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Relationship of tennis play to executive function in children and adolescents

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Abstract

This study evaluated the association between the frequency of tennis play and executive function in children and adolescents. One hundred and six junior tennis players (6–15 years old) participated in this study. Executive function, including inhibitory control, working memory, and cognitive flexibility were evaluated at rest. Females showed better inhibitory control and cognitive flexibility than males. In males, more frequent tennis play was associated with higher basic processing speed and inhibitory control after controlling for age, gender, body mass index (BMI), and tennis experience. More frequent tennis play was associated with better working memory in both males and females after controlling for age, gender, BMI, and tennis experience. Furthermore, longer tennis experience was related to better cognitive flexibility in males after controlling for age, gender, BMI, and frequency of tennis play. These findings suggest that tennis play is associated with the development of three foundational aspects of executive function (i.e., inhibitory control, working memory, cognitive flexibility). Especially, frequent participation in tennis play is related to better inhibitory control and working memory, while longer experience of tennis play is associated with better cognitive flexibility. Although development of inhibitory control and cognitive flexibility is slower in males than in females, the associations between tennis play and inhibitory control and cognitive flexibility appear to be larger in males than in females.

Keywords: cognition; exercise; gender; health; psychology

Relationship of tennis play to executive function in children and adolescents

Higher physical activity/fitness levels support physical health as well as brain health (cognitive function, academic achievement) in children and adolescents (Donnelly et al., 2016; Hillman, Erickson, & Hatfield, 2017, for reviews). Randomized control trials using behavioral and electrophysiological measures of brain function have found that 9-month interventions consisting of after-school physical activity (5 days/week) improved cognitive function in 7–9 year old children (Hillman et al., 2014; Kamijo et al., 2011). Positive associations between physical fitness, as a proxy for regular physical activity, and brain health (cognitive function, academic achievement) have been reported (Ishihara, Sugasawa, Matsuda, & Mizuno, 2017a; Morita et al., 2016; Scudder et al., 2016). Thus, there is empirical evidence of a relationship between physical activity and brain function.

Executive functions (i.e., the regulation of cognitive processes controlling goal-directed behavior) have been found to be more sensitive to exercise than other types of cognitive functions, such as perception and processing speed (Hillman et al., 2014; Kamijo et al., 2011). Executive function consists of three foundational components: 1) inhibitory control, the ability to control one's attention, behavior, thoughts, and/or emotions to override a strong internal predisposition or external distraction, and focus on more adaptive and relevant stimuli instead; 2) working memory, the ability to hold and process new and already stored information; and 3) cognitive flexibility, the ability to switch perspectives or focus of attention (Diamond, 2013, for a review). Relationships have been found between executive function and sports performance (Vestberg, Reinebo, Maurex, Ingvar, & Petrovic, 2017), self-regulation, school readiness, school success (Blair & Diamond, 2008), obesity risk (food intake and physical activity) (Riggs, Chou, Spruijt-Metz, & Pentz, 2010), and academic achievement (Best, Miller, & Naglieri, 2011). Further, given that executive functions during childhood have been reported to influence lifetime success in outcomes such as health, income, and public safety (Moffitt et al., 2011), it is important to monitor the development of executive function through physical/sports activity during childhood.

Improved executive function after participation in physical activity might depend on the type of the activity (Best, 2010; Diamond & Ling, 2016, for reviews). In reviews of experimental studies on the effects of physical activity on children's executive function, it was concluded that cognitively engaging exercise and sensorimotor learning had a stronger effect on children’s executive function than simpler exercise (Best, 2010; Moreau & Conway, 2013). Sports activities require cognitive engagement (e.g., complex bodily movement and mental training via skills acquisition); therefore, participation in sports should lead to greater improvements in executive function.

As different sports activities require different sets of cognitive functions, the relationship between sports and executive function is expected to be moderated by sports type. Open skill sports, such as tennis, require coordination of complex bodily movements, and adaptation to continually changing task demands, whereas closed skill sports require fewer such cognitive activities. Thus, open skill sports are expected to have a stronger relationship with executive functions than closed skill sports. Indeed, stronger relationships of acute and chronic open skill sports activity with executive function in children and adolescents have been reported (Ishihara et al., 2017a; Ishihara, Sugasawa, Matsuda, & Mizuno, 2017b; Koutsandréou, Wegner, Niemann, & Budde, 2016; Schmidt, Jäger, Egger, Roebers, & Conzelmann, 2015). Such characteristics of tennis play are expected to be associated with improved executive functions (Ishihara, Sugasawa, Matsuda, & Mizuno, 2016). Thus, participation in tennis lessons might be a useful tool to facilitate the development of executive function of children.

Ishihara et al., (2017) found that longer tennis experience was associated with improved cognitive flexibility but no such relationship was found for inhibitory control or working memory. Their sample participated in tennis lessons once a week; however, recent studies in which a physical activity intervention was conducted 5 times per week reported positive effects of the intervention on inhibitory control and working memory in 7–9-year-old children (Hillman et al., 2014; Kamijo et al., 2011). Therefore, the frequency of participating in a sports activity might be an important factor in the improvement of inhibitory control and working memory in children. In the position stand by the American College of Sports Medicine (Donnelly et al., 2016), the authors concluded that the association of physical activity with cognitive function was inconsistent, and the effects of numerous elements of physical activity on cognition remain to be explored, such as type, amount, frequency, and timing. Therefore, additional research is needed that focuses on the relationship between frequency of physical activity and cognitive function.

