The beneficial effects of game-based exercise using age-appropriate tennis lessons on the executive functions of 6- to 12-year-old children

Toru Ishihara[1], Shigemi Sugasawa[2], Yusuke Matsuda[2], Masao Mizuno[3]

[1]Department of Physical Fitness Science, Graduate School of Education, Hokkaido University

[2]Nagoya Green Tennis Club Group

[3]Faculty of Education, Hokkaido University

Correspondence to: Toru Ishihara

Graduate School of Education, Hokkaido University, Kita 11-jo, Nishi 7, Kita-ku, Sapporo, Hokkaido 060-0811, JAPAN, Tel: +81-11-706-7524, E-mail: t.ishihara@edu.hokudai.ac.jp

Abstract

This study evaluated the effects of two different types of tennis lessons—those involving a technique-based approach (TBA) and those involving a game-based approach (PLAY+STAY [P+S])—on the executive functions (EFs) of junior tennis players. Eighty-one tennis players (6–12 years old) were recruited and assigned to one of three groups: TBA, P+S, or watching TV (CONT). Subjects completed evaluations of EFs (inhibitory control, working memory, and cognitive flexibility) before and after 50-minute programs. The overall score for EFs improved significantly for both the P+S and TBA groups but not for the CONT group; indeed the CONT group showed no improvement in overall EFs. Furthermore, the overall EF score improved more for P+S participants than for those in TBA. Looking at components of EFs, the pattern for inhibitory control reflected the pattern for the overall EF index: Improvement in the P+S and TBA groups but not in the CONT group. Only the P+S group improved in working memory. Thus, playing tennis and practicing isolated tennis skills both improved EFs of junior players more than did watching TV, and game-based tennis lessons seem to hold more promise for improving EFs than drills of tennis skills.

Keywords: sports activity; cognitive engaging exercise; inhibitory control; working memory; cognitive flexibility

Highlights

- We examined the effects of tennis play on executive functions (EFs) in children.
- A single 50-minute session of tennis play improved EFs of children.
- A single session of game-based exercise improved EFs more than repetitive exercise.
- The short-term EF benefit might be useful for the class immediately after exercise.
- Perhaps more extended practice playing tennis might be useful for EF development.

Introduction

A single (i.e., acute) bout of physical exercise is useful for facilitating cognition, which is expected to support learning in children immediately afterward [1–3]. The benefits of acute exercise for cognitive functions in children have been demonstrated in laboratory settings (e.g., treadmill walking, stationary biking) [4,5] as well as school settings (e.g., group jogging, group games) [6–8]. Further confirmation comes from two meta-analyses, which showed that acute exercise improves cognitive function in children, with effect sizes of 0.52 and 0.32 (Cohen's *d*) [2,3].

An acute bout of exercise improves perception and basic processing speed, as well as higher-order cognitive function (i.e., executive functions: EFs) in children [5,9]. The EFs are comprehensive functions governing goal-directed behavior and comprise three essential components: inhibitory control, working memory, and cognitive flexibility [10]. These three features are seen in both adults and children [10]. Relationships have been found between EFs and healthy food intake (greater fruit/vegetable and less junk food intake) [11], academic achievement and outcomes (school readiness and school success) [12], and performance in other settings such as sports [13]. Furthermore, acceptable levels of EFs in children have been found to predict better health and wealth and a reduced likelihood of having a criminal record [14].

The utility of such exercises may depend on the sensorimotor learning and the degree of cognitive activity they involve (e.g., use of strategic behavior, coordination of complex bodily movements, and adaptation to continually changing task demands) [9,15,16]. Acute exercise involving cognitive activity (e.g., group games, coordinative training) may lead to greater improvements in EFs than simpler exercises (e.g., circuit training) [6,8]. Aerobic games require cooperation with other children, strategic behavior, coordination of complex bodily movements, and adaptation to continually changing task demands. It has been suggested that the differences in the EFs demands between game-based/complex and simpler exercises mean that the game-based/complex exercises facilitate EFs development to a greater extent than do simpler exercises [9,16,17]. Thus, it is important to develop cognitively demanding exercise programs that can be implemented during the school day just prior to an academic class to encourage optimal performance in that class, and to test other possible real world applications of the acute effect of complex physical activity on EFs.

Playing tennis requires more top-down cognitive control and the ability to override automatic behavior than repetitive tennis training (e.g., ball feeding), which might lead to the facilitation of EFs in children. However, usually the same equipment (balls, courts) as adults are used in tennis lessons for children, and repetitive training (i.e., ball feeding) comprises a large proportion of the lessons because their motor and cognitive skills may be too immature to play games with the same equipment as adults.

In February 2007, the International Tennis Federation created a program targeting young children called PLAY+STAY (P+S), which modifies conventional tennis lessons (i.e., those using the technique-based approach; TBA) to better-fit children's needs. P+S tennis lessons focus on games with age-appropriate court sizes and equipment to help children play more strategically. Using the age appropriate equipment, players are able to serve, rally, and score from their first lesson [18]. In contrast, in TBA lessons, ball feeding comprises a large proportion of the lesson because children use the same balls and courts as adults do. Given the P+S program's focus on games and rallying, which requires substantial top-down cognitive control and the ability to override automatic behavior rather than repetitive exercise (i.e., ball feeding), we hypothesized that it would have greater benefits for the EFs (i.e., inhibitory control, cognitive flexibility, and working memory) of junior tennis players than would the TBA. Most previous studies that demonstrated the effects of acute exercise on cognitive function focused on aerobic exercise in laboratory settings. Thus, we evaluated the beneficial effects of P+S tennis lessons as compared to TBA on the EFs of tennis players aged 6–12 years old, and expand previous knowledge toward real world applications.

