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Regular Article

Quadratic associations between cardiovascular stress reactivity and development of cool and hot executive functions in adolescents

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Abstract

Stress affects executive functions and exploring the association between stress-induced physiological reactivity and executive functions could highlight the potential mechanism of the stress-cognitive function link. Our study examined the linear and nonlinear associations between cardiovascular stress reactivity and cool and hot executive functions among adolescents. In November 2021 (T1), 273 Chinese adolescents between 11 and 14 ($M_{age} = 12.93$, $SD_{age} = 0.79$) underwent a speech task during which their cardiovascular data were recorded, and they completed a Flanker task and an Emotional Stroop task. In May 2023 (T2), 253 adolescents again completed the Flanker and Emotional Stroop tasks. Cool and hot executive functions were assessed using the intra-individual reaction time variability of the Flanker task and Emotional Stroop task, respectively. Results showed that cardiovascular stress reactivity was positively linearly associated with cool executive functions at T1 and quadratically (inverted *U*-shaped) associated with cool executive functions at T1 and hot executive functions at T1 and T2. These findings suggest that compared to very high and very low cardiovascular reactivity, moderate to high cardiovascular reactivity to a structured social challenge is associated with better cool and hot executive functions.

Keywords: Adolescents; cardiovascular stress reactivity; cool executive functions; hot executive functions

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Introduction

Executive function, as a high-level cognitive process, refers to the ability to plan, initiate, shift, monitor, and inhibit behaviours (Diamond, 2013). Executive functions generally include three core components: inhibitory control, working memory, and cognitive flexibility (Friedman & Miyake, 2017). In addition, executive functions can be divided into cool and hot executive functions based on whether motivation and emotion are involved (Zelazo & Müller, 2002). Cool executive functions which refer to executive functions in emotionally neutral contexts, are more robustly related to cognitive outcomes, whereas hot executive functions which refer to executive functions in motivational and emotionally laden contexts, are more strongly related to socioemotional behavioral problems (Di et al., 2015; Fernández et al., 2021; Kim et al., 2013). Adolescence is a critical period for the maturity and development of a series of executive functions (Best & Miller, 2010), and cool and hot executive functions are found to develop differently during adolescence (Poon, 2018). Deficits in executive functions have been suggested as the underlying mechanism leading to psychopathological problems (Han et al., 2016; Romer & Pizzagalli, 2021), and cool and hot executive functions have been found to be differently associated with psychopathological symptoms (Zelazo, 2020). Therefore, exploring cool and hot executive functions among adolescents is important for a deeper understanding of the differential mechanisms of developmental psychopathology.

Stress is regarded as a leading environmental factor affecting executive functions (Sandi, 2013). Whether acute or chronic, stress generally has negative effects on working memory (Li et al., 2021; Raver & Blair, 2016), inhibitory control (Afek et al., 2021; Cowell et al., 2015; Roos et al., 2017), cognitive flexibility (Goldfarb et al., 2017; Kalia et al., 2021), and overall executive functions (Moeschl et al., 2022; Shields et al., 2016). However, stress does not inevitably undermine executive functions, and mild or moderate stress tends to facilitate executive functions (Sandi, 2013). The underlying process by which stress affects executive functions remains poorly understood. The arousal of physiological systems under stress, including the autonomic nervous system (ANS) and hypothalamic–pituitary–adrenal (HPA) axis, is considered one of the potential mechanisms that facilitate cognitive activity (Godoy et al., 2018; Wass, 2018). The HPA axis is activated slowly under stress and impacts executive functions through a chronic imbalance in cortisol levels (Peters et al., 1998). Comparatively, the ANS can be aroused very quickly to provide rapid physiological adaptation, which facilitates individuals to utilize cognitive resources and maintain attention to face challenges in the initial phase of a stressful event (Godoy et al., 2018; Peters et al., 1998; Wass, 2018). Studies have also shown that some individuals' ANS is responsive, while their HPA axis is not responsive to stress or challenges, suggesting an asymmetry between the HPA axis and ANS in stress arousal (Del Giudice et al., 2011; Wiemers et al., 2013). Thus, HPA axis arousal and ANS arousal may be differently

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associated with executive functions. The relationship between HPA axis arousal, indexed by cortisol stress reactivity, and executive functions has been extensively explored (e.g., Blair et al., 2005; Feola et al., 2020; Guevara & Murdock, 2020; McCormick et al., 2007); however, the understanding of the association between ANS arousal and executive functions is limited.

Cardiovascular stress reactivity, indexed by heart rate (HR), systolic blood pressure (SBP), and diastolic blood pressure (DBP), which are innervated by the ANS, has been preliminarily explored in relation to executive functions. Some studies have found that higher SBP and DBP reactivity is associated with poor working memory, inhibitory control, and general executive functions among young adults (Hendrawan et al., 2012), and older adults (Waldstein & Katzel, 2005; Wright et al., 2005). However, some studies found that lower HR, SBP, and DBP reactivity are linked to deficits in working memory, inhibitory control, and general executive functions among children (Gao et al., 2015), young adults (Backs & Seljos, 1994) and older adults (Ginty et al., 2012; Lin et al., 2014; Wawrzyniak et al., 2016). Longitudinal studies have also found that lower HR, SBP, and DBP reactivity in young adults are linked to poor inhibitory control and general executive functions in midlife (Lin et al., 2014; Yano et al., 2016). Additionally, null associations between HR, SBP, and DBP reactivity and inhibitory control have also been found among young (Duschek et al., 2009) and middle-aged adults (Mehta, 2012). In short, only the association between cardiovascular stress reactivity and cool executive function has been explored in previous studies with mixed findings, leaving the relationship between cardiovascular stress reactivity and hot executive functions underexplored. Given that, stress-induced cardiovascular arousal is accompanied by motivational engagement (Carroll et al., 2017; Ginty et al., 2020; Lü & Yao, 2021; Lü, 2020), it is thus plausible to assume that cardiovascular stress reactivity would be related to hot executive functions which include motivational and emotional elements.

Moreover, the inconsistent findings regarding the association between cardiovascular stress reactivity and cool executive function might only be due to a linear association. Obradović (2016) indicated that moderate levels of physiological responsivity are optimal for executive function performance, whereas extremely high or low levels of physiological responsivity may undermine it. Carroll et al. (2017) proposed an inverted U-shaped correlation between cardiovascular stress reactivity and behavioural outcomes, suggesting that very high cardiovascular reactivity which reflects allostatic load, and very low cardiovascular reactivity which reflects motivational dysregulation, are related to adverse outcomes (Carroll et al., 2017; O' Riordan et al., 2023; Turner et al., 2020; Whittaker et al., 2021). Therefore, based on theoretical perspectives, and considering that mild stress is considered to facilitate executive functions (Sandi, 2013), moderate rather than very high or very low cardiovascular stress reactivity might be related to optimal executive functions. An empirical study has shown that moderate rather than high or low parasympathetic arousal to stress, indexed by vagal withdrawal, is linked to the best executive functions among children (Marcovitch et al., 2010). Thus, in addition to a linear association, cardiovascular stress reactivity may be quadratically associated with executive functions.

Overall, our study aimed to examine the linear and nonlinear associations between cardiovascular stress reactivity and cool and hot executive functions among adolescents using two-wave data collected 18 months apart. Based on the literature reviewed above, we hypothesized that (a) other than linear associations, cardiovascular stress reactivity would be quadratically associated with cool and hot executive functions assessed at T1. Specifically, adolescents with moderate cardiovascular stress reactivity exhibited better cool and hot executive functions. (b) From a developmental perspective, cardiovascular stress reactivity would be quadratically associated with cool and hot executive functions assessed at T2 after controlling for executive functions assessed at T1.

