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Association Between Heart Rate Variability and Executive Function Performance: A Cross-Sectional Study in Adult Population

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Abstract

The present study aimed at investigating the association between short-term heart rate variability and executive function performance in two groups of the adult population, that is, young adults and middle-aged adults. The influence of physical activity on heart rate variability and executive performance was also analyzed. A cross-sectional study was conducted on 143 adults; 65 middle-aged adults and 78 young adults. Each participant's heart rate variability was recorded during the ideal state, during the executive function task and recovery state. The executive function tests included the Delayed Matching of Sample (DMS), Spatial Working Memory (SWM) and Multitasking Test (MTT) on the Cambridge Neuropsychological Test Automated Battery (CANTAB). Physical activity levels were reported through IPAQ. Results revealed resting HRV indicator, RMSSD was able to predict correct scores in DMS, error rates in SWM, and reaction latencies in MTT in the adult population, and adults with high HRV performed better in the tests. Middle-aged adults demonstrated high sympathetic activity at rest, and reactivity of HRV was seen maximum during the MTT task. Young adults showed higher sympathetic activation to imposed demands of multitasking. Physical activity was able to predict executive scores and resting HRV. HRV was found to be associated with executive function performance in the adult population.

Keywords: executive function; neuropsychological tests; heart rate variability; autonomic function; aging; middle-aged

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Introduction

An individual's ability to engage in goal-directed behavior using creative problem-solving, behavior modification in response to environmental changes, the generation of strategies for complex actions, and the capacity to suppress prepotent behavioral and emotional responses are referred to collectively as executive function (EF; Suchy, 2009; Suchy, 2015; Williams et al., 2019).

EF is controlled by frontal lobes and related brain networks. The area of the prefrontal lobe, in particular, the dorsolateral prefrontal cortex (DLPFC) and the cingulate cortex (e.g., the anterior cingulate) have been related to the cognitive aspects of EF (Raaz, 2000; Reuter-Lorenz, 2000).

The autonomic nervous system (ANS) is responsible for regulating visceral functions through the sympathetic and parasympathetic branches which act antagonistically to preserve a dynamic equilibrium of vital functions. In the cardiovascular system this nonstationary balance results in the fluctuation between intervals of consecutive heartbeats, which is heart rate variability (HRV; Xhyheri et al., 2012). HRV is a marker of cardiac autonomic function and involves the interaction of activity from the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS; Frewen et al., 2013). ANS function is also controlled by cortical circuits located in the prefrontal cortex, the anterior cingulate gyrus, the orbitofrontal cortex, and the amygdala (Critchley, 2009; Parasuraman & Jiang, 2012).

The prefrontal cortex (PFC), which is most frequently active during tasks that require EF, is also involved in the modulation of autonomic activity. Studies on both humans and nonhuman animals have established that a network of higher brain regions that connect directly and indirectly to autonomic motor circuits influence heart regulation by the SNS and PNS (Ter Horst & Postema, 1997). The resting measures of HRV reflect the interaction of these higher and lower mechanisms, or the effectiveness of central-peripheral neural feedback (Thayer & Lane, 2000).

Individual differences in resting HRV can be used to predict cognitive performance in tasks challenging PFC (Thayer et al., 2009). A systematic review highlighted the influence of HRV, as a physiological correlate for ANS, on cognitive functions like global cognition, memory, language, attention, visuospatial skills, and processing speed, as well as EF. However, it was emphasized that a lack of understanding still exists regarding the association between EF and HRV; hence, more research was required (Forte et al., 2019).

Literature has shown a correlation between cognitive function and HRV (Forte et al., 2019; Grässler, Hökelmann, et al., 2020). Studies have been conducted investigating age-related effects on cardiac autonomic control by HRV in two spectrums of age; that is, young adults (in the age range of 18 to 30 years) and older adults (in the age range of 51 to 75 years) at resting state, during cognitive tasks, and in a recovery period after the cognitive testing (Capuana et al., 2012; Grässler, Dordevic, et al., 2021; Schapkin et al., 2012). However, the middle ages (adults in the age range of 40 to 60 years) is largely an unexplored age group where deterioration in both EF (Ferguson et al., 2021) as well as HRV (Britton, Shipley, et al., 2007) is observed.