Material and methods

Participants

Eighty-one junior tennis players (6–12 years old, 38 boys, 43 girls, tennis experience: 0.1–7.3 years) participated in this study. We recruited participants from three tennis clubs. The tennis groups were classified based on the tennis lessons in which they usually participated [TBA (n = 32), P+S (n = 39)], because unfamiliar lesson programs were expected to influence the experimental results. We recruited a control group from among players who had recently changed from TBA lessons to P+S lessons (CONT; n = 10), who watched TV instead of undergoing the tennis lesson. Children who were receiving special needs education due to disorders of cognitive function or attention were excluded. Participants provided written assent and their parents provided written informed consent in accordance with the requirements of the Ethical Committee of Faculty of Education, Hokkaido University.

Procedure

Testing was completed over 2 days that included a cardiorespiratory fitness assessment and experimental session. Cardiorespiratory fitness was evaluated before the lesson by the use of the shuttle stamina test [19]. Seven participants could not participate in the cardiorespiratory fitness assessment due to a conflict with their parents' schedule; therefore, cardiorespiratory fitness data were collected for 74 participants. In the experimental session, participants entered a computer room and rested for 5 minutes. Participants were then instructed to complete the EFs tasks (pre-test assessment). Next, participants underwent a tennis lesson or watched a TV program (a popular animated cartoon) for 50 minutes. In our country, tennis clubs generally comprise 45- to 60-minute programs for children. Our sample typically took part in 50-minute tennis lessons, so we set the lesson duration at 50 minutes. During this time, their heart rates were measured in 1-second intervals using a heart rate (HR) monitor (RS400, Polar, Kempele, Finland). The contents of each tennis lesson and the time spent on each activity during the lesson were recorded. After the programs, participants were taken back to the same room and completed the same cognitive tasks at post-test 15 minutes after the 50 minutes of tennis lesson or watching TV. Participants were required to refrain from caffeine and exercise on the day of the experiment. All experiments were conducted between 13:30 and 17:30.

Differences in equipment and typical examples of instruction in tennis lessons

Equipment and typical examples of instruction in both tennis lessons are presented in Supplementary material. In P+S tennis lessons, junior players used various types of equipment separated into four stages and used age appropriate tennis rackets. By using the age appropriate equipment, instruction of P+S was focused on playing the game.

Assessment of executive functions

Three EFs were evaluated using the Stroop Color and Word Test (SCWT), 2-back Task, and Local-global Task (LGT). The details of the assessment of executive function are listed in Supplementary material. The SCWT is a well-known instrument for measuring inhibitory control [20]. Participants are instructed to name the color of the incongruent color-word stimulus (e.g., blue printed in green ink). Because word reading is a more automatic cognitive process than is color naming, participants are required to inhibit strong internal predispositions. In the 2-back Task, participants are required to monitor a series of stimuli and respond whenever a stimulus is presented that is the same as the one presented in previous trials [21]. During the 2-back Task, participants are required to hold the information and update it (working memory). In the LGT, a geometric figure called a Navon figure [22], comprising a “global” stimuli composed of much smaller, or “local” stimuli, was randomly presented on the computer screen. The target stimuli were equally likely to appear at the global and local levels, whereas neutral stimuli appeared at the opposite level of the target stimuli. When the level of the target stimuli was alternated, i.e., “local” trials were followed by “global” trials and vice versa, participants are required to use cognitive flexibility. Details of these tasks are presented in the supplementary material. The main dependent variables of these tasks were mean reaction time (RT) and accuracy.

Statistical analysis

We assessed the normality of variables using the Kolmogorov-Smirnov test. The accuracy data for the three EFs tasks and HR data did not show a normal distribution; therefore, accuracy and HR were globally ranked before performing the ANCOVA [23]. One-way ANCOVAs were conducted to examine the significance of the differences in demographic data, cardiorespiratory fitness, mean HR (at pre-test, during programs, and at post-test), and EF task performance data at pre-test adjusted for age and gender. Principal components analyses were conducted to obtain the overall score for EFs (RT and accuracy of the SCWT incongruent trial, 2-back Task, LGT switching condition) and basic processing speed/accuracy (requiring less executive aspects of cognition; RT and accuracy of the SCWT control trial, LGT repetitive condition). The mean RT and accuracy data obtained during the three tasks were analyzed using 3 (group: CONT, TBA, P+S) × 2 (time: pre-test or post-test) two-way ANCOVAs that were adjusted for age and gender (coded as 0 = girl, 1 = boy) to determine time dependent change. Previous research suggested that the effects of acute exercise on EFs might have individual differences [4]. In this study, improvement of RT was affected by RT at pre-test [⊿RTs was significantly correlated with RTs at pre-test in all tasks ($pr < -.33$, $p < .01$, data not shown); i.e., lower performer(s) at pre-test showed greater improvement than higher performer(s)], therefore, we conducted one-way ANCOVAs on ⊿RT that adjusted for age, gender, and score at pre-test. Significant main effects of group were further analyzed via Scheffé's post hoc tests.

Results

Participants' characteristics

Descriptive data regarding the participants' demographic characteristics are presented in Table 1. No significant differences in gender ($\chi^2 = 2.13$, $p = .35$) and other variables ($F < 2.42$, $p > .09$, partial $\eta^2 < .06$) were detected between the groups.

Lesson type

The breakdown of TBA lessons by time spent performing various activities was as follows: 32% non-activity time (i.e., explanations and breaks), 5% games, 19% rallies, 27% ball feeding, 5% coordination training, and 12% collecting balls. For the P+S lessons, the breakdown was as follows: 26% non-activity time, 40% games, 24% rallies, 0% ball feeding, 5% coordination training, and 5% collecting balls. All of the lessons ended in a game.