The relationships between physical activity/fitness and brain health might vary by gender (Booth et al., 2013; Drollette et al., 2016; Ishihara et al., 2017a; Morita et al., 2016). The relationships between physical activity/fitness and executive function might be stronger in males than females (Drollette et al., 2016; Ishihara et al., 2017a). The sexual dimorphisms of development of frontal gray matter have been reported and it has been suggested that gray matter in the frontal lobe (govern the executive function) develops earlier in females than males during pre-adolescent (Giedd et al., 1999). Therefore, the relationship between exercise and executive function is expected to have gender modulation because of trainability.

The purpose of this cross-sectional study was to evaluate the association between the frequency of attending tennis lessons and the development of components of executive functions (i.e., inhibitory control, working memory, and cognitive flexibility) and their gender specificity. Given that dose-response relationships between exercise and cognition occur in children (Davis et al., 2011; Hillman et al., 2014), and a relationship that favors males has been reported (Booth et al., 2013; Drollette et al., 2016; Ishihara et al., 2017a), a higher frequency of participation in tennis lessons is expected to be positively associated with improved executive functions, and the relationship is expected to be stronger in males than in females in the present study.

Materials and methods

Participants

A total of 117 junior tennis players (6–15 years old, 57 males and 60 females) who regularly took tennis lessons prior to the study (tennis experience: 2.5 ± 2.0 [range: 0.1 to 9.5] years, frequency: once or 3–6 times per week) agreed to participate in the study. Children enrolled in educational programs for the handicapped because of cognitive or attention disorders were excluded from the study. All of the 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.

Evaluation of executive functions

Inhibitory control was assessed by using a modified Stroop Test, working memory by using the 2-back Task, and cognitive flexibility was assessed by using a Local-global Task (for details, see Supplemental material #1). The Stroop Test is a well-known paradigm for assessing executive functions, particularly interference and inhibitory control (Stroop, 1935). In this test, participants are instructed to name the color of the stimulus. It comprises two trials (control and incongruent). The stimuli used in the control trial were four colored patches (red, yellow, green, and blue), while in the incongruent trial, the names of these four colors were presented; however, the color of the text did not match the named color (e.g., the word “blue” was printed in green). Since word reading is a more automatic cognitive process than is color naming, participants must inhibit their strong internal predispositions to perform well on this task. For this measure, the main dependent variables were the mean reaction time

(RT), the accuracy of each trial (basic processing in the control trials and inhibitory control in the incongruent trials). The 2-back Task is also a widely used paradigm for measuring working memory (Kirchner, 1958). In the 2-back Task, participants compared a currently presented stimulus with a stimulus presented two stimuli previously. This task requires the storage and active employment of information within the mind and updating of information. The main dependent variables were the mean RT and accuracy rate. In the Local-global Task, a geometric figure called a Navon figure (Navon, 1977) comprising a "global" stimulus 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—namely, "local" trials were followed by "global" trials and vice versa—participants had to engage in attentional switching. The main dependent variables were RT and accuracy in the repetitive and switching conditions (basic processing being measured in the repetitive condition and cognitive flexibility in the switching condition).

Statistical analysis

Prior to the analysis, we assessed the normality of the distribution of the variables using the Kolmogorov-Smirnov test. The normally distributed variables included age, RT for the control trial of the Stroop Color and Word Test, and RT for the 2-back Task; other data were not normally distributed. The not normally distributed were log- or square root-transformed to conform to the assumption of normality of distribution; however, some variables were not normally distributed. Therefore, we used the bootstrapping procedure with 2,000 bootstrap replication samples for all statistical analyses for a more accurate assessment of the stability of the parameter estimates. Hierarchical multiple regression was used to assess the associations between tennis experience, frequency of tennis play, and executive functions, after controlling for age, gender, and BMI. Some previous studies demonstrated that adiposity/obesity is associated with lower executive functions (Kamijo et al., 2012, 2014); therefore, we entered BMI into regression model. Variables were entered into the regression model in the following order: (1) age, gender (coded as 0 = female, 1 = male), BMI (Step 1); (2) tennis experience and frequency of tennis play (coded as once a week = 0, 3–6 times per week = 1) (Step 2); and (3) interaction between gender and tennis experience, frequency of tennis play (Step 3). The significance level for all tests was set at $p < .05$. Multicollinearity was evaluated using the variance inflation factor (O'Brien, 2007) and found to be inconsequential (all variance inflation factor values < 2.41). Data for participants were included in the analyses if their task accuracy was higher than chance.

Results

Eleven of the study's participants were excluded from the data set because their task accuracy was lower than chance on the executive function tasks (Stroop Color and Word Test, $n = 4$; 2-back Task, $n = 6$; Local-global Task, $n = 1$). Participants' demographic characteristics and task performance data are presented in Table 1. Intercorrelations between variables are presented in Supplemental material #2. The results of the hierarchical regression analyses are summarized in Table 2.

Basic cognitive processing

The Step 1 regression analysis of the RT on the Stroop Color and Word control trial indicated a significant overall model effect ($R^2 = .52, p < .001$), however, no significant change in the R^2 at Step 2 and Step 3 was found.

