Influence of acute combined physical and cognitive exercise on cognitive function: an NIRS study

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46 **ABSTRACT**

47   The purpose of this study is to investigate the effects of different types of acute exercise on
48 cognitive function and cerebral oxygenation. A within-subject design was adopted. In total, 20
49 healthy older adults were enrolled in the study. They came to the laboratory individually on four
50 separate days and completed four conditions of activity. Four conditions were sedentary reading
51 control (RC), cognitive exercise (CE), physical exercise (PE) and cognitive+physical exercise (CE
52 + PE). During these visits, participants completed the Stroop task before and after the experimental
53 condition when the heartrate returned to baseline, which consisted of 15 min of aerobic exercise,
54 verbal fluency task (VFT), and dual task. The Stroop task included the following two conditions:
55 a naming condition and an executive condition. The fNIRS is an optical method using near-infrared
56 light to measure relative changes of oxygenated (O_2Hb) and deoxygenated (HHb) hemoglobin in
57 the cortex. The results indicate that acute exercise facilitates performance for executive tasks, not
58 only combined cognition, but also combined exercise and single exercise. The fNIRS findings
59 showed that acute single exercise influences oxygenation for executive tasks but not for naming
60 tasks. Greater improvement was observed in the post-exercise session of combined exercise during
61 the modified Stroop. These findings demonstrate that acute single exercise, single cognition
62 exercise, and combined exercise enhanced the performance of the inhibition control task. Only
63 acute combined exercise has a general facilitative effect on inhibition control. Combined exercise
64 was shown to be superior to single exercise for task-efficient cerebral oxygenation and improved
65 oxygen utilization during cortical activation in older individuals. Also, to maximize the
66 performance of cognition it may be important for older adults to take part in more cognitive
67 demand exercise or take more kinds of exercise.

68 **Introduction**

69   Some meta-analytic reviews and interventions have demonstrated that acute exercises
70 including short duration exercises have positive effects on cognition in older adults (Chang et al.
71 2012; Peiffer et al. 2015). However, the mechanism by which acute exercise influences cognitive
72 function is unclear. Inhibition refers to the process of controlling one's attention, behavior,
73 thoughts, and/or emotions to override a strong internal predisposition or external lure (Barkley
74 2012). Bediz et al. (2016) proposed that the change of the prefrontal cortex (PFC) oxygenation
75 may be one of the mechanisms. In recent studies that take advantage of human brain imaging, a
76 change in brain oxygenation has been demonstrated in pre-and post-invention tests. Most of those
77 studies showed an increase in oxygenation of PFC following exercise (Jung et al. 2015). An
78 increase in prefrontal area Oxy-Hb response tends to correlate with better performance in cognitive
79 test (Coetsee 2015; Endo et al. 2013). Near infrared spectroscopy (NIRS) is a non-invasive method
80 for measuring cerebral hemodynamic response to cognitive tasks. More and more studies

81 employed NIRS to record the brain oxygenation during or post intervention conditions. Recent
82 findings from fNIRS studies showed that an acute bout of exercise, regardless of intensity,
83 improves performance on executive function and may induce different prefrontal area
84 oxygenation. Li et al. (2005) reported a higher dorsolateral PFC activation during working memory
85 task by using fNIRS. Endo et al. (2013) demonstrated that exercise at moderate intensity for 15
86 min may improve cognitive function and neural activity in the prefrontal areas. Byun et al. (2014)
87 showed the acute bout of mild exercise can improve Stroop performance, which evoked cortical
88 activations on the left dorsolateral prefrontal cortex and frontopolar area.

89   Despite accumulating evidence for the positive effects of acute exercise on cognition, most
90 of the results were derived from studies focusing on aerobic exercise. Pesce (2012) claimed that
91 future research should not only target quantitative exercise characteristics, but also emphasize the
92 qualitative aspects of exercise, such as the cognitive features during exercise.

93   Moreover, there are limited number of studies investigating the effects of different types of
94 exercise. Hsieh et al. (2016a) found that acute resistance exercise enhances attention control and
95 working memory in both young and older males. Lately, researchers have demonstrated that
96 exercise with more cognitive demands in term of exercise mode was more effective for completing
97 cognitive task (Budde et al. 2008; Chen et al. 2017; Eggenberger et al. 2015). Some studies on
98 chronic exercise have proposed that a combined cognitive and physical exercise may result in
99 greater oxygenation of PFC than either intervention alone. Our earlier work showed that a high
100 cognitive demand may be a potential factor that influences the efficacy of exercise on cognitive
101 function (Ji et al. 2017). However, whether a combination of cognitive and physical exercise
102 exceeds single exercises in acute exercise remains unsolved. To date, previous studies showed
103 unclear results. Holtzer et al. (2011) provided the evidence that Oxy-Hb levels are increased in the
104 PFC during Walk-While-Talk compared with Normal Walk in young and older individuals. Later
105 studies are also consistent with the results that greater brain activation is observed following the
106 combined cognitive and physical exercise (Holtzer et al. 2015; Holtzer et al. 2017; Mirelman et al.
107 2014). In addition, few studies compared the cognitive function after acute exercises with different
108 cognitive demands. According to neurovascular coupling theory (NVC), the metabolic activity can
109 be assessed as an increase in cerebral blood flow (Attwell et al. 2010). We assume that the
110 cognitive characteristic of an exercise might be responsible for the significant differences. The first
111 aim of this study is to reveal the effect of the different exercises on the oxygenation and cognitive
112 function.