Method

Participants

Middle school students (between 11 and 14 years old) were recruited from Northwest China, and data were drawn longitudinally from two time points: November 2021 (T1) and May 2023 (T2). After eliminating three participants at T1 and five participants at T2 due to missing experimental data, the final sample included 273 participants (133 females; $M_{\text{age}} = 12.93$, $SD_{\text{age}} = 0.79$) at T1 and 253 participants (125 females; $M_{\text{age}} = 14.44$, $SD_{\text{age}} = 0.79$) at T2. All participants were physically healthy; reported no diagnosis of primary psychotic or mood disorder; had no history of psychosis, asthma, obesity, or cardiovascular disease; and had a body mass index (BMI) between $15.60\ \text{kg/m}^2 \sim 20.07\ \text{kg/m}^2$. The participants had normal or corrected-to-normal vision. Demographic information of the sample at T1 is presented in Table 1. This study was approved by the local institutional review board and written informed consent was obtained from all participants before the experiment. At the end of the experiment, the participants received a gift as compensation.

Public speaking task

Stress was induced by an impromptu speech about running for a class leader, which was demonstrated to effectively induce subjective and physiological stress responses in previous studies (Hofmann et al., 2006; Huang & Lü, 2023; Lü & Wang, 2017). Participants were given 30 s to prepare a speech and 3 min to deliver it. During the public speaking task, their performances were videotaped, and the confederates showed neutral facial expressions and avoided smiling and nodding. If the participants stopped speaking before 3 min, the confederates said, 'Please continue, I will tell you when your time is up'. If participants had trouble determining what to say, they were asked a series of standard questions as prompts.

Measures

Physiological measurement

Physiological data were continuously recorded using SOMNO touchTM RESP (SOMNOmedics, Germany). Electrocardiogram (ECG) data were collected from the participants using three Ag-AgCl leads (mounted on the right and left clavicles and the lower left rib) with a 1-channel ECG sensor sampled at 512 Hz. HR data were acquired from the R-R intervals in the ECG and SBP and DBP values were obtained via pulse transit time (PTT) method, which has been proven as a valid indirect blood pressure measurement method (Bilo et al., 2015) and has been used in experimental and clinical studies (Gesche et al., 2012; Lü & Yao, 2021). Subsequently, DOMINO light software 1.4.0 was applied for physiological data downloading, artefact control, and computation of average physiological scores for each participant for the baseline and stress periods. In this study, HR, SBP, and DBP values were

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Table 1. The demographic information of the sample ($N = 273$)

		Frequency	%
Gender	Female	133	48.72
	Male	140	51.28
Average monthly household income	Less than ¥3000	70	25.64
	¥3000 - ¥7000	120	43.96
	¥7000 - ¥10,000	54	19.78
	Above ¥10,000	29	10.62
Parents' highest education levels	Illiteracy	2	0.73
	Primary school	54	19.05
	Junior high school	126	46.15
	High school	55	20.15
	University	38	13.92
	Postgraduate or above	0	0.00
Parents' highest occupation	Temporary workers	32	11.72
	Manual workers	127	48.52
	Ordinary managers	63	23.08
	Middle managers	34	12.45
	Senior managers	17	6.23

calculated every minute and averaged to obtain the mean HR, SBP, and DBP values for each study period.

Subjective emotional experience

Subjective emotional experiences involving pleasantness and arousal were assessed immediately after each study phase (baseline, stress exposure) on a 9-point scale from 1 (unpleasant) to 9 (pleasant) and 1 (relaxed) to 9 (aroused) (Lü & Wang, 2018; Lü, 2020).

Socioeconomic status

Socioeconomic status (SES) comprised the monthly family income, highest parental educational level, and parental occupational level. Monthly household income, assessed as the monthly income of all family members, was rated from 1 (less than ¥3000) to 5 (> ¥10,000). The parents' education levels were rated from 1 (illiterate) to 6 (postgraduate or above). Parents' occupations were rated from 1 (temporary workers) to 5 (senior managers) according to China's occupation classification (Shi & Shen, 2007). These three components were condensed into one variable as an index of SES, using principal component analysis (Qiu & Ye, 2023).

Executive function tasks

In the present study, cool and hot executive functions were assessed using intraindividual reaction time variability (IIV) of a Flanker task and an Emotional Stroop task, respectively. The IIV refers to short-term trial-to-trial fluctuations in reaction time, with a larger IIV suggesting poorer executive functions (Ali et al., 2019; Jensen, 1992; MacDonald et al., 2009). Compared with reaction time (RT) and accuracy rates (ACC), the IIV reflects the mean differences in performance within individuals and is regarded as a better indicator of executive functions (Williams et al., 2016).

Cool executive functions. In the present study, cool executive functions were assessed using a modified Flanker task, which was administered via E-Prime 2.0 (Psychology Software Tools, Inc., Sharpsburg, PA). Following previous studies (Lü & Wang, 2018; Williams et al., 2016), the present study set the practice experiment including 20 trials and the formal experiment including three blocks which consisted of 120 trials for each block. The procedure for a single trial is illustrated in Figure 1. In each trial, a fixation cross was first presented at the center of the screen for 1,000 ms and then, a flanker arrow appeared for 250 ms positioned directly to the left or right of the fixation cross. Subsequently, a fixation cross appeared for 50 ms and then a dot appeared to the left or right of the fixation cross for 750 ms. Participants were asked to ignore all other information and indicate whether the dot was located to the left or right of the fixation cross by pressing the left key (F) or the right key (J) on a computer keyboard with the corresponding index finger as quickly and accurately as possible. The experimental program included the congruent trials (the dot was presented in the same position in which the arrow pointed) and the incongruent trials (the dot was presented in the opposite position in which the arrow pointed), with 24 (20%) incongruent and 96 (80%) congruent trials in a random order in the formal experiment. In the formal experiment, the trials with a dot on the left or right side were an even split. During the experiment, accuracy rates (proportion of correct trials), reaction times (reaction time of responding to correct trials), and IIV (standard deviation of reaction time) were obtained for the congruent and incongruent conditions. According to previous studies (e.g., Lü & Wang, 2018; Williams et al., 2016), all trials were combined to give an overall indication of IIV (combined IIV). The IIV on the Flanker task at T1 and T2 were recorded as Flanker IIV-T1, and Flanker IIV-T2, respectively.

Hot executive functions. In the present study, individuals' hot executive functions were assessed by an Emotional Stroop task, which was administered via E-Prime 2.0 (Psychology Software Tools, Inc., Sharpsburg, PA). Following previous studies (Adelhöfer et al., 2020), the present study set up a practice experiment including 20 trials and a formal experience including two blocks which consisted of 80 trials for each block. The procedure for a single trial is illustrated in Figure 2. In each trial, a fixation cross was first displayed in the center of the screen for 500 ms and then, a positive or negative face-word stimulus appeared in the center of the screen for 2,000 ms, followed by a 1,000 ms intertrial interval (blank screen). Participants were asked to respond to positive emotional faces by pressing the left key (F) and negative emotional faces by pressing the right key (J) on a computer keyboard with the corresponding index finger as quickly and accurately as possible. In the formal experiment, the trials with positive or negative faces were an even split. The experimental program included the congruent trials (facial expressions that correspond to the word's emotional valence) and the incongruent trials (facial expressions that differed from the word's emotional valence) and consisted of 80 (50%) incongruent and 80 (50%) congruent trials in random order. There were a total of four conditions based on trial congruency (congruence/incongruence) and facial expressions (positive/negative), and similar to the Flanker task,