The Step 1 regression analysis of the RT on the Local-global Task repetitive condition indicated a significant overall model effect ($R^2 = .40, p < .001$). No significant change in the R^2 at Step 2 was found but a significant change at Step 3 was detected ($\triangle R^2 = .05, p = .02$). There was a significant interaction effect between gender and the frequency of tennis play (β

= -.24, $p = .005$), indicating that a higher frequency of tennis play was associated with a shorter RT only for males (males: $p = .003$, Cohen's $d = 1.12$; females: $p = .37$, Cohen's $d = -0.47$; Figure 1A). Regression analysis of accuracy indicated no significant model effect.

Inhibitory control

The Step 1 regression analysis of the RT on the incongruent trial indicated a significant overall model effect ($R^2 = .49, p < .001$). No significant change in the R^2 at Step 2 was found but a significant change at Step 3 was detected ($\triangle R^2 = .05, p < .001$). There was a significant interaction effect between gender and the frequency of tennis play ($\beta = -.25, p = .003$), indicating that a higher frequency of tennis play was associated with a shorter RT only for males (males: $p < .001$, Cohen's $d = 1.52$; females: $p = .51$, Cohen's $d = -0.34$; Figure 1B). Regression analysis of accuracy indicated no significant model effect.

The Step 1 regression analysis of the interference RT indicated a significant overall model effect ($R^2 = .08, p = .03$). No significant change in the R^2 at Step 2 and 3was found. Regression analysis of accuracy indicated no significant model effect.

Working memory

The Step 1 regression analysis of RT indicated a significant overall model effect ($R^2 = .30, p < .001$). A significant change in the R^2 at Step 2 was found ($\triangle R^2 = .08, p = .002$). There was a significant effect of frequency of tennis play ($\beta = -.32, p < .001$), indicating that more frequent tennis play was associated with a shorter RT (Figure 1C). No significant change in the R^2 at Step 3 was detected.

The Step 1 regression analysis of accuracy indicated a significant overall model effect ($R^2 = .29, p < .001$), but no significant change in the R^2 at Step 2 or 3 was detected.

Cognitive flexibility

The Step 1 regression analysis of RT on the overall switching condition indicated a significant overall model effect ($R^2 = .39, p < .001$). No significant change in the R^2 at Step 2 was found but a significant change at Step 3 was detected ($\triangle R^2 = .06$, $p = .008$). There was a significant interaction effect between gender and the tennis experience ($\beta = -.19$, $p = .03$). Simple slope analyses were conducted separately for each gender to test the significance of the regression slopes predicting RT from tennis experience. Tennis experience did not significantly predict the RT (males: $\beta = -.23$, $p = .11$; females: $\beta = .16$, $p = .21$).

The Step 1 regression analysis of the overall switch cost RT indicated a significant overall model effect ($R^2 = .13$, $p = .003$). No significant change in the R^2 at Step 2 was found but a significant change at Step 3 was detected ($\triangle R^2 = .07$, $p = .02$). There was a significant interaction effect between gender and the tennis experience ($\beta = -.30$, $p = .004$). Simple slope analyses were conducted separately for each gender to test the significance of the regression slopes predicting RT from tennis experience. Tennis experience predicted the overall switch cost RT, but was significant only for the males (males $\beta = -.39$, $p = .02$; females $\beta = .22$, $p = .21$; Figure 1D). These findings indicate that longer tennis experience was associated with greater cognitive flexibility for the study's males. Regression analysis of accuracy indicated no significant model effect.

Associations between tennis play and accuracy independent of reaction time

Across previous analyses, significant effects of tennis play were found to be in models examining RT dependent variables as opposed to accuracy. In the next step, we analyzed the associations between tennis play and accuracy after controlling for RTs (added RT in regression model in Step 1). Although some associations between RT and accuracy were observed, tennis play was not associated with accuracy data after controlling for RTs (Supplemental material #3).

Discussion

The main purpose of this study was to examine the association between the frequency of tennis play and the development of three aspects of executive function (i.e., inhibitory control, working memory, and cognitive flexibility) and its gender specificity. In this study, more frequent tennis play was associated with better working memory in both males and females. Among the males, frequent tennis play was associated with better inhibitory control, and longer tennis experience was associated with higher cognitive flexibility. These results suggest that it is important to increase the frequency of participation in sports activity to support development of executive functions even in physically active children.

Relationships between tennis play and executive function

Our results indicate that tennis lessons associated better with three foundational components of executive function (i.e., inhibitory control, working memory, and cognitive flexibility). Especially, frequency of tennis play was positively correlated with inhibitory control and working memory. Our findings are in accord with those of previous studies that demonstrated the positive relationship of sports participation to multiple aspects of executive functions in children (Crova et al., 2014; Ishihara et al., 2017a). Previous study had reported that tennis experience (just once a week) was not related to inhibitory control and working memory (Ishihara et al., 2017a). In this study, although no relationships were observed between tennis experience and inhibitory control or working memory, frequent tennis play was associated with better inhibitory control and working memory. These findings suggest that frequency of participating in sports activity may be an important factor for development of inhibitory control and working memory. These results are supported by a recent intervention study, which found a dose-response relationship between physical activity and executive functions (Davis et al., 2011; Hillman et al., 2014). A randomized control trial found that 13 weeks of an exercise program consisting of sports activities (e.g., basketball and soccer) improved executive functions, and that have a dose-response relationship in 7–11 year-old children (Davis et al., 2011). In an intervention study, a higher participation rate in a 9-month after school physical-activity intervention was associated with greater improvements in performance on executive function tasks (Hillman et al., 2014).