Heart rates

HR data were collected for 60 subjects, due to a limited number of HR monitors. During the programs, participants in the TBA and P+S groups showed a higher mean HR than did those in the CONT group ($F = 36.31$, $p < .01$, partial $\eta^2 = .57$; $t > 8.04$, $p < .01$, $d > 3.82$). No significant difference was observed between the TBA and P+S groups ($t = 0.10$, $p = .92$, *d*

= 0.03). We noted no group differences at either pre- or post-test ($F < 1.47$, $p > .23$, partial $\eta^2 < .06$) (Table 1).

Executive functions

Results of principal components factor analysis, task performance data, and summary of ANCOVA results on EFs task performance are provided in the supplementary material (Supplementary Table 1-4).

No significant group difference was detected for EF task performance at pre-test ($F < 12.62$, $p > .07$, partial $\eta^2 < .07$). There were no main effects of group, time, and group × time interaction on accuracy for any EF task.

There were significant main effects of time on RT for all tasks ($F > 5.12$, $p < .03$, partial $\eta^2 > .06$). Post-hoc testing demonstrated the subjects' post-test RTs were shorter than were their pre-test RTs for all tasks. No main effect of group on reaction time was observed for any of the tasks ($F < 1.58$, $p > .21$, partial $\eta^2 < .05$).

Group × time interaction on RT for overall EFs, SCWT incongruent trial, and 2-back Task was observed ($F > 4.25$, $p < .02$, partial $\eta^2 > .10$) (Figure 1A). The RTs of the P+S group were shorter than they had been at pre-test on the three measures ($t > 4.71$, $p < .01$, $d > .63$). The RTs of the TBA group were shorter than they had been at pre-test on the overall EFs and SCWT incongruent trial ($t > 2.81$, $p < .01$, $d > .38$), but not 2-back Task ($t = 1.86$, $p = .07$, $d = 0.28$). No time point differences were observed on the three measures in the CONT group ($t < 1.96$, $p > .05$, $d < .48$). No group differences were observed at pre- and post-test ($t < 1.86$, $p > .07$, $d < 1.00$). There was no significant group × time interaction on RTs for other tasks.

One-way ANCOVA revealed a significant main effect of group on ⊿RT for overall EFs after controlling for the RT at pre-test ($F = 7.62$, $p < .01$, partial $\eta^2 = .18$). Post hoc analysis on ⊿RT for overall EFs showed there was greater facilitation of RT in the P+S group than in the CONT and the TBA groups (versus CONT: $t = 3.68$, $p < .01$, $d = 1.37$; versus

TBA: $t = 2.27$, $p = .03$, $d = 0.58$). In addition, the TBA group showed greater improvements than in the CONT group ($t = 2.02$, $p = .05$, $d = 0.79$) (Figure 1B).

One-way ANCOVA revealed a significant main effect of group on △RT at post-test for the SCWT incongruent trial after controlling for the RT at pre-test ($F = 3.25$, $p = .04$, partial $\eta^2 = .08$). Post hoc analysis on △RT for the SCWT incongruent trial showed there was only marginally greater facilitation of RT in the P+S group than in the CONT and TBA groups ($t > 1.71$, $p < .10$, $d > 0.58$) (Figure 1B).

One-way ANCOVA revealed a significant main effect of group on △RT for the 2-back Task after controlling for the RT at pre-test ($F = 5.18$, $p < .01$, partial $\eta^2 = .13$). Post hoc analysis on △RT for the 2-back Task showed there was greater facilitation of RT in the TBA and the P+S groups than in the CONT group ($t > 2.13$, $p < .04$, $d > 0.83$) (Figure 1B).

Discussion

This study examined the effects of two types of tennis lessons—a technique-based approach (TBA) and a game-based approach (PLAY+STAY [P+S])—on the executive functions (EFs) of junior tennis players. We found that one TBA or P+S lesson resulted in greater immediate improvement in EFs as compared to watching a TV program (CONT); the P+S lessons might be especially beneficial for promoting EFs given that this group improved the most on the EF composite index. Our results expand previous knowledge on the effects of an acute bout of exercise on cognition found in laboratory settings toward real world applications.

The present study suggests that both the TBA and P+S lessons improve EFs. Following both types of tennis lessons, participants' overall RT for EFs was shortened to a greater extent than following watching TV. Inhibitory control was facilitated after both types of tennis lessons, while it was unchanged after watching TV. Our findings are in accord with those of previous studies that demonstrated the positive effect of acute exercise on EFs in children [4–8]. In this study, TBA and P+S demonstrated larger effect sizes than reported in recent meta-analyses (Cohen's d = 0.32 or 0.52)[2,3]. Our findings suggest that sports activity (i.e., tennis) may be a useful tool for facilitating EFs in children.

Participants' RT in overall EFs was shortened to a greater extent by P+S lessons than TBA lessons. However, those who started off with worse (i.e., longer) RTs always improved more than those who started off with better RTs regardless of condition, and P+S participants started off with slower RTs than TBA participants[§]. [[§]Footnote: Indeed, one reviewer suggested that we might simply be seeing variation around a common mean. The simple-exercisers started out with a good RT of 1052 ms and ended up improving a little to 943 ms. The game-players started out with a longer mean RT (1090 ms) and ended up improving more to 916 ms. The mean RT across both time points on the EF-composite index was 998 ms for the simple exercisers and 1003 ms for the game-players (both of which round to 1000 ms). Thus, the reviewer suggested this might be normal variation around a common mean for both groups.] Furthermore, working memory was facilitated in the P+S group, while it was maintained after the TBA and CONT groups. These results suggest that P+S might be more beneficial than TBA for facilitating EFs. Recent studies using a longitudinal design have suggested that chronic cognitive engaging exercise has beneficial effects on EFs of children [24–26]. Further research using longitudinal design is needed to examine whether chronic game-based tennis lessons (P+S) enhance EFs more than technique-based tennis lessons in children.