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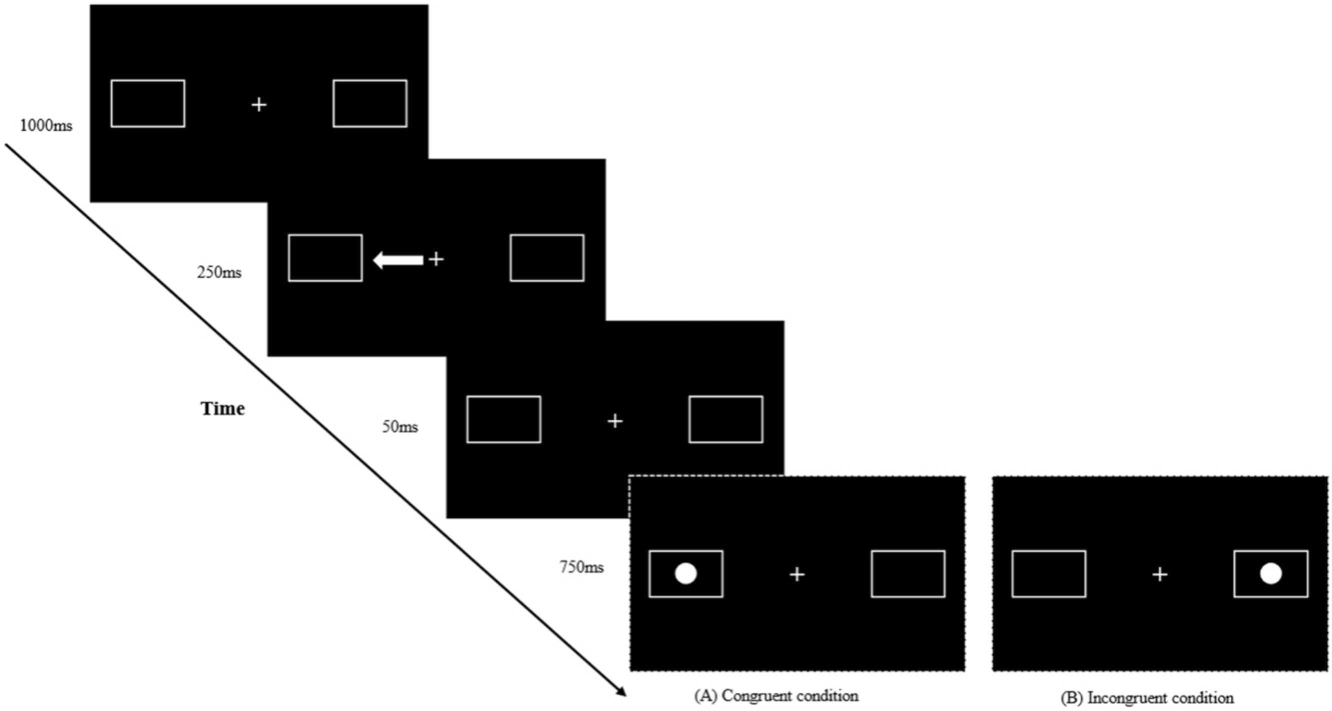

Figure 1. Schematic diagram of the Flanker task.

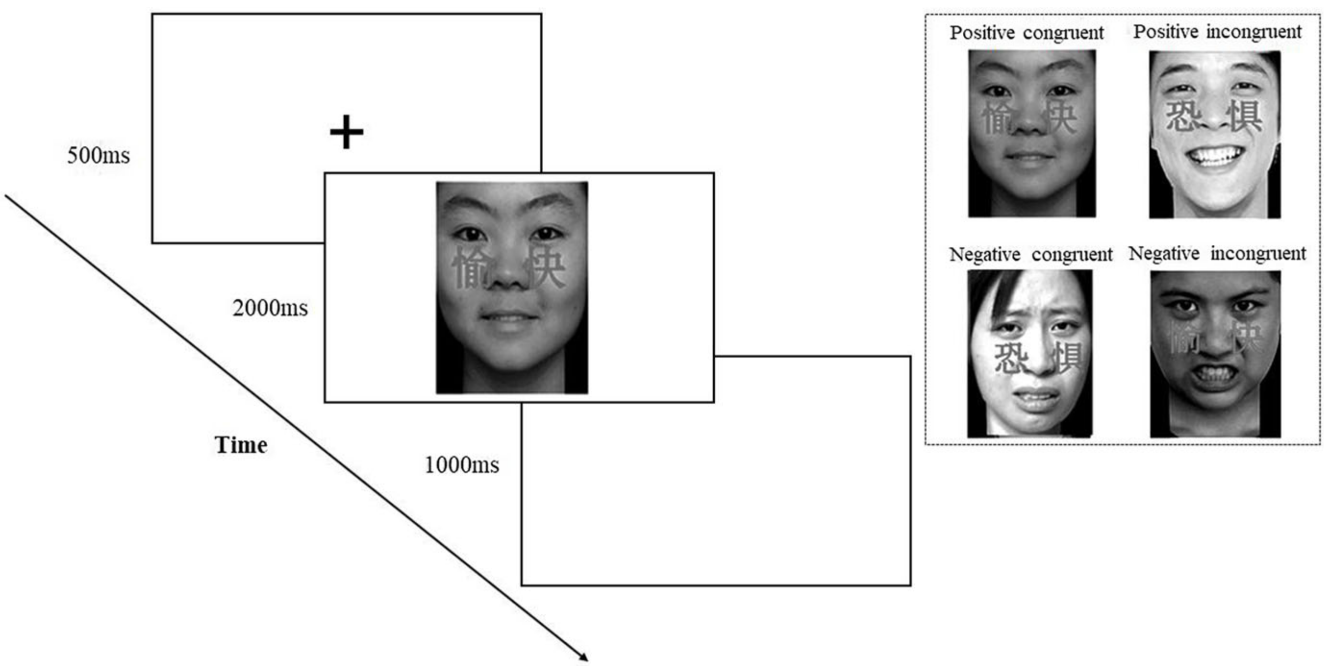

Figure 2. Schematic diagram of the Emotional Stroop task.

accuracy rates, reaction time, and IIV were obtained for four conditions separately (positive-congruent, positive-incongruent, negative-incongruent, and negative-incongruent). According to previous studies (e.g., Adelhöfer et al., 2020; Lü & Wang, 2018), all trials with positive face were combined to give an overall indication of IIV (Positive combined IIV) and all trials with negative face were combined to give an overall indication of IIV (Negative combined IIV). The IIV on the Emotional Stroop task at T1 and T2 were recorded as Stroop IIV-T1 and Stroop IIV-T2, respectively.

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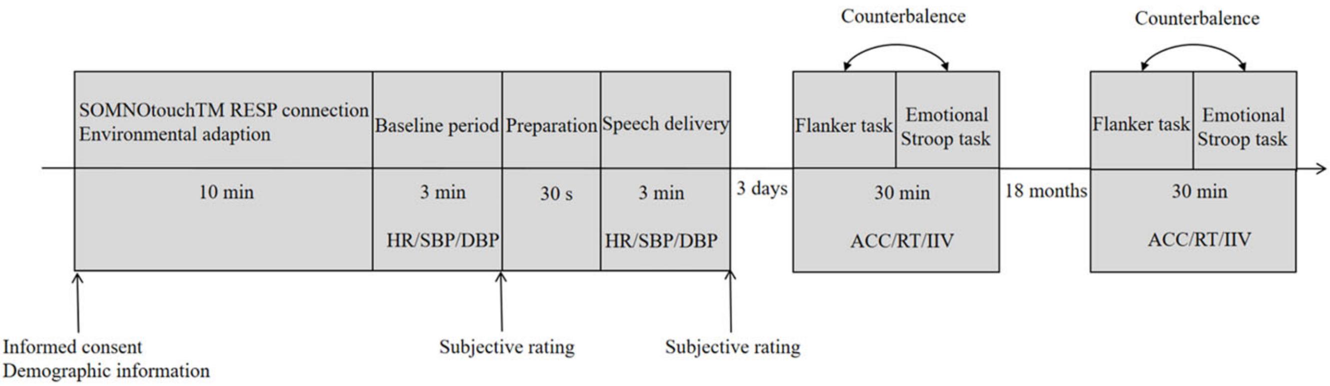

Figure 3. Schematic of the experimental procedure.