In this study, the positive relationships between frequency of tennis play and executive function demonstrated larger effect sizes (Cohen's $d = 0.92$ to 1.52) than reported in meta-analyses of randomized control trial and cross sectional design (Cohen's $d = 0.14$ and Hedge's $g = 0.35$, respectively) (Sibley & Etnier, 2003; Verburgh, Königs, Scherder, & Oosterlaan, 2014). Our findings suggest that sports activity (i.e., tennis) may be a useful tool for facilitating executive functions in children and adolescents. Sensorimotor learning in sports and cognitive engagement during exercise has been postulated as a key mechanism linking training and cognitive enhancement (Best, 2010; Moreau & Conway, 2013, for reviews). Playing tennis requires cognitive engagement (e.g., coordination of complex bodily movements, adaptation to continually changing task demands, strategic behavior, superior reactivity, anticipation, and decision-making capacities) and sensorimotor learning (Fernandez-Fernandez et al., 2009; Moreau & Conway, 2013, for reviews). These characteristics of tennis may lead to improved executive function in children.

The level of motor and cognitive development in the individual children and adolescents depends on their age, making it difficult to establish relationships between tennis play and executive function, without analyzing the data by age group. Because developmental changes occur during these ages, we cannot establish global hypotheses for subjects of such a large age range (6-15 years). Further research is needed to establish intervention studies that would allow us to demonstrate causal relations between both variables, as well as to define studies with subjects of different ages, since the studied variables are strongly influenced by the age of the subjects, given the existing developmental differences in functioning of the cognitive-motor areas.

Gender specificity of the relationships between tennis play and executive function

This study is one of the few investigations of gender specificity, which examined the relationship between exercise and executive functions. More frequent tennis play was related to better inhibitory control among the males but not among the females. Furthermore, tennis experience was positively correlated with cognitive flexibility only in males but not in females. As noted in this article's introduction, the relationship between exercise or physical fitness and executive function might be stronger in males than females (Drollette et al., 2016; Ishihara et al., 2017a), and this study's results support this premise.

The gender specificity in the relationship between tennis training and executive functions was found on measures of inhibitory control and cognitive flexibility but not in working memory. We could not elucidate the mechanisms behind these relationships. One possible explanation could be sexual dimorphisms in brain structure, development, and function (Blakemore & Choudhury, 2006; Giedd et al., 1999). Previous study demonstrated that frontal and parietal gray matter peaks approximately one year earlier in females during development (Giedd et al., 1999). Furthermore, the gender specificity in performance on a Stroop-like task was reported, with males showing a lower level of inhibitory control than females (Berlin & Bohlin, 2002). In the present study, females demonstrated better inhibitory control and cognitive flexibility than males, but not for working memory. These results suggest that development of inhibitory control and cognitive flexibility were slower in males than females, and that tennis training is positively associated with development of inhibitory control in males. Working memory continues to develop into young-adulthood, whereas inhibitory control and cognitive flexibility reach maturity during adolescence (Huizinga, Dolan, & van der Molen, 2006). This difference in developmental processes might have affected the gender specificity in the relationship between tennis play and each component of executive function. As such, future studies should attempt to clarify the role of gender specificity in the relationship between exercise and executive function.

Strengths and limitations

The positive associations between physical activity/fitness and executive functions were reported in healthy children (Hillman et al., 2014; Kamijo et al., 2011) as well as in children with developmental disorders (Pontifex, Fine, da Cruz, Parks, & Smith, 2014). However, the effect of additional exercise intervention on executive function in physically active children is unclear. This study provides evidence of a dose-response relationship between exercise and executive functions in junior athletes. Therefore, it may be important to increase participation in sports activity to support the development of executive functions even in physically active children.

Although our study provides evidence of a relationship between tennis training and executive functions, several limitations should be acknowledged. First, this study used a cross-sectional design and participants were consisted to be a wide range of age groups (6-15 years); therefore, the effects of tennis play on executive functions or its moderation by gender and age cannot be determined. Second, the present study did not include non-athletic schoolchildren, because tennis players are expected to have a stronger motivation for physical activity. Thus, the difference of tennis players and non-athletic children may be detected due to not only tennis play but also some biases, such as psychological/emotional characteristics (e.g., preference of exercise/sports). Instead, we recruited children with a varied range of tennis experience (0.1 to 9.5 years), and analyzed a relationship between the tennis experience and executive functions to mollifying somewhat any concerns about the lack of non-athletic group. Third, this study did not measure socioeconomic status (SES; e.g., family income, parent education level). Several studies have reported that SES is associated with executive functions (Hackman & Farah, 2009, for a review). As such, future studies using longitudinal or interventional designs and more diverse measures (e.g., SES) should investigate the associations among executive function, sports activity, and the gender specificity of these relationships.

Conclusion

The present study examined the relationship between frequent participation in sports activities (i.e., tennis) and aspects of executive function in physically active children. Our findings supported the hypothesis that a more frequent and longer experience of participating in sports activity are associated with better inhibitory control, working memory, and cognitive flexibility. Although males show slower development of inhibitory control and cognitive flexibility than females, the relationships between tennis play and inhibitory control and cognitive flexibility appear to be stronger in males than in females. Future research using longitudinal or intervention design and considering developmental stages, may usefully be directed at understanding more precisely the relationship of sports to cognitive development and its gender specificity.