113   While many aspects of cognitive function are associated with aging, the cognitive domain of
114 executive function is particularly relevant. Yanagisawa et al. (2010) revealed a selective
115 improvement on the executive task of the Stroop task following acute exercise, which may depend
116 on heightened activation of dorsolateral prefrontal cortex. Some meta-analyses indicate that acute
117 exercise can be used to promote performance in subsequent higher-order cognition such as
118 attention, executive control, and short-term memory (Chang et al. 2012; Hung et al. 2013; Pesce
119 & Audiffren 2011). However, Chang et al. (2017) suggested that the improvement in cognitive
120 function is generalized rather than selective improvement after moderate intensity acute exercise.
121 In our earlier cross-sectional research, we also found different benefit for different process level

122 of cognition between Tai Chi and brisk walking (Ji et al. 2017). In this study, The Tai chi group
123 showed better performance of the naming and the executive conditions than the brisk walking
124 group. These findings demonstrated that regular participation in brisk walking and Tai Chi have
125 significant beneficial effects on executive function and fitness. A meta-analysis by Ludyga et al.
126 (2016) revealed that preadolescent children and older adults who participate in a single
127 moderately-intense aerobic exercise may get less benefit than younger adults, while the aerobic
128 activities have potential neuroenhancing effect as higher education, professional training and work
129 temporarily place high demands on the executive function system.
130   The aim of this study is to address the gap in knowledge regarding the effects of acute
131 combined and single exercise on cognitive function and cerebral oxygenation. A major question is
132 to explore the influence of acute combined physical and cognitive exercise on cognitive function.
133 We hypothesize that combined exercise would lead to a general pre-activation of cognitive-related
134 prefrontal cortex (PFC) oxygenation and would be more effective in improving the speed and
135 accuracy of the modified Stroop compared to single exercise.

136 **MATERIALS AND METHODS**

137 **Ethical approval**

138 The study was conducted ethically and received approval from the Ethics Committee of Shanghai
139 University of Sport (No. 2017032).

140 **Participants**

141   Twenty participants (9 female, mean age = 67 ± 3.2 year) were recruited from the Shanghai
142 Yanji community via flyers and personal referrals. All participants provided written informed
143 consent that is obtained by the Shanghai University of Sport. Additionally, participants finished a
144 health history questionnaire, reported being free from any neurological diseases, and had normal
145 or corrected-to-normal vision, normal color vision. Table 1 presents participant demographics.

146   (Insert Table 1. about here)

147 **Experimental procedure**

148   The participants joined the laboratory individually on four separate days, the interval between
149 each visit is 3-day. On the first visit, participants completed an informed consent and the Physical
150 Activity Readiness Questionnaire (PAR-Q) to confirmed the health issues of the participants that
151 may be exacerbated by acute exercise (Pontifex et al. 2009). Participants were instructed to
152 completed a cardiorespiratory fitness test that was used by the YMCA cycle ergometry protocol
153 (Ofusa & Golding 2000) and cognitive function was assessed using the Mini-mental State
154 Examination (Tombaugh & Mcintyre 1992).

155   On laboratory visits 1-4, participants completed a reading control condition (RC) and three
156 treatment conditions, cognitive exercise (CE), physical exercise (PE) and cognitive+physical
157 exercise (CE + PE). To minimize any order or learning effects, the condition order was
158 counterbalanced across participants. The reading control condition was complicated read materials
159 related to exercise. Participants completed the Stroop task before and immediately after the control
160 and treatment conditions (when the heart rate returned to rest level). During the Stroop task,
161 oxygenation changes in the cortex were measured throughout the session using fNIRS.
162 Additionally, we make sure that most anterior and ventral pairs were positioned in similar locations

163   for each participant and in each visit. Before the experimental trials, participants completed
164   practice trials to become familiarized and an 85% correct rate was allowed. Next, participants were
165   instructed to complete an acute session, which included 5-min warm-up to become familiarized
166   with the test procedure. For the RC, participants sit quietly in a chair and completed Verbal Fluency
167   Task (VFT) for approximately 15 min. Participants were asked to think of as many animal/ sport/
168   country/ vegetable/ fruit names as possible in each 2 min with 1 min interval. The single exercise
169   procedure consisted of three stages: a 5-min warm-up, a 15-min primary exercising (65% heart
170   rate returned), and a 5-min cool-down. The CE + PE condition which combined walking at the
171   same velocity as the 15-min primary exercising of PE condition with the VFT. The control
172   condition was proposed to keep an arousal level compared to the exercise condition.