Procedure

In November 2021 (T1), participants were requested to sleep well the night before the experiment and to avoid consuming nicotine or caffeine for 2 h before the experiment to control any exogenous effects on physiological measurements. After arriving at the laboratory at their scheduled appointments between 2:30 pm and 5:30 pm, the participants were asked to provide informed consent and demographic information. After the SOMNOtouchTM RESP device was attached, the participants were allowed 10 min to acclimatize to the laboratory. The physiological experiment session was initiated with a 3 min baseline period, during which participants were asked to rest and view a neutral picture (a picture of an umbrella drawn from the International Affective Picture System, IAPS; Lang et al., 2005) presented on the monitor screen. Subsequently, they were asked to rate their subjective emotional experiences using pleasantness and arousal scales. Then, two unfamiliar adult confederates (one female and one male) entered the room, and participants were given 30 s to prepare a speech and then delivered the speech for 3 min (stress period) in front of the confederates. Immediately after the stress period, participants rated their emotional pleasantness and arousal. Three days later, participants returned to participate in the Flanker task and Emotional Stroop task (the order of the two tasks was counterbalanced between participants). In May 2023 (T2), the participants were invited to complete the Flanker and Emotional Stroop tasks. The study procedure is illustrated in Figure 3.

Analysis review

In this study, cardiovascular (HR, SBP, and DBP) reactivity was calculated by subtracting the mean baseline value from the mean stress exposure value, with higher change scores indicating greater cardiovascular response to stress (Lü, 2020; Llabre et al., 1991).

Data analysis was conducted using IBM SPSS Statistics 25.0, and Mplus 7.0. First, paired sample t-tests were performed to explore whether the public speech task effectively elicited a subjective stressful experience and physiological activation at T1 and the effects of the trial type (congruent and incongruent conditions) on the performance of the Flanker task and Emotional Stroop task at T1 and T2. Second, zero-order correlations of the study variables were performed at T1 and T2. Third, separate hierarchical regression analyses were performed to examine the linear and quadratic effects of standardized cardiovascular reactivity at T1 on IIV-T1 and IIV-T2 of the Flanker task and the Emotional Stroop task. In each regression equation, age, sex, SES, and BMI, which are closely related to executive functions and cardiovascular stress reactivity (Hackman et al., 2015; Steptoe & Wardle, 2005), were entered as control variables in the first step. In addition, the IIV in the corresponding task condition at T1 was entered as a control variable in separate hierarchical regression analyses for the IIV at T2. Finally, if the quadratic associations between cardiovascular reactivity and IIV were significant, the Johnson-Neyman technique and Mplus 7.0 were used to calculate the slope of cardiovascular reactivity on IIV at different levels of cardiovascular reactivity.

Table 2. Means and *SD*s for subjective and physiological values across different study phases

	Baseline	Stress Exposure	*t* (272)
Emotional Arousal	4.47 (1.37)	6.85 (1.10)	−24.80***
Emotional Pleasantness	5.61 (1.15)	3.79 (0.80)	21.85***
HR (bpm)	86.66 (11.82)	98.94 (14.00)	21.85***
SBP (mmHg)	103.95 (12.41)	115.08 (15.31)	21.86***
DBP (mmHg)	64.76 (8.26)	71.22 (8.91)	21.26***

Note. HR = heart rate; SBP = systolic blood pressure; DBP = diastolic blood pressure. $^*p < 0.05$. $^{**}p < 0.01$. $^{***}p < 0.001$.

Result

Manipulation checks

Physiological experiment checks

The means and standard deviations of the subjective and physiological values at baseline and during stress exposure are presented in Table 2.

The results of the paired sample *t*-tests showed that emotional arousal in the stress task was significantly higher than at baseline, $t\,(272) = -24.80$, $p < .001$, and emotional pleasantness in the stress task was significantly lower than at baseline, $t\,(272) = 21.85$, $p < .001$. The HR, SBP, and DBP values in the stress task were significantly lower than those at baseline ($t\,(272) = 21.85$, $p < .001$,

Table 3. Means and *SD*s for accuracy rates, reaction time and IIV on the flanker task and Emotional Stroop task

	Flanker task		Stroop task			
	Congruent	Incongruent	Positive Congruent	Positive Incongruent	Negative Congruent	Negative Incongruent
Accuracy Rates-T1	0.97 (0.05)	0.82 (0.15)	0.90 (0.14)	0.81 (0.18)	0.88 (0.14)	0.80 (0.17)
Reaction Time-T1	332.23 (51.80)	379.13 (64.67)	740.31 (118.63)	794.15 (137.17)	788.38 (32.40)	821.63 (134.61)
IIV-T1	111.07 (28.52)	127.08 (34.17)	212.29 (78.44)	245.72 (87.80)	242.64 (97.34)	247.61 (86.94)
Accuracy Rates-T2	0.96 (0.06)	0.85 (0.13)	0.95 (0.10)	0.88 (0.13)	0.93 (0.10)	0.88 (0.12)
Reaction Time-T2	323.57 (43.53)	369.37 (52.79)	694.04 (115.66)	743.97 (122.39)	737.19 (123.52)	770.19 (117.98)
IIV-T2	107.36 (31.75)	120.95 (38.81)	183.08 (75.28)	215.12 (79.55)	210.96 (84.77)	220.24 (84.16)

Note. IIV = intraindividual reaction time variability.

t (272) = 21.26, $p < .001$, t (272) = 30.04, and $p < .001$. These results indicate that the public-speaking task was successfully manipulated to elicit subjective and physiological responses.

Behavioural experiment checks

The means and standard deviations of the accuracy rate, reaction time, and IIV on the Flanker task and Emotional Stroop task are presented in Table 3.

The results of paired samples t-tests showed that on the Flanker task, better accuracy rate-T1 (t (272) = 19.05, $p < .001$), shorter reaction time-T1 (t (272) = −29.05, $p < .001$), lower IIV-T1 (t (272) = −15.42, $p < .001$), and better accuracy rate-T2 (t (252) = 17.79, $p < .001$), shorter reaction time-T2 (t (252) = −31.98, $p < .001$), lower IIV-T2 (t (252) = −12.37, $p < .001$), were found on congruent trials in comparison to incongruent trials. On the Emotional Stroop task, better accuracy rate-T1 (t (272) = 11.16, $p < .001$), shorter reaction time-T1 (t (272) = −15.88, $p < .001$), lower IIV-T1 (t (272) = −9.95, $p < .001$), and better accuracy rate-T2 (t (252) = 9.96, $p < .001$), shorter reaction time-T2 (t (252) = −15.71, $p < .001$), lower IIV-T2 (t (252) = −9.38, $p < .001$), were found on positive congruent trials in comparison to positive incongruent trials. However, better accuracy rate-T1 (t (272) = 10.83, $p < .001$), shorter reaction time-T1 (t (272) = −9.95, $p < .001$), but not IIV-T1 (t (272) = −1.29, $p = .200$), and better accuracy rate-T2 (t (252) = 8.50, $p < .001$), shorter reaction time-T2 (t (252) = -11.44, $p < .001$), lower IIV-T2 (t (252) = −2.65, $p = .009$), were found on negative congruent trials in comparison to negative incongruent trials. Moreover, IIV-T2 was not significantly different from IIV-T1 on the Flanker task (t (252) = 0.77, $p = .441$), whereas IIV-T2 was lower than IIV-T1 in positive and negative trials in the Emotional Stroop task (t (252) = 6.01, $p < .001$; t (252) = 5.57, $p < .001$).

Zero-order correlations

The correlations among all study variables are presented in Table 4.