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Table 1
Descriptive characteristics of the study participants

	Males	Females
N	52	54
Age (years)	9.9 (1.8)	9.9 (1.7)
Height (cm)	135.7 (12.4)	136.0 (10.8)
Weight (kg)	31.6 (8.3)	30.7 (7.5)
BMI (kg/m^2)	16.9 (2.1)	16.4 (2.0)
Tennis experience (years)	2.6 (1.9)	2.5 (2.1)
Frequency of tennis play (once a week/3-6 times per week)	41/11	43/11
Basic processing speed/accuracy		
SCWT control trial RT (ms)	910.7 (217.8)	852.6 (166.8)
SCWT control trial accuracy (%)	95.9 (5.6)	96.4 (4.9)
LGT repetitive condition RT (ms)	803.2 (197.1)	746.4 (102.3)
LGT repetitive condition accuracy (%)	97.0 (3.8)	97.3 (3.4)
Inhibitory Control		
SCWT incongruent trial RT (ms)	1025.0 (302.8)	930.6 (160.9)
SCWT incongruent trial accuracy (%)	96.0 (7.4)	96.5 (4.4)
Interference RT (ms)	114.3 (148.0)	78.1 (85.41
Interference accuracy (%)	0.0 (8.9)	-0.1 (6.1)
Working Memory		
2-back Task RT (ms)	1191.2 (363.0)	1194.5 (331.7)
2-back Task accuracy (%)	85.9 (12.4)	88.5 (9.7)
Cognitive flexibility		
LGT switching condition RT (ms)	1017.9 (279.6)	940.0 (168.1)
LGT switching condition accuracy (%)	92.5 (6.5)	92.0 (6.2)
Switch cost RT (ms)	214.6 (131.7)	193.6 (123.8)
Switch cost accuracy (%)	4.6 (6.0)	5.3 (6.3)

Note: values are presented as *N* or mean (*SD*); BMI = body mass index; RT = reaction time, SCWT = Stroop Color and Word Test; LGT = Local-global Task.

Table 2

Hierarchical regression predicting executive functions task performance

		Basic processing speed/accuracy				Inhibitory control				Working memory		Cognitive flexibility			
		SCWT control		LGT repetitive		SCWT incongruent		SCWT interference		2-back Task		LGT switching		LGT switch cost	
		β	$\triangle R^2$	β	$\triangle R^2$	β	$\triangle R^2$	β	$\triangle R^2$	β	$\triangle R^2$	β	$\triangle R^2$	β	$\triangle R^2$
RT	Step 1														
	Age	-.70***		-.57***		-.65***		-.19		-.57***		-.55***		-.29**	
	Gender	.17*		.20*		.22**		.17		.00		.20*		.10	
	BMI	-.02	.52***	-.09	.40***	-.07	.49***	-.11	.08*	.09	.30***	-.12	.39***	-.12	.13**
	Step 2														
	TE	-.02		.01		.11		.26*		.05		-.01		-.04	
	FTP	-.11	.01	-.12	.01	-.17*	.02	-.17*	.04	-.32***	.08**	-.13	.02	-.08	.01
	Step 3														
	Gender × TE	-.04		-.04		-.06		-.05		.03		-.19*		-.30**	
	Gender × FTP	-.16	.02	-.24**	.05*	-.25**	.05**	-.23*	.07	-.04	.00	-.10	.06**	.12	.07*
Accuracy	Step 1														
	Age	.00		-.10		.13		-.09		.54***		-.18		.12	
	Gender	-.06		-.02		-.03		-.01		-.12		.03		-.05	
	BMI	.14	.02	-.07	.02	-.04	.02	.14	.02	-.04	.29***	.06	.03	-.10	.02
	Step 2														
	TE	.22		-.09		-.10		.24*		-.10		-.16		.11	
	FTP	.03	.03	.04	.00	.09	.01	-.05	.03	.13	.01	.07	.01	-.05	.01
	Step 3														
	Gender × TE	.01		-.09		.03		.00		-.02		-.07		.02	
	Gender × FTP	.03	.00	.13	.01	.10	.01	-.05	.00	.01	.00	.00	.00	.08	.01

Note: RT = reaction time; BMI = body mass index; TE = tennis experience; FTP = frequency of tennis play; SCWT = Stroop Color and Word Test; LGT = Local-global Task; gender was coded as 0 = female, 1 = male; frequency of tennis play was coded as once a week = 0, 3–6 times per week = 1; * $p < .05$, ** $p < .01$, *** $p < .001$.

