A Cognitive-Motor Training Intervention Reshapes EEG-Derived Functional Connectome Comparative Geometry in Older Adults

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Synopsis

Dual-task training has emerged as a promising intervention for healthy aging, yet its neural mechanisms remain poorly understood. This study examined functional connectivity (FC) during Rest, Physical, Cognitive, and Dual-Task assessments before and after a 12-week exercise-only (EO) or combined cognitive-motor (CT) exercise intervention in older adults. CT subjects improved Dual-Task performance and showed trends toward FC convergence between Cognitive and other tasks. Across both groups, the Dual-Task FC consistently resembled Cognitive more than Physical, a pattern deepening post-intervention. These findings suggest cognitive-motor training reshapes neural coordination strategies in a task-specific manner, with implications for intervention design in healthy aging.

Background

As our population ages, we need improved approaches to supporting healthy longevity. Dual-task exercise is a recent development in combating age-related cognitive and physical decline. There is growing interest in determining how these dual-task training interventions support healthy cognitive function. While behavioral outcomes of dual-task training have been characterized, the neural mechanisms underlying training-induced adaptation remain poorly understood. Electroencephalography (EEG) offers high temporal resolution well-suited for capturing task-based changes in the whole-brain dynamics of neural coordination. A suite of techniques developed for analysis of functional magnetic resonance imaging (fMRI) supporting task-based connectivity analyses can be applied the quantification of whole-brain FC in EEG (1, 2). In the present study, EEG was collected during dynamic Physical, Cognitive, and Dual assessments conducted before and after a 12-week EO or CT training program.

Methods

Variable	Source	F	p-value
Physical Task (reps)	Group	0.28	0.602
	Session	17.72	**<.001**
	Interaction	1.03	0.316
Cognitive Task (reps)	Group	0.14	0.712
	Session	4.77	**0.035**
	Interaction	0.00	0.976
Dual Task (reps)	Group	0.30	0.586
	Session	5.20	**0.028**
	Interaction	3.40	0.072
Dual Task Cost (reps)	Group	1.52	0.224
	Session	0.10	0.752
	Interaction	1.82	0.185
FC Distance (Physical to Dual Tasks)	Group	0.06	0.806
	Session	0.37	0.548
	Interaction	3.72	0.062
FC Distance (Cognitive to Dual Tasks)	Group	0.01	0.906
	Session	1.49	0.231
	Interaction	2.44	0.127
FC Distance (Physical to Cognitive Tasks)	Group	0.87	0.357
	Session	1.26	0.269
	Interaction	0.52	0.475
FC Distance (Rest to Physical Tasks)	Group	0.23	0.634
	Session	1.05	0.313
	Interaction	0.93	0.343
FC Distance (Rest to Cognitive Tasks)	Group	0.07	0.787
	Session	0.35	0.560
	Interaction	4.27	**0.046**
FC Distance (Rest to Dual Tasks)	Group	0.00	0.983
	Session	0.42	0.522
	Interaction	3.68	0.063

Table 1: RM-ANOVA results by Group, Session, and Group × Session for each assessment having uncorrected p-values.

SUBJECTS: 45 older adults (15/35 M/F; age > 50 years) completed a 12-week training program (of 50 enrollees) with random assignment to physical-only or dual-task training programs. Both EO and CT groups engaged in the same physical training program, while the CT group had the incremental inclusion of SMARTfit (SMARTfit, Inc.) and Twall (Exergame) boards for cognitive exercises. Subjects were assessed with four tasks before and after intervention, Rest, Physical, Cognitive, and Dual-Tasks. The number of repetitions executed in one minute was recorded.

EEG: Cortical activity was collected using a 32-channel dry EEG headset (CGX Systems Quick-32r) during the assessment. Collected data were pre-processed using commonly applied cleaning and component extraction methods (3-6) to obtain time-domain signals in the 2-50 Hz range (7). Functional Connectivity was analyzed for each participant using the FC approach previously developed for functional MRI (8), treating the known channel locations on scalp surface as physical nodes of interest. Pairwise distances between all task FCs were extracted for each subject-session.