The present study could not elucidate the mechanisms behind the greater improvement of EFs following the P+S lesson than the TBA lesson. One possible explanation is that games in tennis lessons require more effortful cognitive processing with top-down cognitive control and the ability to override automatic behavior and bodily movement. As mentioned previously, tennis games require cooperation with other children, strategic behavior, the coordination of complex bodily movements, and adaptation to continually changing task demands, whereas repetitive exercises (i.e., ball feeding) require less such cognitive activities. Thus, the P+S lesson may require more EF activity and therefore should lead to greater improvements in EFs than a TBA lesson. The more one practices a skill (such as EFs) and the more the skill is challenged, the more the skill improves [17,27]. Many functional magnetic resonance imaging studies reported that more effortful processing imposes greater demands on EFs-related circuitry, as highlighted by greater frontal activation [28–30].

Given the children who participated in this study were tennis players, it might be inappropriate to apply the results to children not involved in competitive sports such as tennis. Considering length of competition history of participants (tennis experience = 0.1 to 7.3 years), there were no significant correlations between tennis experience and change in EF task performances after controlling for age, gender, and group ($|r| < .20$, $p > .09$, data not shown). This finding indicates that the effects of acute bout of tennis lessons on EFs were irrespective of tennis experience. As such, we believe the present study can apply to children other than those who are tennis players.

Contrary to the findings of a recent study that reported a positive effect of acute exercise on cognitive flexibility [7] and accuracy data [5], we found no group difference for cognitive flexibility and accuracy data. Furthermore, on the individual EFs tasks, there were no significant differences between the two tennis groups. This inconsistency might have been due to the tasks lacking sufficient sensitivity. The Local-global Task and Stroop Color and Word Test were conducted in a way that minimized their difficulty; therefore, our sample showed high accuracy at pre-test (94.30% and 96.16%) and there might have been ceiling effects.

This study has several limitations that should be acknowledged. The participants in this study were highly heterogeneous in terms of age and sample size and were not randomly allocated to the three groups; it is possible that our results might have been biased by these factors. Another study is needed using a randomized controlled trial or crossover design. The several limitations noted in this study are listed below: not randomly assigned; ceiling effects on our EF tasks (otherwise might have found stronger effects); no group differences on any individual EF measure; were post-test differences on the EF composite meaningful?; only examined benefits that dissipate quickly (benefits from a single session disappear within minutes).

Conclusion

The current study suggests that a single tennis lesson of either technique-based approach (TBA) or game-based approach (PLAY+STAY [P+S]) improves EFs immediately afterward to a greater extent than does watching TV. Furthermore, P+S lessons might be more beneficial than TBA lessons for facilitation of EFs. Further research is needed to determine whether chronic game-based exercise enhances EFs more than simple exercise in children. Moreover, there is a need to evaluate the role of enhanced EF performance (ability to concentration and pay attention, stay on task, complete assignments, follow multi-step instructions, see things from multiple perspectives) immediately after the exercise session on school performance.

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Table 1

Descriptive characteristics of the study participants

Variables	CONT		TBA			P+S		
N	10		32			39		
Gender								
Males	6		12			20		
Females	4		20			19		
Age (years)	9.1	(0.5)	9.7	(0.3)		9.8	(0.2)	
Height (cm)	134.2	(3.0)	133.2	(1.7)		134.7	(1.5)	
Weight (kg)	30.8	(2.0)	28.7	(1.1)		30.1	(1.0)	
Body mass index (kg/m^2)	16.9	(0.6)	16.1	(0.3)		16.4	(0.3)	
Tennis experience	1.4	(0.2)	2.2	(0.3)		2.6	(0.3)	
Shuttle stamina test (m) [a]	404.57	(20.02)	427.33	(9.67)		429.78	(8.71)	
Mean heart rate [b]								
During pre-test (bpm)	101.59	(4.29)	91.50	(2.15)		94.50	(1.92)	
During programs (bpm)	94.88	(2.04)	142.39	(3.56)	**	142.77	(1.78)	**
During post-test (bpm)	94.85	(3.48)	94.80	(2.61)		97.29	(1.70)	

Note: Values presented as *N* or mean (SEM), CONT = control group (i.e., watching TV), TBA = technique-based approach, P+S = PLAY+STAY (game-based approach), ** versus CONT, $p < .01$, [a] N = 74 (CONT = 7, TBA = 30, P+S = 37), [b] N = 60 (CONT = 6, TBA = 24, P+S = 30).