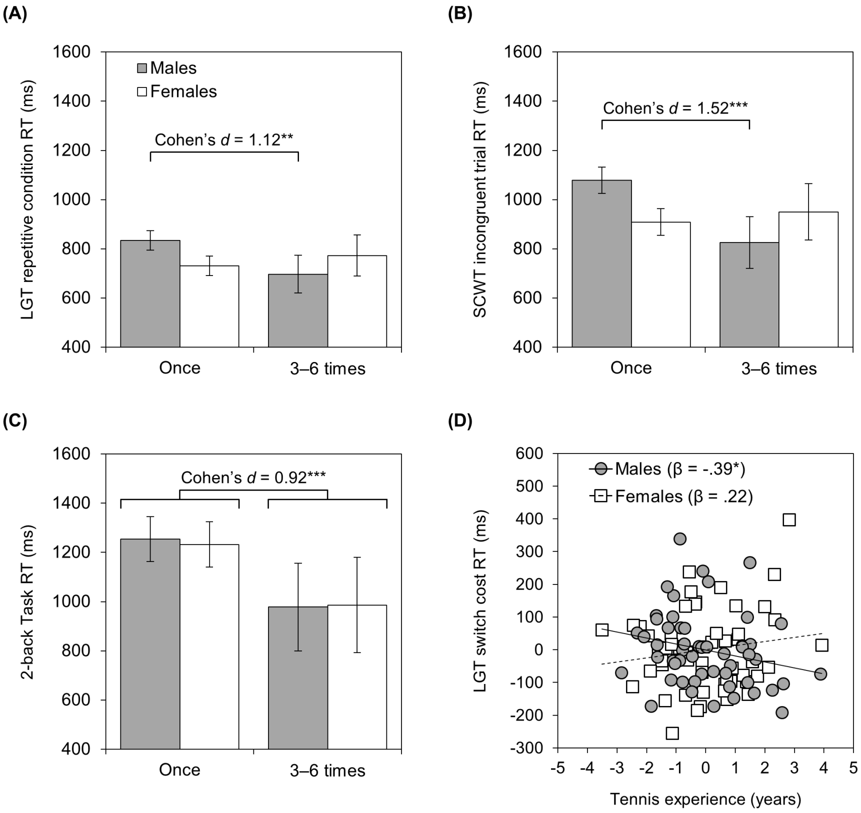


Figure 1. The relationship between the frequency of tennis play, tennis experience, and the executive function task performance. (A) Reaction time on the Local-global Task repetitive condition after controlling for age, gender, BMI, and tennis experience is presented as mean and 95% confidence interval. Higher frequency of tennis play was associated with a shorter RT only for males; (B) Reaction time on the Stroop Color and Word Test incongruent trial after controlling for age, gender, BMI, and tennis experience is presented as mean and 95% confidence interval. Higher frequency of tennis play was associated with a shorter RT only for males; (C) Reaction time on the 2-back Task, the RT after controlling for age, gender, BMI, and tennis experience is presented as mean and 95% confidence interval. Higher frequency tennis play was associated with a shorter RT; (D) The relationship between the tennis experience and the reaction time on the Local-global Task overall switch cost after controlling for age, gender, BMI, and frequency of tennis play. Tennis experience predicted the switch cost RT only for the males; RT = reaction time; SCWT = Stroop Color and Word Test; LGT = Local-global Task; * $p < .05$; ** $p < .01$; ***: $p < .001$.

Supplemental material #1

Evaluation of executive functions

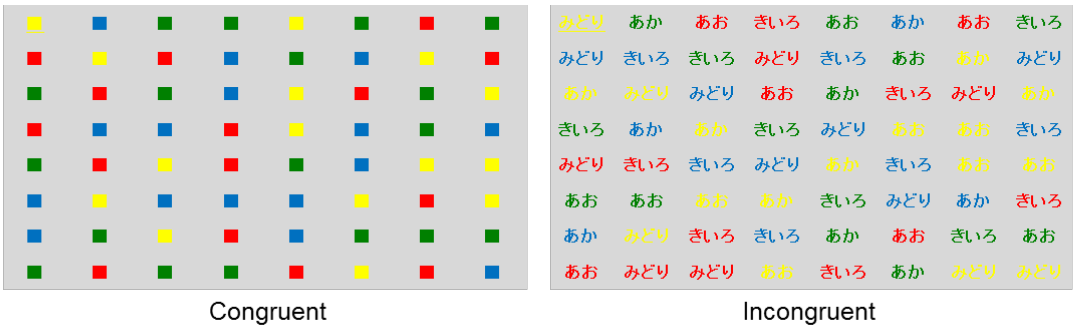
To measure executive function, three computer-based tasks were used: the Stroop Color and Word Task, the Local-global Task, and the 2-back Task (Ishihara, Sugasawa, Matsuda, & Mizuno, 2017a, 2017b). The distance between the participants' eyes and the display was maintained at 50 cm.

Stroop Color and Word Test. Basic cognitive processing and inhibitory control were assessed using modified versions of the Stroop Color and Word Test (Stroop, 1935). This test comprises two trials (control and incongruent). The stimuli used in the control trial were four patches of color (red, yellow, green, and blue patches), whereas in the incongruent trial the stimuli were the names of colors; however, the color of the text did not match the named color (e.g., the word “blue” was printed in yellow). The stimuli for each of these tasks appeared on a gray background. In each trial, 8 sets of 8 stimuli were presented and evenly distributed throughout the screen (visual angle: patches of color = 0.92° × 0.92°, names of colors = 3.67° × 0.92°, intrastimulus horizontal interval: patches of color = 4.12°; names of colors = 1.15°, interstimulus vertical interval: patches of color = 1.43°; names of colors = 1.43°; Figure 1A). Participants experienced 16 practice stimuli; this was followed by the control and incongruent trials with a 1-min rest between each trial. 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. Participants were instructed to press the key corresponding to the target stimuli color as quickly and as accurately as possible. The target stimulus was underlined and the underline moved to the stimulus on the right after each response. The main dependent variables were the mean reaction time (RT), the accuracy of each trial (control trial: basic cognitive processing;