173   **Cardiorespiratory Fitness Assessment**

174   The YMCA protocol involves three consecutive stages. The first level was at a power and
175   pedaling rate of 25W and 50 rpm for 3 min (150 kpm/min). The heart rate (HR) was assessed using
176   a Polar heart rate monitor (Sport Tester PE 3000, Polar Electro Oy, Kempele, Finland). The next
177   two exercise stages were decided according to the last minute of cycling. Two heart rate values
178   were recorded during the final 15 to 30 s of the first and second stages. These two heart rate values,
179   along with the YMCA equations, the individual's body weight, and age, were used to calculate the
180   estimated VO_2peak (Beekley et al. 2004).

181   **Cognitive Task**

182   The computerized modified Stroop task was based on the Stroop task and included the
183   following two tasks: a naming task (non-executive) and an executive task (Bohnen et al. 1992;
184   Olivier et al. 2015). Each block lasted 60s and was interspersed with 60-s resting blocks. The
185   blocks were always offered in the same order: Rest–Naming–Rest–Executive–Rest–Naming–
186   Rest–Executive. All trials began with a fixation cross that appeared at the center of the computer
187   screen for 1000 ms, and visual stimuli for a duration of 2000 ms.

188   Participants provided their responses by the response key mapping that was used in the task
189   (i.e., red—J key, blue—F key). In the naming task, a visual stimulus was presented as ink colors
190   of XXX and participants were instructed to indicate the color of the ink by pressing a response key
191   (i.e., red—J key, blue—F key). In the executive task, part of the presented stimuli is the ink colors
192   of color names, such as "RED" printed in blue ink, and the other part of the stimuli were words
193   surrounded by rectangles, the participants were instructed to read the word, ignore the color of the
194   ink (Figure 1). Participants did not speak during either the naming or the executive task to avoid
195   artefacts resulting from speaking. Reaction times (in milliseconds) and accuracy values were
196   recorded for all tasks. Dependent variables were reaction times and the number of errors committed
197   (%).

198   *(Insert Figure 1. about here)*

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200   **fNIRS Recordings**

201   A multi-channel continuous wave fNIRS instrument (NIRScout, NIRx Medical Technologies
202   LLC, USA) was used. The system collects (NIRStar 15.2) data that was sampled at 3.91 Hz. The
203   fNIRS sensor had 20 channels created by 8 LED light sources and 8 photodetectors, the source-

204   detector separation was 3 cm. The probe locations and specific brain regions were selected
205   according to studies of Masako et al. (2004) and Daisuke et al. (2007). NIRS-SPM (Ye et al., 2009)
206   and the software which integrates a 3D digitizer (FASTRAK-Polhemus, Polhemus, VT, USA) was
207   used to complete the 3-dimensional spatial registration of NIRS channel locations.
208   Four different approximate regions of interests (ROI) were defined, but do not refer exactly to
209   the underlying brain regions. Areas of interest were the left ventrolateral prefrontal cortex
210   (VLPFC) (channels 1–4), the left dorsolateral prefrontal cortex (DLPFC) (channels 5、6、7 and
211   11), the right DLPFC (channels 13-16) and the posterior right VLPFC (channels 17-20) for both
212   hemispheres (Figure 2). The fNIRS transmitters were tightly secured with a black bandage
213   wrapped to ensure that there was no interference of extraneous light and to limit movement during
214   cognitive task. Variables of interest were relative changes in concentration of Oxy-Hb and Deoxy-
215   Hb compared to the baseline (1 min at rest before the computerized Stroop task) (Gagnon et al.
216   2012; Laguë-Beauvais et al. 2013).
217   (Insert Figure2. about here)

218   **Analysis**
219   **fNIRS Analysis**
220   NIRS data analysis was performed in nirsLAB based on SPM and NIRS_SPM with additional
221   modules for ANOVAs. The fNIRS signals were bandpass filtered between 0.01 Hz and 0.2 Hz to
222   remove baseline drift, artefacts and physiological noise. The analysis of fNIRS signal was
223   performed by block (i.e., by task, including all trials), without separating out error trials. For the
224   fNIRS data, we calculated the value of the Oxy-Hb change, by subtracting the mean Oxy-Hb of
225   the pre-intervention task period from the mean Oxy-Hb of the post-intervention task period.
226   Previous studies revealed that the changes in Oxy-Hb are more sensitive to changes in regional
227   CBF than Deoxy-Hb, while the changes in Deoxy-Hb are mainly determined by venous
228   oxygenation and blood volume than blood flow changes (Hoshi et al. 2001). Thus, we only present
229   the results of Oxy-Hb in the current study.
230   **Statistical Analysis**
231   Behavioral and Oxy-Hb data were analyzed in SPSS (v19.0) using a 3 (conditions) × 2
232   (assessments) repeated-measures ANOVA. ANOVAs were performed on each task (Naming and
233   Executive) and post-hoc test P values were Bonferroni corrected for multiple comparisons.
234   **RESULTS**
235   **Behavioral Findings**
236   When the response time was considered, in the naming task, there was a significant main
237   effects of time ($F_{(1,76)}$ = 25.49,$p < 0.001$,$\eta^2 = 0.25$) and a interaction between time and
238   condition ($F_{(3,76)}$ = 4.31, $p < 0.001$, $\eta^2 = 0.15$). No significant main effects of condition ($F_{(3,76)}$
239   = 0.63, $p = 0.621$). The post-hoc comparison showed that the participants reduced reaction time
240   from pre-test to post-test (p = 0.043) in CE+ PE condition. In the executive task, there was a
241   significant main effects of time ($F_{(1,76)}$ = 39.56, $p < 0.001$, $\eta^2 = 0.34$) and a interaction between
242   time and condition ($F_{(3,76)}$ = 11.58, $p < 0.001$, $\eta^2 = 0.31$). No main effect of condition ($F_{(3,76)}$ =
243   1.25, $p = 0.303$) was observed. The post-hoc comparison showed that the participants reduced
244   reaction time from pre-test to post-test in CE+ PE ($p = 0.031$) and PE ($p = 0.043$) condition. All