As shown in Table 4, HR reactivity was positively associated with SBP ($r = 0.66$, $p<0.001$) and DBP reactivity ($r = 0.58$, $p<0.001$), whereas SBP reactivity was positively associated with DBP reactivity ($r = 0.77$, $p < 0.001$). Within measures, Flanker combined IIV-T1 was positively related to Stroop-Positive combined IIV-T1 ($r = 0.46$, $p < 0.001$) and Stroop-negative combined IIV-T1 ($r = 0.37$, $p < 0.001$). Flanker combined IIV-T2 was positively related to Stroop-Positive combined IIV-T2 ($r = 0.44$, $p < 0.001$) and Stroop-negative combined IIV-T2 ($r = 0.36$, $p < 0.001$). Across measures, Flanker combined IIV-T1 was positively correlated with Flanker combined IIV-T2 ($r = 0.50$, $p < 0.001$), Stroop positive-combined IIV-T1 was positively correlated with Stroop-Positive combined IIV-T2 ($r = 0.48$, $p < 0.001$), and Stroop-negative combined IIV-T1 was positively correlated with Stroop-negative combined IIV-T2 ($r = 0.38$, $p < 0.001$), which indicated consistency between measurements at T1 and T2.

Hierarchical regression

Hierarchical regression on the flanker task

The results of the hierarchical regression analyses are presented in Table 5.

As shown in Table 5, the linear effects of HR and SBP reactivity were marginally significant for Flanker combined IIV-T1 ($b = −3.20$, $t = −1.90$, 95 % CI [−6.51, 0.11], $p = .058$; $b = −3.30$, $t = −1.94$, 95 % CI [−6.66, 0.06], $p = .054$), and the linear effects of DBP reactivity were significant for Flanker combined IIV-T1 ($b = −3.61$, $t = −2.05$, 95% CI [−7.08, 0.14], $p = .042$). The linear effects of HR, SBP and DBP reactivity were not significant for Flanker combined IIV-T2 ($b = −2.25$, t = -1.29, 95 % CI [−5.69, 1.20], $p = .200$; $b = 0.76$, $t = 0.43$, 95 % CI [−2.71, 4.23], $p = .667$; $b = 3.02$, $t = 1.68$, 95 % CI [−0.52, 6.55], $p = .094$).

The quadratic effects of HR and SBP reactivity were significant for Flanker combined IIV-T1 ($b = 3.64$, $t = 2.99$, 95 % CI [1.25, 6.04], $p = .003$; $b = 3.98$, $t = 3.52$, 95% CI [1.75, 6.20], $p < .001$), but were not significant for Flanker combined IIV-T2 ($b = 1.89$, $t = 1.42$, 95% CI [−0.72, 4.49], $p = .156$; $b = 1.85$, $t = 1.55$, 95% CI [−0.50, 4.21], $p = .122$). The quadratic effects of DBP reactivity were significant for Flanker combined IIV-T1 ($b = 4.67$, $t = 4.03$, 95% CI [2.39, 6.95], $p < .001$) and Flanker combined IIV-T2 ($b = 2.87$, $t = 2.33$, 95% CI [0.44, 5.30], $p = .021$).

As shown in Figure 4, with an increase in HR reactivity, Flanker combined IIV-T1 first decreased significantly (HR reactivity lower than 0.38 Z), then changed insignificantly (HR reactivity between 0.38 Z and 1.47 Z), and finally increased significantly (HR reactivity higher than 1.47 Z). With the increase of SBP reactivity, Flanker combined IIV-T1 firstly decreased significantly (SBP reactivity lower than 0.68 Z), then changed non-significantly (SBP reactivity between 0.68 Z and 1.59 Z), and finally increased significantly (SBP reactivity higher than 1.59 Z). With the increase in DBP reactivity, Flanker combined IIV-T1 first decreased significantly (DBP reactivity lower than 0.23 Z), changed non-significantly (DBP reactivity between 0.23 Z and 0.99 Z), and finally increased significantly (DBP reactivity higher than 0.99 Z); Flanker combined IIV-T2 first decreased significantly (DBP

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Table 4. Descriptive statistics and correlations among study variables

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Gender													
2. Age	0.05												
3. BMI	0.05	0.08											
4. SES	0.10	−0.15*	−0.009										
5. HR Reactivity	−0.15**	0.008	0.02	0.09									
6. SBP Reactivity	−0.25***	−0.02	−0.02	−0.04	0.66***								
7. DBP Reactivity	−0.34***	−0.09	<0.001	−0.08	0.58***	0.77***							
8. Flanker combined IIV-T1	−0.07	−0.13*	−0.04	−0.003	−0.11	−0.10	−0.08						
9. Stroop-Positive combined IIV-T1	0.07	−0.01	−0.09	−0.07	−0.07	−0.04	−0.08	0.46***					
10. Stroop-Negative combined IIV-T1	0.17**	−0.01	−0.15*	−0.05	−0.06	−0.07	−0.09	0.37***	0.77***				
11. Flanker combined IIV-T2	0.006	0.04	−0.02	−0.02	−0.13*	−0.04	0.02	0.50***	0.39***	0.32***			
12. Stroop-Positive combined IIV-T2	0.05	−0.03	−0.03	0.02	−0.10	−0.01	−0.02	0.39***	0.48***	0.43***	0.44***		
13. Stroop-Negative combined IIV-T2	0.06	−0.03	−0.05	0.02	0.02	0.003	−0.02	0.33***	0.38***	0.38***	0.36***	0.79***	
M		12.93	18.44	0.00	12.29	11.13	6.46	113.96	227.51	244.64	112.42	201.46	216.21
SD		0.79	1.02	1.00	9.29	8.65	3.55	27.48	74.54	81.02	31.13	68.63	74.88

Note. SES = socioeconomic status; BMI = body mass index = weight / $height^2$; HR = heart rate; HR reactivity = average HR at stress − average baseline HR; SBP = systolic blood pressure; SBP reactivity = average SBP at stress − average baseline SBP; DBP = diastolic blood pressure; DBP reactivity = average DBP at stress − average baseline DBP. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

Table 5. Linear and quadratic effects of cardiovascular reactivity in predicting IIV on the flanker task

		Flanker combined IIV-T1				Flanker combined IIV-T2			
Step	Predictor	*b*	*SE*	*t*	ΔR^2	*b*	*SE*	*t*	ΔR^2
Step1	Gender	−3.27	3.34	−0.98	0.02	1.81	3.42	0.53	0.27
	Age	−4.42	2.13	−2.08*		4.31	2.20	1.96†	
	BMI	−0.92	1.64	−0.56		0.24	1.63	0.14	
	SES	−0.45	1.69	−0.27		−0.05	1.77	−0.03	
	Corresponding IIV-T1					0.58	0.06	9.45***	
Step2	HR reactivity	−3.20	1.68	−1.90†	0.01	−2.25	1.75	−1.29	0.005
Step3	HR reactivity^2	3.64	1.22	2.99**	0.03	1.89	1.32	1.42	0.006
Step1	Gender	−3.27	3.34	−0.98	0.02	1.81	3.42	0.53	0.27
	Age	−4.42	2.13	−2.08*		4.31	2.20	1.96†	
	BMI	−0.92	1.64	−0.56		0.24	1.63	0.14	
	SES	−0.45	1.69	−0.27		−0.05	1.77	−0.03	
	Corresponding IIV-T1					0.58	0.06	9.45***	
Step2	SBP reactivity	−3.30	1.71	−1.94†	0.01	0.76	1.76	0.43	0.001
Step3	SBP reactivity^2	3.98	1.13	3.52***	0.04	1.85	1.19	1.55	0.007
Step1	Gender	−3.27	3.34	−0.98	0.02	1.81	3.42	0.53	0.27
	Age	−4.42	2.13	−2.08*		4.31	2.20	1.96†	
	BMI	−0.92	1.64	−0.56		0.24	1.63	0.14	
	SES	−0.45	1.69	−0.27		−0.05	1.77	−0.03	
	Corresponding IIV-T1					0.58	0.06	9.45***	
Step2	DBP reactivity	−3.61	1.76	−2.05*	0.02	3.02	1.80	1.68†	0.008
Step3	DBP reactivity^2	4.67	1.16	4.03***	0.06	2.87	1.23	2.33*	0.02

Note. SES = socioeconomic status; BMI = body mass index = weight / height^2; HR = heart rate; HR reactivity = average HR at stress − average baseline HR; HR^2 = HR × HR; SBP = systolic blood pressure; SBP reactivity = average SBP at stress − average baseline SBP; SBP^2 = SBP × SBP; DBP = diastolic blood pressure; DBP reactivity = average DBP at stress − average baseline DBP; DBP^2 = DBP × DBP. † $p < 0.10$. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

reactivity lower than −1.82 Z), then changed non-significantly (DBP reactivity between −1.82 Z and 0.21 Z), and finally increased significantly (DBP reactivity higher than 0.21 Z).