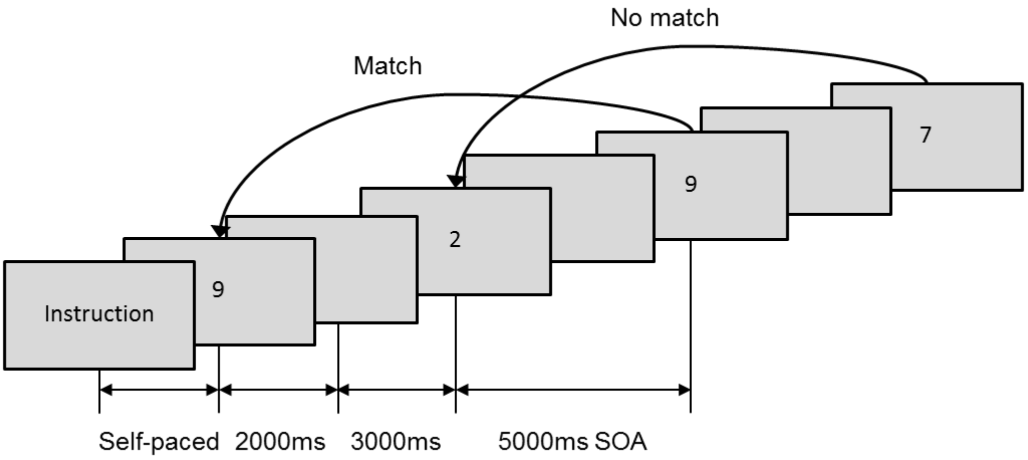
incongruent trial: inhibitory control), the interference score for the RT (RT [incongruent condition] − RT [control condition]), and the interference score for accuracy (accuracy [control condition] − accuracy [incongruent condition]).

2-back Task. Working memory was assessed using a modified version of the 2-back task, which has been widely used for this purpose (Kirchner, 1958). The 2-back task requires participants to compare the current stimulus with two stimuli presented previously. They were instructed to push the right Ctrl key if the current stimulus was different from the two previous stimuli, and to push the left Ctrl key if the current stimulus was identical to the two previous stimuli. The stimuli consisted of nine numbers (i.e., 1–9; visual angle of 1.72° × 1.72°). All stimuli appeared on a gray background for 2,000 ms each, and the stimulus-onset asynchrony was set at 3,000 ms (Figure 1B). The participants performed 12 practice trials, followed by two blocks of 25 trials each, with a 1-min rest interval between the blocks. The main dependent variables were the mean RT and participants' accuracy.

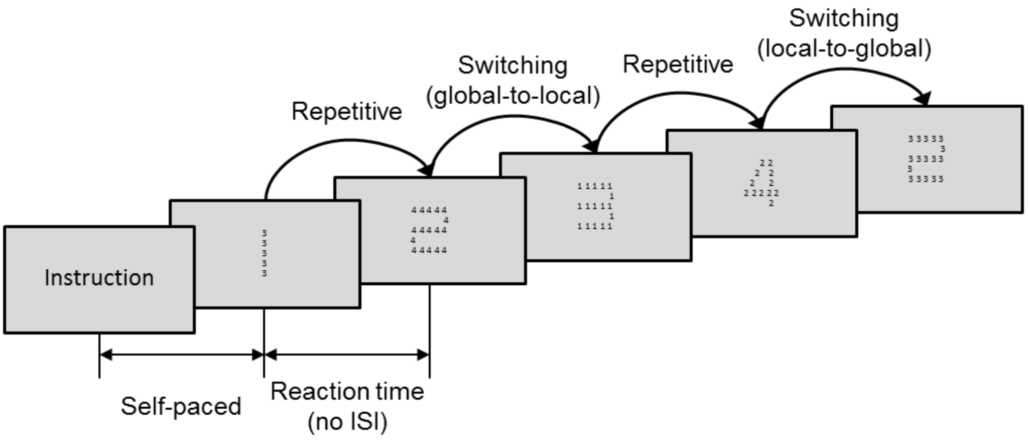
Local-global Task. Basic cognitive processing and cognitive flexibility were assessed using a modified version of the Local-global Task. In this task, a geometric figure known as a Navon figure (Navon, 1977), comprising a "global" number (1, 2, 3, or 4) composed of much smaller, or "local," numbers (1, 2, 3, or 4), was randomly presented on the computer screen (Figure 1C). 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°, while the local configurations subtended an angle of 0.57° × 0.57°. A number-labeled keyboard was prepared for this task: The F key was labeled 1, while the J key was labeled 2. Participants were instructed 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 appeared on a gray background with no interstimulus interval until participants responded accurately. The participants had 48 practice trials (24 global and 24 local), followed by two blocks of 36 trials each, with a 1-min 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 (repetitive condition: basic cognitive processing, and switching condition: cognitive flexibility), the switch cost RT (RT [switching condition] – RT [repetitive condition]), and the switch cost accuracy (accuracy [repetitive condition] – accuracy [switching condition]). Switching condition performance was calculated from the average of the local-to-global and global-to-local conditions.