245 results are shown in Figure 3.

(Insert Figure 3. about here)

247 When the accuracy was considered, in the naming task, there was no significant main effects
248 of time ($F_{(1, 76)} = 0.04$, $p = 0.852$), condition ($F_{(3,76)} = 0.57$, $p = 0.648$) and interaction between time
249 and condition ($F_{(3,76)} = 0.35$, $p = 0.798$). In the executive task, there was no significant main effects
250 of time ($F_{(1, 76)} = 0.28$, $p = 0.601$), condition ($F_{(3,76)} = 0.67$, $p = 0.581$) and interaction between time
251 and condition ($F_{(3,76)} = 0.19$, $p = 0.915$).

252 **fNIRS Findings**

253 Figure 4 presents the effects of four conditions on task-related changes in Oxy-Hb levels.
254 According to these analyses, in the naming task, there was a significant main effects of condition
255 ($F_{(3,76)} = 10.45$, $p < 0.001$, $\eta^2 = 0.29$) and an interaction between ROI and condition ($F_{(9,228)} =$
256 2.13, $p = 0.028$, $\eta^2 = 0.08$). No significant main effects of ROI were observed ($F_{(3,228)} = 1.80$,
257 $p = 0.153$). Post-hoc comparison showed, in the L-VLPFC area, CE conditions were significantly
258 higher than RC conditions ($p < 0.001$). In the R-VLPFC area, CE+ PE conditions were
259 significantly higher than RC conditions ($p < 0.001$), CE+ PE conditions were significantly higher
260 than CE ($p = 0.033$), and PE were significantly higher than RC ($p = 0.041$).

261 In executive task, there was a significant main effect of condition ($F_{(3,76)} = 7.68$, $p <$
262 0.001, $\eta^2 = 0.23$), ROI ($F_{(3,228)} = 3.08$, $p = 0.028$, $\eta^2 = 0.04$) and an interaction between ROI
263 and condition ($F_{(9,228)} = 1.97$, $p = 0.043$, $\eta^2 = 0.07$). Post-hoc test revealed that, in L-DLPFC,
264 PE ($p = 0.031$) and CE+ PE ($p = 0.035$) showed greater oxygenation levels than RC. In R-DLPFC,
265 PE showed greater level than RC ($p = 0.031$) and CE ($p = 0.042$), and CE+ PE showed greater
266 than level RC ($p = 0.041$) and CE ($p = 0.043$). No other significant difference was observed
267 between two intervention conditions. All results of fNIRS are shown in Figure 4.

(Insert Figure 4. about here)

269 **DISCUSSION**

270 The purpose of this study is to determine whether different types of acute exercise result in a
271 general or selective improvement in cognitive function and to investigate potential neurobiological
272 mechanisms by examining cognitive-related prefrontal cortex oxygenation. The findings reveal
273 that acute exercise facilitates performance for executive tasks, not only combined cognition, but
274 also the different results between combined exercise and single exercise. On one hand, single
275 exercise showed selective effects for task requiring executive function (i.e., executive task).
276 Additionally, the fNIRS findings demonstrate that acute single exercise influences oxygenation
277 for executive tasks, but does not influence oxygenation for naming tasks. On the other hand, a
278 general improvement hypothesis was supported by the results of acute combined exercise. In this
279 study, higher oxy-Hb levels and greater increments in the post-exercise session of combined
280 exercise during the modified Stroop suggested a better performance of the naming and executive
281 blocks in Stroop task. In contrast, in the control and cognitive condition, no significant
282 improvement in inhibition control and oxy-Hb levels were observed between pre-test and post-
283 test.