These results revealed that, compared to very high or very low cardiovascular reactivity, adolescents with moderate to high cardiovascular stress reactivity at T1 exhibited better cool executive functions at T1, but not at T2.

Hierarchical regression on the emotional Stroop task

The results of the hierarchical regression analyses are presented in Table 6.

As shown in Table 6, the quadratic effects of HR, SBP and DBP reactivity were significant or marginally significant for Stroop-positive combined IIV-T1 ($b = 6.04$, $t = 1.80$, 95% CI [-0.57, 12.66], $p = .073$; $b = 10.72$, $t = 3.47$, 95% CI [4.64, 16.80], $p < .001$; $b = 9.14$, $t = 2.85$, 95% CI [2.81, 15.46], $p = .005$), Stroop-Negative combined IIV-T1 ($b = 10.79$, $t = 3.04$, 95% CI [3.80, 17.77], $p = .003$; $b = 10.04$, $t = 3.03$, 95% CI [3.52, 16.56], $p = .003$; $b = 9.30$, $t = 2.71$, 95% CI [2.54, 16.07], $p = .007$), Stroop-Positive combined IIV-T2 ($b = 9.43$, $t = 3.25$, 95% CI [3.71, 15.14], $p = .001$; $b = 7.46$, $t = 2.81$, 95% CI [2.24, 12.68], $p = .005$; $b = 7.47$, $t = 2.73$, 95% CI [2.09, 12.86], $p = .007$) and Stroop-Negative combined IIV-T2 ($b = 9.50$, $t = 2.78$, 95% CI [2.78, 16.22], $p = .006$; $b = 10.60$, $t = 3.52$, 95% CI [4.66, 16.54], $p = .001$; $b = 8.18$, $t = 2.60$, 95% CI [1.97, 14.39], $p = .010$).

As shown in Figure 5, with the increase of HR reactivity, Stroop-Negative combined IIV-T1 first decreased significantly (HR reactivity lower than 0.003 Z), then changed non-significantly (HR reactivity between 0.003 Z and 0.81 Z), and finally increased significantly (HR reactivity higher than 0.81 Z); Stroop-Positive combined IIV-T2 first decreased significantly (HR reactivity lower than 0.16 Z), then changed non-significantly (HR reactivity between 0.16 Z and 1.04 Z), and finally increased significantly (HR reactivity higher than 1.04 Z); and, Stroop-Negative combined IIV-T2 first decreased significantly (HR reactivity lower than −0.40 Z), then changed non-significantly (HR reactivity between −0.40 Z and 0.57 Z); and, finally increased significantly (HR reactivity higher than 0.57 Z). With the increase of SBP reactivity, Stroop-Positive combined IIV-T1 first decreased significantly (SBP reactivity lower than 0.39 Z), then changed non-significantly (SBP reactivity between 0.39 Z and 1.20 Z), and finally increased significantly (SBP reactivity higher than 1.20 Z); Stroop-Negative combined IIV-T1 first decreased significantly (SBP reactivity lower than 0.31 Z), then changed non-significantly (SBP reactivity between 0.31 Z and 1.18 Z); and, finally increased significantly (SBP reactivity higher than 1.18 Z); Stroop-Positive combined IIV-T2 first decreased significantly (SBP reactivity lower than 0.08 Z), then changed non-significantly (SBP reactivity between 0.08 Z and 1.17 Z), and finally increased significantly (SBP reactivity higher than 1.17 Z); Stroop-Negative combined IIV-T2 first decreased significantly (SBP reactivity lower than 0.15 Z), then changed non-significantly (SBP reactivity between 0.15 Z and 0.97 Z), and finally increased significantly (SBP reactivity higher than 0.97 Z). With the increase of DBP reactivity, Stroop-Positive combined IIV-T1

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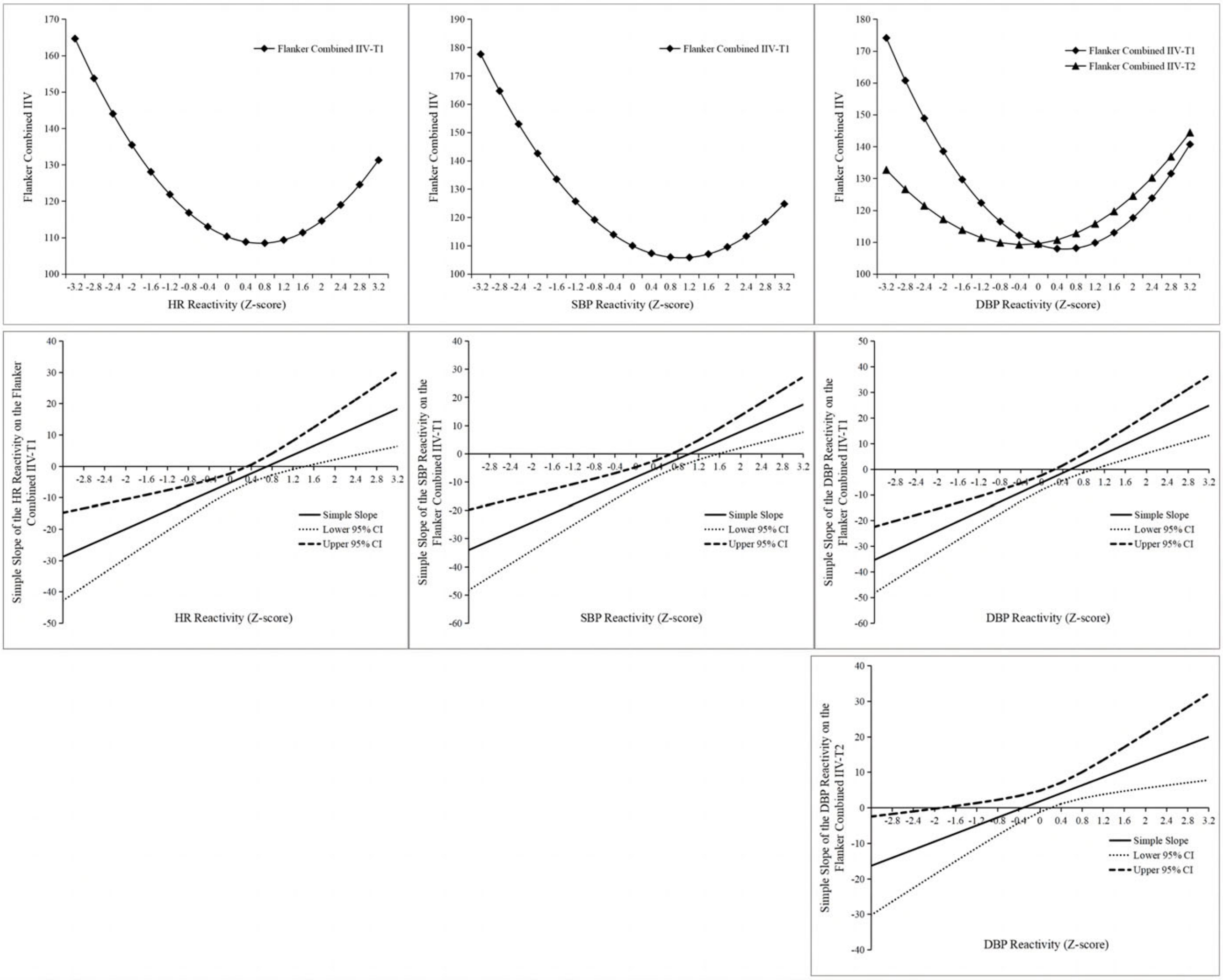