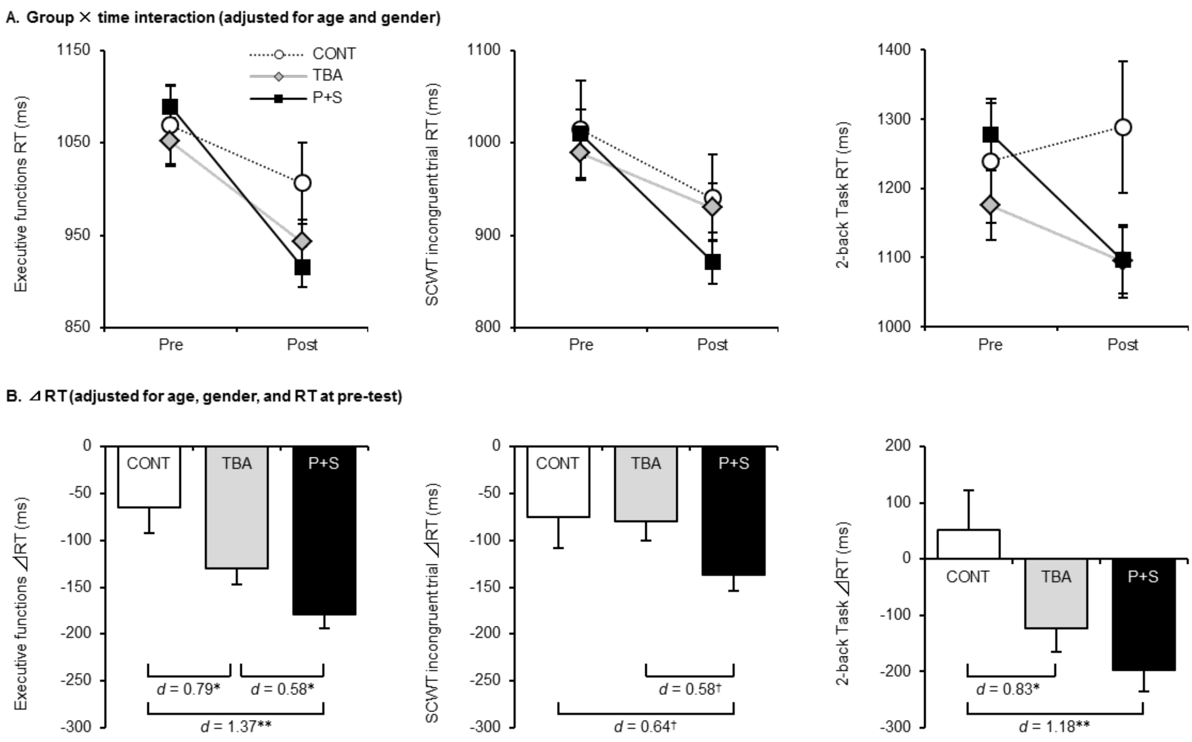

Figure 1. (A) Mean (SEM) RTs for each group and condition at pre- and post-test after controlling for age and gender, illustrating the group × time interaction. (B) ⊿RTs after controlling forage, gender, and RTs at pre-test. RT, reaction time; CONT, control group (i.e., watching TV); TBA, technique-based approach; P+S, PLAY+STAY (game-based approach); SCWT, Stroop Color and Word Test, ** $p < .01$, * $p < .05$, † $p < .10$.

Data article

Title:

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Authors:

Toru Ishihara[a], Shigemi Sugasawa[b], Yusuke Matsuda[b], Masao Mizuno[c]

Affiliations:

[a]Department of Physical Fitness Science, Graduate School of Education, Hokkaido University

[b]Nagoya Green Tennis Club Group

[c]Faculty of Education, Hokkaido University

Contact email:

t.ishihara@edu.hokudai.ac.jp (Toru Ishihara)

Equipment in Both Lessons

Technique-based approach	Game-based approach (PLAY+STAY)
Age appropriate tennis rackets (23 to 29 inches), normal court and balls.	・Red stage (5 to 8 years old) Age appropriate tennis rackets (23 to 29 inches), court size 11–12 m × 5–6 m, net height 80 cm, balls 75% slower than normal ball. ・Orange stage (8 to 10 years old) Age appropriate tennis rackets (23 to 29 inches), court size 18 m × 6.5–8.23 m, net height 80–91 cm, balls 50% slower than normal ball. ・Green stage (9 to 10 years old) Age appropriate tennis rackets (23 to 29 inches), court size 23.77 m × 8.23 m (full size court), net height 91 cm, balls 25% slower than normal ball.

Typical Examples of Instruction in Both Lessons

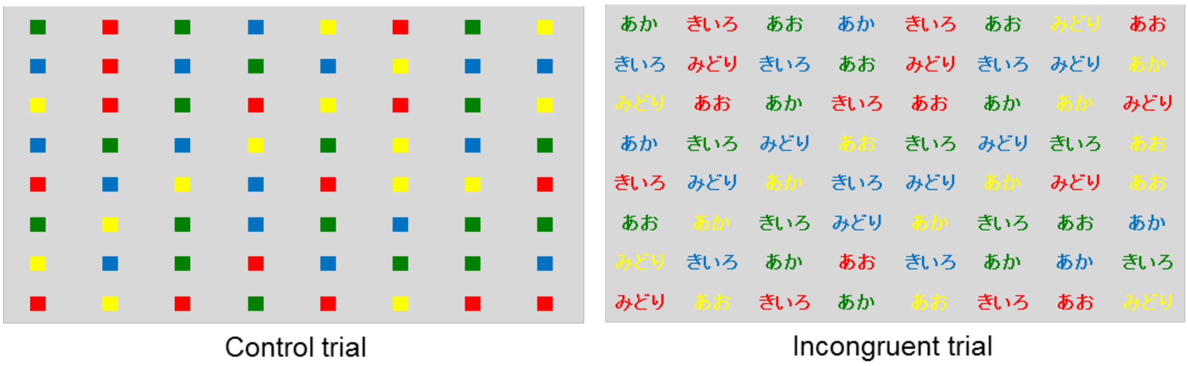
	Technique-based approach	Game-based approach (PLAY+STAY)
Coordination training	・Running (e.g., dash, side step, cross step) ・Ladder training ・Self-rally ・Play catch	・Running (e.g., dash, side step, cross step) ・Ladder training ・Self-rally ・Play catch
Ball feeding	・Forehand stroke ・Backhand stroke ・Volley	・No ball feeding
Rally	・Normal rally (free)	・Play with using only forehand or backhand stroke ・Play with using only volley in small court ・Normal rally (free)
Game	・Normal game (free)	・Play with using only forehand or backhand stroke ・Play with using only volley in small court ・If finished point with volley or smash, get two points ・Normal game (free)

Executive Functions Assessment

Three EFs were evaluated using the Stroop Color and Word Test, 2-back Task, and Local-global Task [1]. All tasks were performed on a PC with a 15.6-inch screen. The distance between the subjects' eyes and the display was kept at 50 cm.