284 Behavioral measurements showed that the older adults demonstrated a consistently better
285 performance for executive task after both combined and single exercise compared with the control

and cognition condition. The effect of acute single exercise on executive function has been demonstrated in previous studies. Browne et al. (2016) and Peruyero et al. (2017) found acute aerobic exercise improved the inhibitory control in adolescents. The improvement also has be found in study among older adults. Ludyga et al. (2016) provided evidence that older adults can improve performance of the task demanding high executive control by an acute aerobic exercise. Additionally, the obtained effect sizes were not influenced by factors include age, aerobic fitness and the executive function component. Results of acute aerobic exercise by Peiffer et al. (2015) indicated that older adults improved performance in a modified flanker task after both moderate and vigorous intensity aerobic exercise and these effects would last 30 min post-exercise. Recent studies suggested that other exercises may also improve executive function in older adults. Acute resistance exercise benefited working memory measured by Sternberg working memory in older males (Hsieh et al. 2016). The results supported a selective facilitation rather than a general one (Hsieh et al. 2016). However, single exercises were used in their intervention studies. The effects of acute exercises combined with cognitive training on cognitive function was unclear. Interestingly, we find that acute combined exercise enhances cognitive performance in both naming task and executive task, further supporting a general improvement hypothesis of acute exercise rather than a selective improvement in cognition. Altered prefrontal cortex oxygenation might be a possible underlying mechanism of the beneficial Stroop effect associated with acute exercise. In contrast, no significant improvement was observed in control and cognitive condition. These results were similar to previous studies which showed that a control group that reads for the same length of time has no facilitative effects on the executive functions (Chang et al. 2011).

In this study, we observed significant oxy-Hb signal increases associated with the execution (naming contrast) in the LPFC covering the bilateral VLPFC and DLPFC. This spatially specific activation pattern is consistent with the results of previous fNIRS studies on Stroop interference, reporting bilateral LPFC activity (Schroeter et al. 2004; Yanagisawa et al. 2010). Previous fMRI studies have also consistently showed LPFC activation reflecting Stroop interference along with activation of ACC (Derrfuss et al. 2005). In the related literature, it has been demonstrated that the oxy-Hb level increases in PFC during post-exercise cognitive task. A previous task-based fMRI study (Newman et al. 2003) showed that although both the right and left PFC were activated by a planning task, the activation in the right DLPFC was sensitive to task difficulty. Moreover, Yanagisawa et al. (2010) concluded that the LPFC activation may reflect interference processing/response inhibition, and suggested that the left LPFC is likely the neural substrate for the improved Stroop performance. In our study, the oxy-Hb level increases also in LPFC, the brain areas of Stroop-interference-related activation were not only left LPFC but also right LPFC. A potential explanation for the shift of the action in this finding might be due to "reduced lateralization" in old age (Psychology & aging 2002). Cabeza et al. (2002) showed that the bilateral activation during tasks was observed in old people, while in young people the two areas are clearly defined and have separate roles.

fNIRS is a reliable method to explore the mechanisms of physical exercise on brain oxygenation in relation to cognitive performance for decades. However, studies demonstrating the difference between combined exercise and single exercise are very limited and these mechanisms

327 are not well understood. The behavioral data of this study demonstrated that acute combined
328 exercise has greater benefits on naming task. The results of fNIRS showed that combined exercise
329 could cause higher oxygenation responses for naming task in VLPFC. The VLPFC is the end area
330 of the ventral pathway involved in processing/recognition of visual stimuli, while the DLPFC is
331 implicated in the choice, manipulation, and monitoring of information (Itakura et al. 2017).
332 Milham et al. (2003) reported that the DLPFC were more active for executive function than
333 VLPFC. The difference of VLPFC may be the potential cause of different performance in naming
334 tasks.

335   This study demonstrates the effects of different acute exercise on cognitive function, but some
336 potential limitations should be considered when interpreting our findings. Firstly, additional
337 subcomponents of executive function should be investigated, including working memory,
338 updating, switching, and planning, and their responses to exercise may be specific. Secondly, the
339 number of the subjects in the fNIRS experiments was small. Although the within-subject design
340 suffers less from variation, a larger sample size would be more powerful. Finally, artefacts of
341 physical activity can be removed by filtering. Artefacts due to speaking may have impacted the
342 results, but the language area was not our ROI. Further studies could optimize task modules to
343 minimize the impact of artefacts.

344 CONCLUSION

345   In summary, both acute single exercise and combined exercise can significantly improve the
346 performance of the executive task. However, acute combined exercise has a general facilitative
347 effect on the performance of the naming task. Combined exercise was shown to be superior to
348 single exercise for cognitive function, which was supported by task-efficient cerebral oxygenation
349 and improved oxygen utilization during cortical activation in older individuals. In addition, in
350 order to maximize cognitive function it may be important for older adults to take part in more
351 cognitive demand exercise or take more kinds of exercise.

352

353   Figure 1, Illustration of the modified Stroop task: (A) the naming condition of the Modified
354 Stroop task; (B) the executive conditions of the Modified Stroop task.

355

356   Figure 2, The location of the fNIRS probes and the ROI.

357

358   Figure 3, Reaction time of the naming task and executive task in the modified Stroop task:
359 RC, Reading control condition; CE, cognitive exercise; PE, Physical exercise; CE＋PE, cognitive
360 ＋ physical exercise. Reaction time of the naming task (A) and executive task (B); (C) scatter plot
361 of the pre-test during naming task; (D) scatter plot of the pre-test during executive task; (E) scatter
362 plot of the post-test during naming task; (F) scatter plot that the post-test during executive task.
363 *Significant difference between pro-test and post-test, p < 0.05.