Figure 4. Quadratic associations between cardiovascular stress reactivity and IIV on the Flanker task and Johnson-Neyman plot for the simple slope of quadratic effects.

first decreased significantly (DBP reactivity lower than 0.01 Z), then changed non-significantly (DBP reactivity between 0.01 Z and 1.17 Z), and finally increased significantly (DBP reactivity higher than 1.17 Z); Stroop-Negative combined IIV-T1 first decreased significantly (DBP reactivity lower than −0.08 Z), then changed non-significantly (DBP reactivity between -0.08 Z and 0.93 Z), and finally increased significantly (DBP reactivity higher than 0.93 Z); Stroop-Positive combined IIV-T2 first decreased significantly (DBP reactivity lower than −0.43 Z), then changed non-significantly (DBP reactivity between −0.43 Z and 0.64 Z), and finally increased significantly (DBP reactivity higher than 0.64 Z); and, Stroop-Negative combined IIV-T2 first decreased significantly (DBP reactivity lower than −0.43 Z), then changed non-significantly (DBP reactivity between −0.43 Z and 0.69 Z), and finally increased significantly (DBP reactivity higher than 0.69 Z).

Therefore, compared with very high or very low cardiovascular reactivity, adolescents with moderate to high cardiovascular stress reactivity at T1 exhibited better hot executive functions at T1 and T2.

Post-hoc analysis

Considering that there were sex differences in cardiovascular reactivity and Stroop-Negative combined IIV-T1, the moderating effects of sex on the quadratic associations between cardiovascular reactivity and Stroop-Negative combined IIV-T1 were analyzed. No significant moderating effects of sex were found among the quadratic associations ($p > .05$).

Discussion

The present study found positive linear associations between cardiovascular stress reactivity (HR, SBP, and DBP) at T1 and cool executive functions at T1. This is in line with previous cross-sectional studies (Gao et al., 2015; Ginty et al., 2012; Wawrzyniak et al., 2016), showing that adolescents with higher cardiovascular stress reactivity exhibited better cool executive functions. However, after controlling for cool executive functions at T1, the associations between cardiovascular stress reactivity at T1 and cool executive functions at T2 were not significant, suggesting that the initial linear associations did not change significantly 18 months later.

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Table 6. Linear and quadratic effects of cardiovascular reactivity in predicting IIV on the Emotional Stroop task

		Stroop-Positive combined IIV-T1				Stroop-Negative combined IIV-T1				Stroop-Positive combined IIV-T2				Stroop-Negative combined IIV-T2			
Step	Predictor	*b*	*SE*	*t*	ΔR^2	*b*	*SE*	*t*	ΔR^2	*b*	*SE*	*t*	ΔR^2	*b*	*SE*	*t*	ΔR^2
Step1	Gender	11.63	9.08	1.28	0.02	28.28	9.68	2.92**	0.06	−0.49	7.74	−0.06	0.24	−3.46	9.07	−0.38	0.15
	Age	−2.45	5.78	−0.43		−2.50	6.16	−0.41		−1.76	4.91	−0.36		−2.66	5.66	−0.47	
	BMI	−6.36	4.44	−1.43		−11.67	4.74	−2.46*		1.18	3.68	0.32		0.48	4.27	0.11	
	SES	−6.23	4.59	−1.36		−5.66	4.90	−1.16		2.87	3.99	0.72		1.90	4.60	0.41	
	Corresponding IIV-T1									0.45	0.05	8.65***		0.36	0.06	6.35***	
Step2	HR Reactivity	−3.84	4.59	−0.84	0.003	−2.37	4.90	−0.48	0.001	−4.87	3.91	−1.25	0.005	2.68	4.52	0.59	0.001
Step3	HR Reactivity^2	6.04	3.36	1.80†	0.01	10.79	3.55	3.04**	0.03	9.43	2.90	3.25***	0.03	9.50	3.41	2.78**	0.03
Step1	Gender	11.63	9.08	1.28	0.02	28.28	9.68	2.92**	0.06	−0.49	7.74	−0.06	0.24	−3.46	9.07	−0.38	0.15
	Age	−2.45	5.78	−0.43		−2.50	6.16	−0.41		−1.76	4.91	−0.36		−2.66	5.66	−0.47	
	BMI	−6.36	4.44	−1.43		−11.67	4.74	−2.46*		1.18	3.68	0.32		0.48	4.27	0.11	
	SES	−6.23	4.59	−1.36		−5.66	4.90	−1.16		2.87	3.99	0.72		1.90	4.60	0.41	
	Corresponding IIV-T1									0.45	0.05	8.65		0.36	0.06	6.35***	
Step2	SBP Reactivity	−2.39	4.66	−0.51	0.001	−2.56	4.97	−0.52	0.001	0.51	3.94	0.13	<0.001	1.71	4.54	0.38	<0.001
Step3	SBP Reactivity^2	10.72	3.09	3.47***	0.04	10.04	3.31	3.03**	0.03	7.46	2.65	2.81**	0.02	10.60	3.02	3.52***	0.04
Step1	Gender	11.63	9.08	1.28	0.02	28.28	9.68	2.92**	0.06	−0.49	7.74	−0.06	0.24	−3.46	9.07	−0.38	0.15
	Age	−2.45	5.78	−0.43		−2.50	6.16	−0.41		−1.76	4.91	−0.36		−2.66	5.66	−0.47	
	BMI	−6.36	4.44	−1.43		−11.67	4.74	−2.46*		1.18	3.68	0.32		0.48	4.27	0.11	
	SES	−6.23	4.59	−1.36		−5.66	4.90	−1.16		2.87	3.99	0.72		1.90	4.60	0.41***	
	Corresponding IIV-T1									0.45	0.05	8.65		0.36	0.06	6.35	
Step2	DBP Reactivity	−5.20	4.81	−1.08	0.004	−3.63	5.14	−0.71	0.002	1.47	4.04	0.36	<0.001	1.02	4.66	0.22	<0.001
Step3	DBP Reactivity^2	9.14	3.21	2.85**	0.03	9.30	3.44	2.71**	0.03	7.47	2.74	2.73**	0.02	8.18	3.15	2.60**	0.02

Note. SES = socioeconomic status; BMI = body mass index = weight / height^2; HR = heart rate; HR reactivity = average HR at stress − average baseline HR; HR^2 = HR × HR. SBP = systolic blood pressure; SBP reactivity = average SBP at stress − average baseline SBP; SBP^2 = SBP × SBP; DBP = diastolic blood pressure; DBP reactivity = average DBP at stress − average baseline DBP; DBP^2 = DBP × DBP. † $p < 0.10$. * $p < 0.05$. ** $p < 0.01$. *** $p < 0.001$.