STATISTICAL ANALYSIS: Differences in pre-to-post change were evaluated using repeated-measures ANOVA (RM-ANOVA) with time (Pre, Post) as the within-subject factor and group (CT, EO) as the between-subject factor, with the Time × Group interaction serving as the primary test of differential training effects. Within-group pre-to-post changes were examined using paired-samples t-tests with Cohen's *d*. FC distances between task states (Baseline, Physical, Cognitive, Dual) were computed as normalized Euclidean distances and analyzed with the same framework.

Results

PERFORMANCE: Both groups significantly improved Physical task performance (CT: d = 0.78, p = .001; EO: d = 0.49, p = .040), with no significant between-group difference (Group × Session: F(1,42) = 1.03, p = .316), as demonstrated in Table 1. Cognitive task performance did not significantly improve in either group (CT: d = 0.34, p = .112; EO: d = 0.32, p = .165). Only the CT group demonstrated a significant pre-to-post improvement in Dual assessment performance (d = 0.65, p = .004), while the EO group showed no change (d = 0.06, p = .780), yielding a trend in the Group × Session interaction (F(1,42) = 3.40, p = .072). Dual-Task Cost did not significantly change in either group.

Figure 2: Pre-to-Post training effects assessed for each group through paired samples t-testing, with Cohen's d effect size reported here. Small and moderate-to-large effect sizes are shaded in grey to indicate where trend wise changes may exist despite insignificant corrected findings.

NEURAL CORRELATES: Figure 1 summarizes pre-to-post effect sizes (Cohen's *d*) for all performance and FC distance measures by group. The distance between Rest and Cognitive FC states showed the only significant Group × Session interaction (F(1,36) = 4.27, p = .046). the CT group insignitfcantly trended toward reduced distance between Rest and Cognitive (d = −0.31, p = .16) while the EO group trended toward increased distance between these tasks (d = 0.35, p = .18), reflecting divergent trajectories in how Resting and Cognitive FC states relate across groups. Trend-level interactions were observed for Resting-Dual (F(1,36) = 3.68, p = .063; CT: d = −0.41, p = .069; EO: d = 0.22, p = .395) and Physical-Dual distances (F(1,36) = 3.72, p = .062;

CT: d = −0.24, p = .282; EO: d = 0.38, p = .15). Within the CT group, Cognitive-Dual distance decreased significantly (d = −0.47, p = .037), while the EO group showed no change (d = 0.05, p = .832), though the interaction was not significant (F(1,36) = 2.44, p = .127).

Discussion

The physical training intervention was highly effective and non-differential, with both groups capable of more Physical Task reptitions post-intervention. A selective improvement in Dual-Task performance was observed in the CT group. This observation, accompanied by a trend-level group-by-time interaction, suggests that practicing multiple domain exercise may be necessary to drive performance gains in dual-tasks.

Similarity between FCs indicates convergence of task-specific connectivity. Shrinking distances between baseline and task FCs may indicate improving neural efficiency, likely accomplished through a reduction in neuronal activation for task-accomplishment. Given the CT group Baseline and Cognitive FCs converged at post-intervention, we can conclude that the CT group was able to more closely functionally match their resting cognitive state, despite the incrementally challenging Cognitive assessment. The EO group, on the other hand, employed a divergent strategy from Rest, indicating a distict cognitive loading pattern from their Rest pattern. These trends are paralleled in the Physical-Dual and Rest-Dual distances, further suggesting a broader shift in how the dual-task group's FC relates across task states.

Taken together, these findings provide preliminary evidence that a cognitive-motor training program induces both behavioral and neural adaptations that exercise training alone does not. The consistent directionality of effects across multiple distance measures, despite modest sample sizes, supports the theoretical relevance of connectome state geometry as a framework for quantifying dual-task learning and costs. Replication with larger samples is needed to establish the robustness of these effects.

Disclosures (if any)

None.

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