364   Figure 4, The interaction effects of the naming task and executive task on task-related changes
365 in Oxy-Hb levels: RC, Reading control condition; CE, cognitive exercise; PE, Physical exercise;
366 CE＋PE, cognitive ＋ physical exercise. Oxy-Hb levels of the naming task (A) and executive
367 task (F); (B) scatter plot of the Oxy-Hb levels of l-DLPFC during the naming task; (C) scatter plot

368 of the Oxy-Hb levels of l-VLPF during naming task; (D) scatter plot of the Oxy-Hb levels of r-
369 VLPF during the naming task; (G) scatter plot of the Oxy-Hb levels of r-DLPF during the executive
370 task; (H) scatter plot of the Oxy-Hb levels of l-DLPFC during executive task; (I) scatter plot of the
371 Oxy-Hb levels of l-VLPF during executive task; (J) scatter plot of the Oxy-Hb levels of r-DLPF
372 during executive task.*Significant difference between four conditions, p <0 .05.

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474

Figure 1

Illustration of the modified Stroop task

(A) the naming condition of the Modified Stroop task; (B) the executive conditions of the Modified Stroop task.

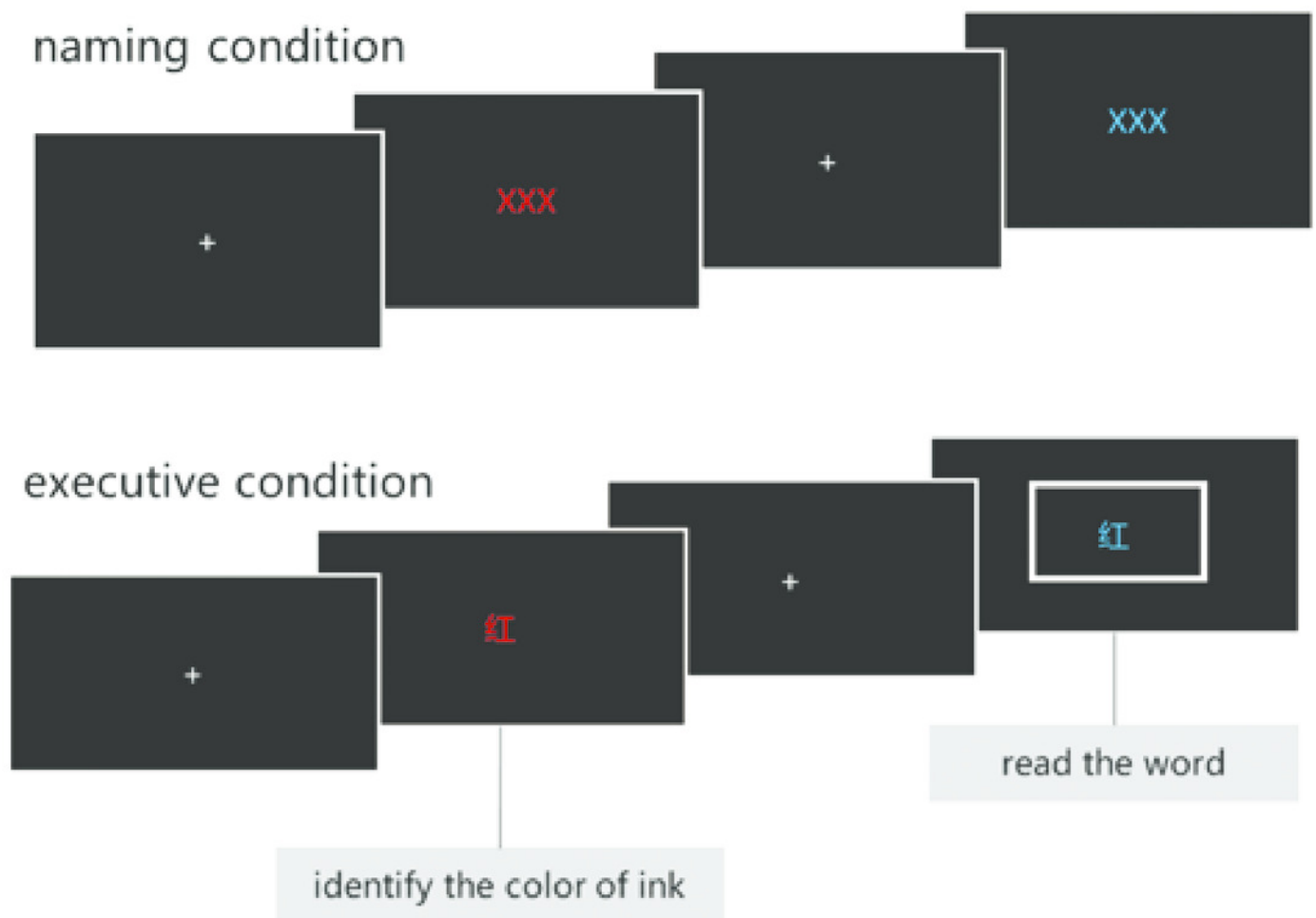



Figure 2

The location of the fNIRS probes and the ROI

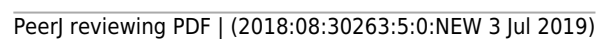



Figure 3

Reaction time of the naming task and executive task in the modified Stroop task