(A) Stroop Color and Word Test



(B) 2-back Task



(C) Local-global Task

Figure 1. A schematic diagram of the three executive function tasks. (A) Stroop Color and Word Test; (B) 2-back Task; (C) Local-global Task. In the Stroop Color and Word Test incongruent trials, stimuli are presented in Japanese colored words (i.e., “あか”: red, “あお”: blue, “きいろ”: yellow, and “みどり”: green). SOA = stimulus onset asynchrony; ISI = interstimulus interval.

Reference

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Supplemental material #2
Intercorrelations between variables

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. Age	-																	
2. Gender	.02	-																
3. BMI	.31 **	.12	-															
Tennis play																		
4. Experience	.54 ***	.02	.43 ***	-														
5. Frequency	.32 ***	.06	.20 *	.49 ***	-													
Basic processing																		
6. SCWT control trial RT	-.70 ***	.15	-.22 *	-.43 ***	-.32 ***	-												
7. LGT repetitive condition RT	-.60 ***	.18	-.24 *	-.37 ***	-.30 **	.65 ***	-											
8. SCWT control trial accuracy	.04	-.04	.13	.20 *	.11	-.12	-.05	-										
9. LGT repetitive condition accuracy	-.12	-.03	-.10	-.13	-.03	-.13	.23 *	.20 *	-									
Inhibitory control																		
10. SCWT incongruent trial RT	-.67 ***	.19 *	-.24 *	-.35 ***	-.33 ***	.87 ***	.72 ***	-.04	-.07	-								
11. SCWT interference RT	-.22 *	.15	-.15	-.03	-.15	.15	.41 ***	.10	.06	.62 ***	-							
12. SCWT incongruent trial accuracy	.12	-.04	.00	.02	.08	-.33 ***	.02	.11	.21 *	-.32 ***	-.11	-						
13. SCWT interference accuracy	-.05	.01	.11	.15	.03	.17	-.06	.60 ***	-.02	.21 *	.14	-.72 ***	-					
Working memory																		
14. 2-back Task RT	-.55 ***	.00	-.09	-.33 ***	-.43 ***	.56 ***	.50 ***	-.01	-.03	.62 ***	.36 ***	-.18	.12	-				
15. 2-back Task accuracy	.52 ***	-.11	.11	.24 *	.24 *	-.59 ***	-.49 ***	.14	.03	-.59 ***	-.24 *	.13	.00	-.56 ***	-			
Cognitive flexibility																		
16. LGT switching condition RT	-.59 ***	.17	-.27 **	-.39 ***	-.31 **	.63 ***	.85 ***	-.02	.16	.71 ***	.43 ***	.01	-.04	.49 ***	-.47 ***	-		
17. Switch cost RT	-.33 ***	.08	-.20 *	-.25 **	-.19 *	.33 ***	.31 **	.02	.01	.40 ***	.28 **	.00	.01	.27 **	-.23 *	.76 ***	-	
18. LGT switching condition accuracy	-.16	.04	.01	-.15	-.02	-.02	.32 ***	.11	.33 ***	.05	.12	.31 **	-.18	.04	.00	.27 **	.10	-
19. Switch cost accuracy	.09	-.06	-.07	.08	.01	-.06	-.19 *	.01	.24 *	-.09	-.09	-.20 *	.17	-.06	.02	-.19	-.10	-.84 ***

Note: values are presented as Pearson's coefficient; BMI = body mass index; RT = reaction time; SCWT = Stroop Color and Word Test; LGT = Local-global Task; gender was coded as 0 = female, 1 = male; frequency of tennis play was coded as once a week = 0, 3–6 times per week = 1; * $p < .05$; ** $p < .01$; *** $p < .001$.

Supplemental material #3

Hierarchical regression predicting accuracy on executive functions task

	Basic processing				Inhibitory control				Working memory		Cognitive flexibility			
	SCWT control		LGT repetitive		SCWT incongruent		SCWT interference		2-back Task		LGT switching		LGT switch cost	
	β	⊿R^2	β	⊿R^2	β	⊿R^2	β	⊿R^2	β	⊿R^2	β	⊿R^2	β	⊿R^2
Step 1														
Age	-.11		.05		-.16		-.06		.31**		-.01		.10	
Sex	-.03		-.07		.06		-.03		-.12		-.02		-.04	
BMI	.14		-.04		-.07		.16		-.01		.10		-.11	
RT	-.16	.03	.26*	.06	-.45**	.12**	.16	.04	-.39***	.40***	.29*	.08	-.08	.03
Step 2														
TE	.22		-.10		-.05		.21*		-.08		-.15		.10	
FTP	.01	.03	.08	.01	.01	.00	-.03	.02	.00	.00	.11	.02	-.05	.01
Step 3														
Sex × TE	.01		-.08		.00		.00		-.01		-.01		-.01	
Sex × FTP	.01	.00	.21	.02	-.01	.00	-.02	.00	-.01	.00	.03	.00	.09	.00

Note: RT = reaction time; BMI = body mass index; TE = tennis experience; FTP = frequency of tennis play; SCWT = Stroop Color and Word Test; LGT = Local-global Task; gender was coded as 0 = female, 1 = male; frequency of tennis play was coded as once a week = 0, 3–6 times per week = 1; * $p < .05$, ** $p < .01$, *** $p < .001$.