Stroop Color and Word Test

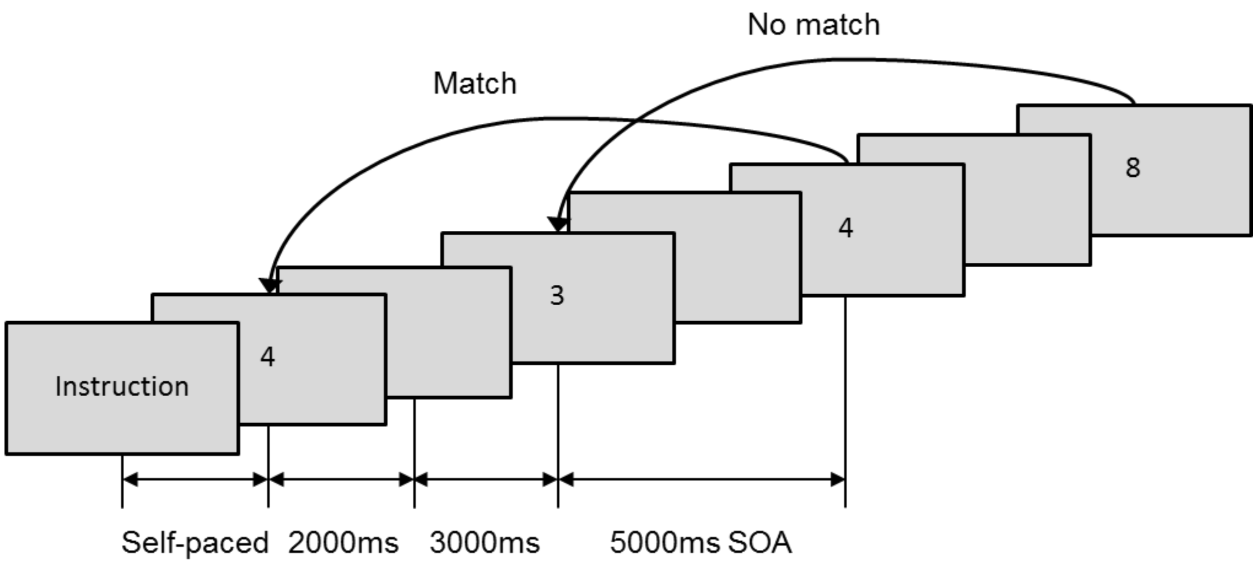
Inhibitory control was evaluated using a modified version of the Stroop Color and Word Test [1,2,3]. The stimuli used in the control trial were four patches of color (red, yellow, green, and blue patches). In the incongruent trial, the names of colors were presented; however, the color of the text did not match the named color (e.g., the word "blue" was printed in red). The stimuli for each of these tasks were presented on a gray background. In each trial, 64 stimuli (8 sets of 8 stimuli) were presented [visual angle: patches of color = 0.92° × 0.92° (0.8 cm × 0.8 cm), names of colors = 3.67° × 0.92° (3.2 cm × 0.8 cm)], and evenly distributed throughout the screen [intrastimulus horizontal interval: patches of color = 4.12° (3.6 cm); names of colors = 1.15° (1.0 cm), interstimulus vertical interval: patches of color = 1.43° (1.3 cm); names of colors = 1.43° (1.3 cm)] (Supplementary Figure 1). We prepared a color-labeled keyboard for use with this task: the C key was labeled red, the V key yellow, the N key green, and the M key blue. The instructions for responding using the fingers were as follows: the C key, left middle finger; the V key, left index finger; the N key, right index finger; and the M key, right middle finger. The participants were required to press the key that corresponded to the color of the stimulus as quickly and as accurately as possible. The rest between control trial and incongruent trial was set at 1-minute. Participants were exposed to 16 practice stimuli (2 sets of 8 stimuli) before each trial. The main dependent variables were the mean reaction time (RT) and the accuracy of each trial. In the congruent trial, RT and accuracy corresponded to basic processing speed/accuracy, while in the incongruent trial it corresponded to inhibitory control.



Supplementary Figure 1. A schematic diagram of the Stroop Color and Word Task.
Note: In the incongruent trials, stimuli were presented in Japanese color words.