RC, Reading control condition; CE, cognitive exercise; PE, Physical exercise; CE⬜PE, cognitive ⬜ physical exercise. Reaction time of the naming task (A) and executive task (B); (C) scatter plot of the pre-test during naming task; (D) scatter plot of the pre-test during executive task; (E) scatter plot of the post-test during naming task; (F) scatter plot that the post-test during executive task. *Significant difference between pro-test and post-test, $p < 0.05$.

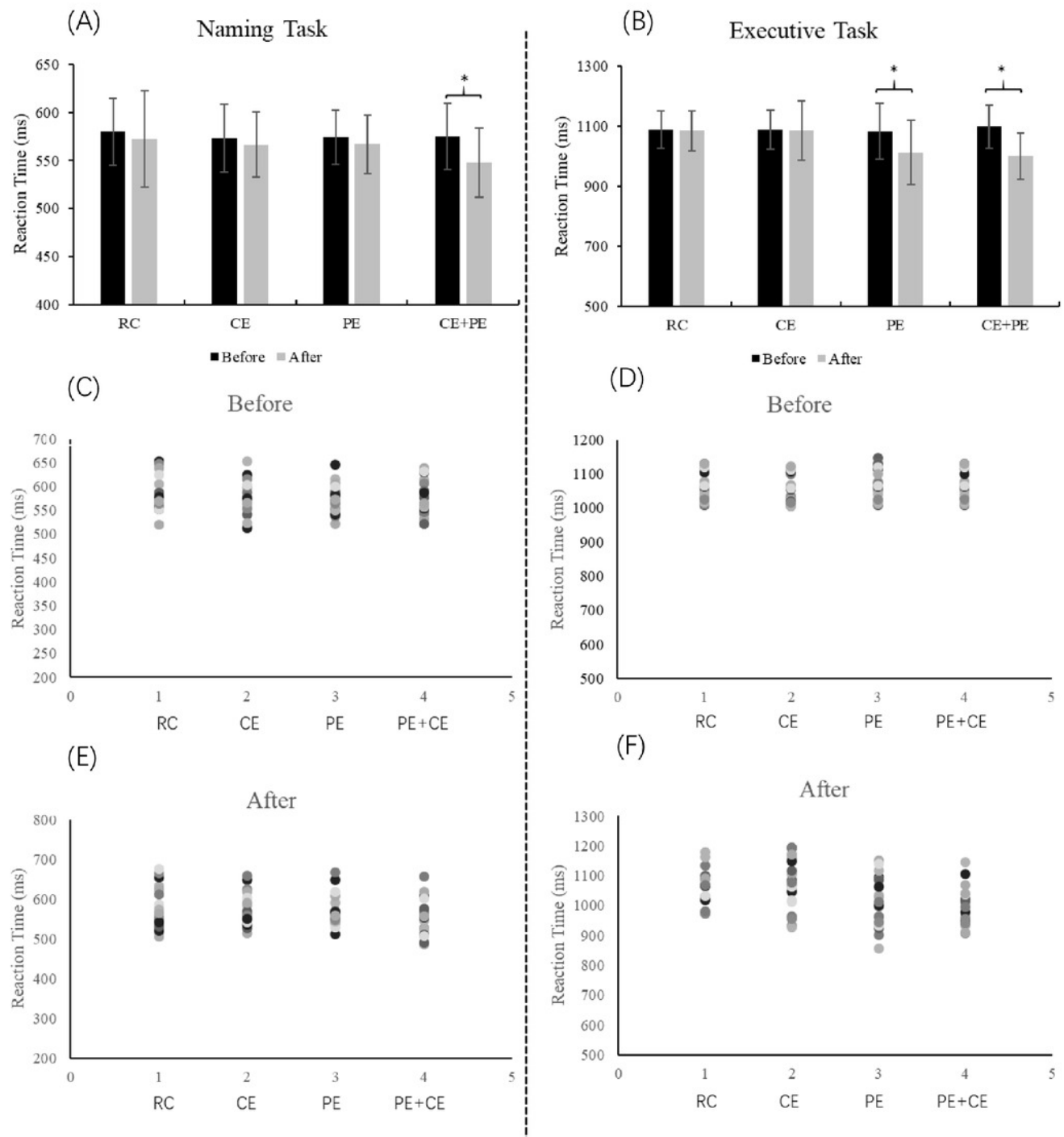



Figure 4

The interaction effects of the naming task and executive task on task-related changes in Oxy-Hb levels

RC, Reading control condition; CE, cognitive exercise; PE, Physical exercise; CE☐PE, cognitive ☐ physical exercise. Oxy-Hb levels of the naming task (A) and executive task (F); (B) scatter plot of the Oxy-Hb levels of l-DLPFC during the naming task; (C) scatter plot of the Oxy-Hb levels of l-VLPF during naming task; (D) scatter plot of the Oxy-Hb levels of r-VLPF during the naming task; (G) scatter plot of the Oxy-Hb levels of r-DLPF during the executive task; (H) scatter plot of the Oxy-Hb levels of l-DLPFC during executive task; (I) scatter plot of the Oxy-Hb levels of l-VLPF during executive task; (J) scatter plot of the Oxy-Hb levels of r-DLPF during executive task.*Significant difference between four conditions, p <0 .05.

