimensional and the participants focus exclusively on the cognitive tasks, leading to significant improvements in general cognitive function for the COG group. In addition, the computerized cognitive training program provided numerous tasks associated with visual recognition, such as recognition, eye for detail and Hawk Eye tasks, possibly resulting in significant enhancements in visual recognition memory as opposed to spatial and verbal memory. Despite the dosage of SIMUL motor-cognitive training being equivalent to COG training, the presence of dual-task cost (the phenomenon where SIMUL engagement in two tasks leads to a decline in performance compared to when each task is performed individually)[37] or prioritization effects (the allocation of cognitive resources to favor one task over another, thus affecting overall task performance)[8] might lead to suboptimal cognitive activity practice, resulting in less effective outcomes.

For the visuospatial working memory measured by WMS-SS, the SIMUL motor-cognitive training showed larger gains than the single modes and the SEQ motor-cognitive training. Our results are consistent with a previous study indicating that visuospatial memory improved significantly after the SIMUL motor-cognitive training.[38] One potential explanation is that SIMUL motor-cognitive training may lead to reduced neural effort in the prefrontal regions, suggesting an increase in neural efficiency within these areas.[39] The efficiency of brain activation in the prefrontal regions is associated with the improvement of visual memory abilities.[40] Additionally, the findings might be attributed to the fact that the SIMUL motor-cognitive training we provided encompasses a variety of tasks demanding substantial visual-spatial processing to meet the physical requirements of body positioning (e.g. stepping into the grid on the right front) and working memory functions to address cognitive tasks (e.g. stepping into the grid on the right front and recalling the same number of identical symbols as previously encountered). These challenging tasks may contribute to significant improvements in visual-spatial working memory ability among the SIMUL group. However, caution might be exercised for making a definite conclusion. The baseline WMS-SS score in the SIMUL group was lower than that in the other groups, and the SIMUL group might have a greater potential for improvement in WMS-SS. Future studies may enhance the sample size to minimize the potential for baseline discrepancies in participant characteristics.

The results of our study are inconsistent with the findings of a previous study[13] that reported non-significant effects of the SIMUL motor-cognitive training on working memory function in older adults with mild cognitive impairments. A possible reason is that the training in the previous study was conducted for 60 min per session for a total of 24 training sessions, whereas our study comprised 36 training sessions for 90 min per session. A higher dose (i.e. duration of the training and duration of a single training session) is perhaps necessary and more beneficial to enhance the cognitive performance capacities in older adults with cognitive impairment.

Regarding verbal learning and short-term memory as measured by WMS-WL, the SEQ motor-cognitive training demonstrated significant positive changes, with more benefits compared with the other three modes. This finding is consistent with previous studies showing greater improvements of verbal learning and memory after the SEQ motor-cognitive training than after single-mode trainings for people with mild cognitive impairment.[41,42] There is a possible explanation for these findings. Based on the framework of guided plasticity facilitation, physical exercises enhance neuroplasticity, while cognitive tasks facilitate neural integration.[8] Engaging in physical training prior to cognitive training may enhance physiological arousal and attention, potentially aiding the encoding and retrieval of information during subsequent cognitive exercises.[43] Physical training can also contribute to improve memory consolidation and retrieval performance through heightened neuroplasticity and hippocampal activation.[44,45] Cognitive training may lead to the formation of additional synapses and redundant neuronal networks and potentially enhance neuronal survival and memory resolution, both integral processes linked to memory.[46] Furthermore, the combination of physical and cognitive activities produces a beneficial synergistic effect. Utilizing the principles of the guided plasticity facilitation framework mentioned earlier and taking into account the lack of potential dual-task costs,[37] the SEQ motor-cognitive training mode exhibited superiority compared to other training modes in terms of verbal learning and short-term memory performance.

We employed a research design with four groups with duration-matched training sessions, which was more rigorous compared to the design in the study by Hagovska et al.[42] As their SEQ motor-cognitive training was twice as long as that of the single-mode interventions. Our study provides evidence that SEQ motor-cognitive trainings are effective to preserve cognitive performance in older adults with cognitive impairment.

IADL did not significantly improve among the four groups. Thus, a possible transfer effect from cognitive function to daily function was not found. A higher percentage of tasks with daily functioning, such as meal preparation, may be required to integrate into the motor-cognitive training. Incorporation of immersive virtual reality to simulate real-life contexts for functional cognitive training might be another possible approach to generalize the training effects to daily function. Our finding is in line with Park et al.'s study,[39] which suggests that cognitive-physical dual-task training has limitations in terms of its transfer effect to daily life. While SIMUL motor-cognitive training is intended to closely simulate real-life situations, our results did not exhibit notable transfer effects to everyday contexts. One possible reason might be the dual-task cost,[37] which means that when participants engage in both physical and cognitive activities simultaneously, the increased cognitive load may lead to a decrease in motor performance, or the heightened motor load may result in reduced cognitive performance. Alternatively, if both domains experience elevated loads, resulting in diminished performance in both, it can affect the training effectiveness and even transfer effects. On the contrary, only the COG group, which demonstrated significantly greater improvements in global cognitive function after training than before, improved significantly on IADL performance in present study. As suggested by Karssemeijer et al.,[47] improved global cognitive function may be an important mediator for enhancing ADL function.

The current study has some limitations. First, the SIMUL group showed the lowest performance of visuospatial working memory compared with the other groups at baseline, although they were randomly allocated to this group. Increasing the sample size in each group might decrease the possibility of unequal participant characteristics at baseline. Second, future studies may consider more sensitive measurement tools (e.g. performance-based measures of IADL)[48] to detect change in the performance of ADL. Finally, the heart rate of the participants was measured one time rather than during periods of time in the physical training. We could not ensure that the participants always reached the target aerobic intensity in the physical training.

Conclusions

To the best of our knowledge, this is the first study to directly compare the effectiveness of different types of motor-cognitive training with PHY training and COG training alone. In this context, our study findings provide evidence that in community-based older adults with cognitive impairment, such SEQ and SIMUL motor-cognitive training is feasible and safe and leads to more pronounced improvements in visuospatial working memory or verbal memory compared with isolated COG or PHY training. These findings support the advantage of the application of the motor-cognitive training to improve cognitive abilities, given no significant group differences in ADL outcome. Future studies should use context-enriched cognitive training, such as immersive virtual reality devices, in conjunction with sensitive measurement tools (e.g. performance-based measures of IADL), to study the generalizability of the training effects to daily functioning and accurately detect changes in ADL performance.

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Author contributions: ICC and CYW contributed to the study design, coordination and project management. ICC, HYC and CYW interpreted data and drafted and revised the manuscript. WWL performed the data analyses and helped to draft the manuscript. YRW participated in subject recruitment and provided consultation. CHC performed the data analyses. All authors read and approved the final manuscript. Trial registration: ClinicalTrials.gov Identifier NCT02512627 (31/07/2015).

Availability of data and materials: The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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