2-back Task

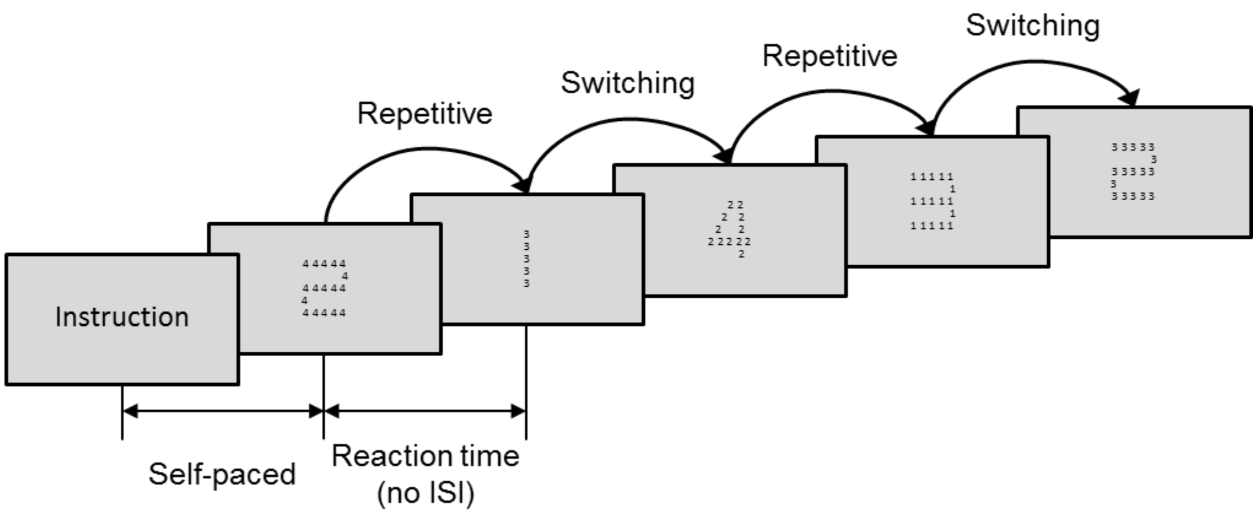
Working memory was evaluated using a modified version of the 2-back Task, which has been widely used for this purpose [1,4,5]. In the 2-back task, participants compared the current stimulus with the two stimuli presented previously. They were instructed to push the right Ctrl key if the current stimulus differed from the two previous stimuli, and to push the left Ctrl key if the current stimulus was the same as the two previous stimuli (Supplementary Figure 2). The instructions for responding using the fingers were as follows: the left Ctrl key, left index finger, and the right Ctrl key, right index finger. The stimuli consisted of nine numbers (i.e., 1–9). All stimuli were presented on a gray background for 2,000 ms each, and the stimulus-onset asynchrony was set at 3,000 ms. The stimulus configurations subtended a visual angle of 1.72° × 1.72° (1.5 cm × 1.5 cm). The participants performed 12 practice trials and then completed two blocks of 25 trials each with a 1-minute rest interval between the blocks. The main dependent variables were the mean RT and participants' accuracy.



Supplementary Figure 2. A schematic diagram of the 2-back Task.
Note: SOA = stimulus onset asynchrony.

Local-global Task

Cognitive flexibility was evaluated using a modified version of the Local-global Task [1,6,7]. In this task, a geometric figure called a Navon figure, comprising a “global” number (1, 2, 3, or 4) composed of much smaller, or “local” numbers (1, 2, 3, or 4), was randomly presented on the computer screen (Supplementary Figure 3). Numbers 1 and 2 were the target numbers and were equally likely to appear at the global and local levels, whereas numbers 3 and 4 were neutral distracters appearing at the opposite level of the target numbers. All global stimulus configurations subtended a visual angle of 3.44° × 3.44° (3 cm × 3 cm), while the local configurations subtended an angle of 0.57° × 0.57° (5 mm × 5 mm). We prepared a number-labeled keyboard for use with this task: The F key was labeled 1, while the J key was labeled 2. The instructions for responding using fingers were as follows: the F key, left index finger, and the J key, right index finger. The participants were required to press the appropriate key as quickly and as accurately as possible when the target number (1 or 2) appeared at the global (global trial) or local level (local trial). All stimuli were presented on a gray background with no interstimulus interval until the response was accurately carried out. The participants performed 48 practice trials (24 global and 24 local) and then completed two blocks of 36 trials each with a 1-minute rest interval between the blocks. The switching (in which the level of the target number was alternated; i.e., “local” trials were followed by “global” trials and vice versa) and repetitive conditions (in which the level of the target number was not alternated; i.e., “local” trials were followed by “local” trials and “global” trials were followed by “global” trials) were evaluated separately. The main dependent variables were RT and accuracy in the repetitive and switching conditions. In the repetitive condition, RT and accuracy corresponded to basic processing speed/accuracy, while in the switching condition it corresponded to cognitive flexibility.



Supplementary Figure 3. A schematic diagram of the Local-global Task.
Note: ISI = interstimulus interval.

Supplementary Table 1

Principal components factor analysis of all participants' RT and accuracy

	RT		Accuracy	
	Pre	Post	Pre	Post
Basic processing speed/accuracy				
SCWT control trial	.88	.84	.81	.80
LGT repetitive condition	.88	.84	.81	.80
ω	.87	.82	.79	.78
Executive function				
SCWT incongruent trial	.85	.87	.67	.83
2-back Task	.76	.76	.66	.46
LGT switching condition	.70	.63	.71	.70
ω	.81	.79	.72	.71

Note: Values presented as principal component values, RT = reaction time, SCWT = Stroop Color and Word Test, LGT = Local-global Task.