(A)

(B)

(C)

(D)

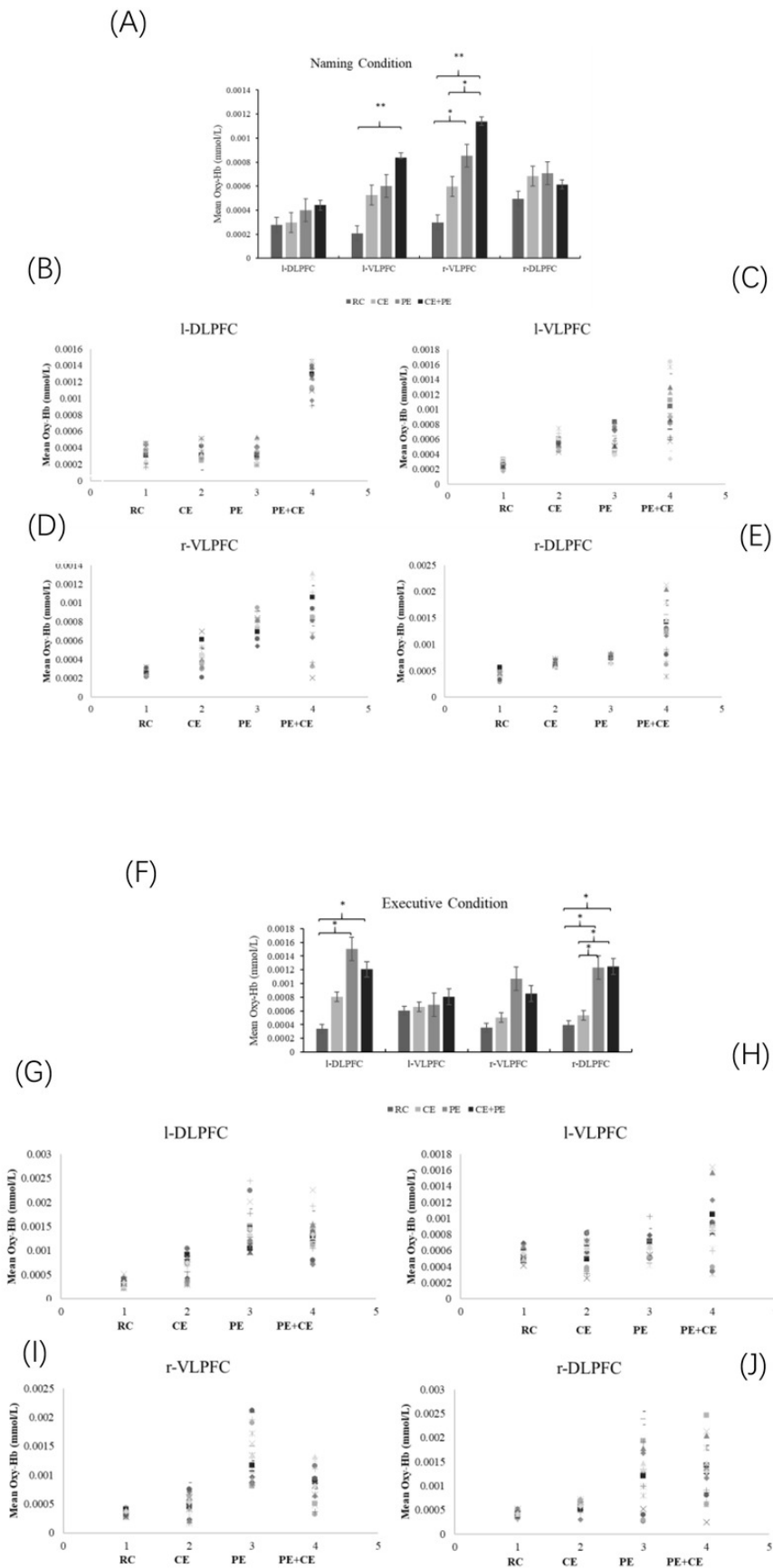
(E)

(F)

(G)

(H)

(I)

(J)

Participants' characteristics.

Note. BMI = body mass index; MMSE = Mini-Mental State Exam; IPAQ = International Physical Activity Questionnaire

	MEAN	SD
Age, years	65.60	1.32
Weight, kg	59.35	6.15
Hight, cm	161.75	5.58
BMI	22.66	1.71
MMSN	27.90	0.62
Education, years	11.25	1.48
M/F	0.45	/
VO2peak,	26.00	2.09