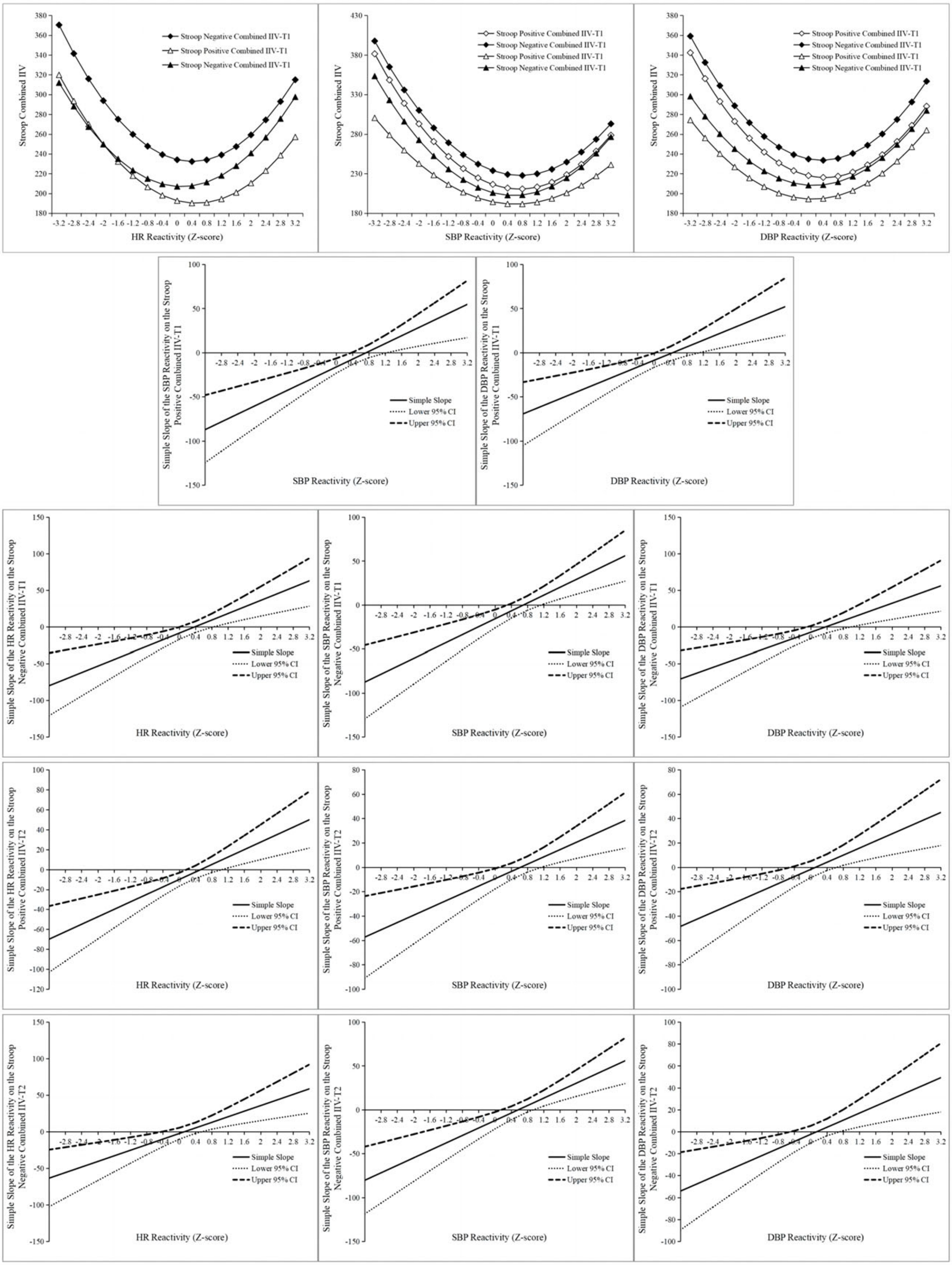

Figure 5. Quadratic associations between cardiovascular stess reactivity and IIV on the Emotional Stroop task and Johnson-Neyman plot for the simple slope of quadratic effects.

This finding is somewhat different from those of previous studies using a longitudinal design that obtained a linear association between cardiovascular reactivity at T1 and cool executive functions at T2 (Lin et al., 2014; Yano et al., 2016). This is partly because the longitudinal associations observed in previous studies did not control for the initial level of cool executive functions, which may be underpowered to detect the influence of cardiovascular stress reactivity on changes in cool executive functions with age. Additionally, extending previous studies, the present study further found that cardiovascular (HR, SBP, and DBP) stress reactivity at T1 was quadratically associated with cool executive functions at T1, but the quadratic association was only significant between DBP reactivity (rather than HR or SBP reactivity) at T1 and cool executive functions at T2 after controlling for cool executive function at T1. These findings suggest that adolescents with moderate to high rather than very high or very low cardiovascular stress reactivity showed better cool executive function, but this effect did not change 18 months later.

Moreover, the present study is the first to explore the association between cardiovascular stress reactivity and hot executive functions. We did not find any linear associations between cardiovascular stress reactivity at T1 and hot executive functions at T1 and T2. However, significant quadratic associations were observed between cardiovascular (HR, SBP, and DBP) stress reactivity at T1, hot executive functions at T1, and hot executive functions at T2 after controlling for hot executive functions at T1. These findings suggest that adolescents with moderate to high rather than very high or very low cardiovascular stress reactivity show better hot executive functions with development. Although there is a lack of direct evidence, relevant studies have suggested that higher physiological stress reactivity is associated with better socioemotional functioning (Carroll et al., 2017; O' Riordan et al., 2023; Turner et al., 2020; Whittaker et al., 2021). Considering that hot executive functions involve motivational and emotional elements, the pattern of the present study's findings partly supports indirect evidence. However, it should be noted that the conclusion of indirect evidence is based on a linear association, which cannot reveal the extent to which 'higher' physiological stress reactivity is optimal. The present study's findings emphasize that moderate to high rather than very high cardiovascular stress reactivity is related to better hot executive functions. Additionally, hot executive function has been found to show a bell-shaped development curve during adolescence, with an upward slope from early adolescence (i.e., from age 12 to 14) to reach a peak in middle adolescence (ages 14 and 15) (Poon, 2018). Therefore, we found quadratic associations between cardiovascular stress reactivity and changes in hot executive functions over 18 months among adolescents aged 11 to 14 years.

Taken together, in addition to the linear relationships, the present study is the first to reveal quadratic associations between cardiovascular reactivity to a structured social challenge (i.e., public speaking task) and cool and hot executive functions among Chinese adolescents, suggesting that moderate to high rather than very high or very low cardiovascular reactivity is related to better cool and hot executive functions. This finding highlights the underlying mechanisms by which mild or moderate stress facilitates executive functions. Additionally, from a developmental perspective, the associations between cardiovascular stress reactivity and hot executive functions, rather than cool executive functions, changed after 18 months in the present study. This differential association change trajectory may contribute to the identification of cool and hot executive functions related to developmental psychopathology, particularly psychopathological symptoms associated with hot executive functions such as externalizing behavioural problems and substance abuse (Kim et al., 2013; Woltering et al., 2016; Yang et al., 2022).

Our study had several limitations. First, the findings of the present study were obtained in terms of social stress induced by a public speaking task and cool and hot executive functions operated by the Flanker and Emotional Stroop task, respectively, in Chinese junior school students. Whether these findings could be extended to other types of stressors, such as mental arithmetic tasks and other cool and hot executive function tasks, such as the GO/No-Go task and the delay-discounting task, for all children or clinical samples needs to be further explored. Second, the findings of cardiovascular reactivity induced by the speech task may be affected by speaking style, including sound size, and speaking rate. Future studies need to retest these findings by ruling out these potential impacts and further explore the specific associations of parasympathetic and sympathetic activity with cool and hot executive functions. Third, environmental factors, such as home adversity, schooling environment, and the context of the COVID-19 epidemic, were not controlled; thus, whether the findings could be extended to the daily life background needs to be further examined.

In conclusion, the present study revealed that cardiovascular reactivity to a structured social challenge was quadratically associated with baseline cool executive functions and 18 months later hot executive functions among Chinese early adolescents. Specifically, adolescents with moderate to high cardiovascular stress reactivity exhibited better performance of cool executive functions, and better performance of hot executive functions with development, whereas adolescents with very high or very low cardiovascular stress reactivity exhibited worse performance in cool and hot executive functions.

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Competing interests. None.

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