Supplementary Table 2

Reaction time and accuracy during various executive functions tasks

	CONT		TBA		P+S	
	pre	post	pre	post	pre	post
Reaction time						
Basic processing speed	879.45	785.57	850.47	734.98	842.90	718.32
	(31.29)	(25.35)	(17.46)	(14.14)	(15.73)	(12.74)
Executive function	1069.49	1006.76	1052.14	943.17	1089.86	915.73
	(45.83)	(41.85)	(25.57)	(23.35)	(23.04)	(21.04)
SCWT control trial	963.38	881.30	908.30	816.49	903.40	788.14
	(44.73)	(38.73)	(24.95)	(21.60)	(22.49)	(19.47)
SCWT incongruent trial	1014.68	940.50	989.39	929.85	1010.18	871.66
	(52.50)	(46.99)	(29.29)	(26.21)	(26.39)	(23.62)
2-back Task	1239.19	1288.53	1174.90	1094.54	1277.46	1095.96
	(89.75)	(95.00)	(50.07)	(52.99)	(45.12)	(47.76)
LGT repetitive condition	795.52	689.84	792.64	653.48	782.39	648.50
	(32.49)	(24.89)	(18.13)	(13.89)	(16.33)	(12.51)
LGT switching condition	954.59	791.25	992.12	805.11	981.95	779.56
	(50.82)	(37.05)	(28.35)	(20.67)	(25.55)	(18.63)
Accuracy						
Basic processing accuracy	96.21	97.32	96.65	95.16	96.26	94.63
	(2.12)	(1.06)	(0.50)	(0.90)	(0.58)	(0.69)
Executive function	89.03	91.57	92.07	91.46	92.33	90.77
	(1.93)	(2.11)	(1.09)	(1.18)	(0.61)	(0.94)
SCWT control trial	95.31	96.72	96.04	96.00	96.71	95.71
	(2.15)	(0.92)	(0.89)	(1.04)	(0.70)	(0.79)
SCWT incongruent trial	96.09	96.09	95.12	95.46	96.79	96.47
	(1.99)	(1.94)	(1.62)	(1.24)	(0.57)	(0.91)
2-back Task	79.57	86.96	89.20	90.22	87.85	87.01
	(3.29)	(3.48)	(1.58)	(1.52)	(1.57)	(2.02)
LGT repetitive condition	97.10	97.93	97.25	94.33	95.81	93.56
	(2.13)	(1.36)	(0.47)	(1.25)	(0.85)	(1.04)
LGT switching condition	91.43	91.66	91.89	88.69	92.36	88.81
	(1.82)	(3.17)	(1.27)	(1.97)	(0.94)	(1.33)

Note: Values presented as mean (SEM), adjusted for age and gender, CONT = control group (i.e., watching TV), TBA = technique-based approach, P+S = PLAY+STAY (game-based approach), SCWT = Stroop Color and Word Test, LGT = Local-global Task, * $p < .05$, ** $p < .01$.

Supplementary Table 3

Summary of two-way ANCOVA results on executive functions task performance

	Time	Group	Group × Time	Age	Gender
Reaction time					
Basic processing speed	174.90**	1.52	0.93	61.04**	3.21
	(.70)	(.04)	(.02)	(.45)	(.04)
Executive function	81.61**	0.38	7.13**	53.19**	2.66
	(.52)	(< .01)	(.16)	(.41)	(.03)
SCWT control trial	50.61**	1.58	0.67	56.58**	4.27*
	(.40)	(.04)	(.02)	(.43)	(.05)
SCWT incongruent trial	35.48**	0.31	4.38*	53.73**	7.24**
	(.32)	(< .01)	(.10)	(.42)	(.09)
2-back Task	5.13*	0.95	4.25*	17.26**	0.05
	(.06)	(.02)	(.10)	(.19)	(< .01)
LGT repetitive condition	113.40**	0.47	0.52	25.10**	0.39
	(.60)	(.01)	(.01)	(.25)	(< .01)
LGT switching condition	156.70**	0.23	0.53	26.35**	1.97
	(.68)	(< .01)	(.01)	(.26)	(.03)
Accuracy					
Basic processing accuracy	0.34	0.81	1.72	< .01	< .01
	(< .01)	(.02)	(.04)	(< .01)	(< .01)
Executive function	1.03	0.08	2.05	7.21	< .01
	(.01)	(< .01)	(.05)	(.09)**	(< .01)
SCWT control trial	0.13	0.04	1.27	0.59	0.34
	(< .01)	(< .01)	(.03)	(< .01)	(< .01)
SCWT incongruent trial	0.02	0.35	0.29	0.93	0.02
	(< .01)	(< .01)	(< .01)	(.01)	(< .01)
2-back Task	1.48	1.10	2.67	17.16	0.21
	(.02)	(.03)	(.07)	(.19)**	(< .01)
LGT repetitive condition	0.25	2.90	0.98	0.67	0.19
	(< .01)	(.07)	(.03)	(< .01)	(< .01)
LGT switching condition	0.85	0.35	1.48	0.36	0.03
	(.01)	(< .01)	(.04)	(< .01)	(< .01)

Note: Values presented as F (partial η^2), CONT = control group (i.e., watching TV), TBA = technique-based approach, P+S = PLAY+STAY (game-based approach), SCWT = Stroop Color and Word Test, LGT = Local-global Task, * $p < .05$, ** $p < .01$.

Supplementary Table 4

Summary of one-way ANCOVA results on change in executive functions task RTs

	Group	Score at pre-test	Age	Gender
Basic processing speed	2.44	40.01**	0.06	3.03
	(.06)	(.36)	(< .01)	(.04)
Executive function	7.62**	18.42**	4.68*	< .01
	(.18)	(.21)	(.06)	(< .01)
SCWT control trial	1.88	27.41**	0.91	0.01
	(.05)	(.28)	(.01)	(< .01)
SCWT incongruent trial	3.25*	19.74**	8.12**	0.68
	(.08)	(.22)	(.10)	(< .01)
2-back Task	5.18**	9.42**	3.75	1.85
	(.13)	(.12)	(.05)	(.03)
LGT repetitive condition	0.47	44.73**	< 0.01	4.16*
	(.01)	(.39)	(< .01)	(.06)
LGT switching condition	0.55	62.25**	0.14	2.25
	(.02)	(.47)	(< .01)	(.03)

Note: Values presented as *F* (partial η^2), CONT = control group (i.e., watching TV), TBA = technique-based approach, P+S = PLAY+STAY (game-based approach), SCWT = Stroop Color and Word Test, LGT = Local-global Task, * $p < .05$, ** $p < .01$.

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