Due to inconsistent findings regarding the middle-aged population in the existing literature (Britton, Singh-Manoux, et al., 2008; Kimhy et al., 2013; Mathewson et al., 2010; Zeki Al Hazzouri et al., 2018), there is a need to establish the relationship between autonomic function and EF abilities. The present study was planned with aim of determining the relationship between HRV and EF abilities in the middle-aged population. As many studies have confirmed the influence of HRV on EF abilities in young adults (Canabarro et al., 2017; Hansen et al., 2003; Luque-Casado et al., 2016), young adults were also examined in the study for comparison.

In order to make predictions regarding parasympathetic activity, all aspects of cardiac vagal control adaptability need to be integrated (i.e., resting, reactivity, and recovery HRV in response to cognitive tasks). Reactivity represents the transition between a resting state and a cognitive task (Laborde et al., 2018). As a result, many researchers have tried to analyze the changes in HRV with the varying mental workload. However, in all of the studies only a few aspects of EF were investigated, like attentional biases towards affective or highly salient information (Mathewson et al., 2010), attention (Duschek et al., 2009), working memory, and sustained attention (Hansen et al., 2003; Luque-Casado et al., 2016). These studies found HRV sensitive to task demands of different cognitive domains. But this research mostly focused on a single aspect of EF through a limited neuropsychological test. In the present study, Cambridge Neuropsychological Test Automated Battery (CANTAB), a fair neuropsychological validated and reliable computerized test battery was used to assess cognitive function (Green et al., 2019; Robbins et al., 1994). Some of the extensive subsets of CANTAB which allow measuring various cognitive domains tests for EF were employed.

The present study aimed to identify if resting HRV parameters were able to predict EF task scores. Also, we planned to investigate the effects of age group and condition (resting state, during the cognitive tasks, and in a recovery phase after the cognitive testing) on cardiac autonomic control. For this purpose, the HRV of young (YA) and middle-aged adults (MA) were recorded before, during, and after three different EF tests: Delayed Matching of Sample (DMS) for measuring short-term memory, Spatial Working Memory (SWM) for measuring visuospatial working memory, and Multitasking Test (MTT). Since physical activity levels are known to influence HRV levels (Melo et al., 2005), the physical activity levels of individuals were also taken into consideration and their influence on autonomic parameters and EF task was also analyzed.

As per previous findings, it was hypothesized that individuals with high resting parasympathetic activity would have better EF performance (Colzato et al., 2018; Frewen et al., 2013; Hansen et al., 2003; Stenfors et al., 2016). As HRV declines with increasing age, we expected lower resting HRV in MA compared to YA (Abhishekh et al., 2013).

Interpretation of HRV during cognitive tasks and HRV reactivity is more challenging compared to the interpretation of HRV obtained at resting state as it depends on the task difficulty (Laborde et al., 2018). We assumed lower EF capacities in MA compared to YA, and thus a higher mental workload for MA compared to YA resulting in more sympathetic activation with respect to the high cognitive load (Mathewson et al., 2010). We also expected individuals with high physical activity levels will influence their HRV levels (Melo et al., 2005).

Methodology

Participants

One hundred forty-eight adults, 67 MA and 81 YA from Guru Nanak Dev University, voluntarily took part in the study. Advertisements posted on notice boards throughout the administrative and academic blocks invited volunteers for the study from those who were either studying, working, or living on the university campus. The inclusion criteria for recruiting the subjects were as follows: (a) participants in the age group of 40 to 60 years were included in the MA group; (b) participants in the age group of 21 to 30 years were included in the YA group; (c) participants who had completed formal education up to class 12; (d) participants who were able to understand the English language; (e) participants who scored above 26 on the Mini-Mental State Examination (MMSE); and (f) participants who were willing to volunteer for the study.

Subjects were excluded under the following criteria: (a) obesity [body mass index (BMI) > 30 kg/m2], (b) any known case of neurological and psychiatric diseases, (c) any terminal disease, or (d) alcohol abuse or dependence in the last 2 years.

Participants maintained a regular sleep cycle a day before the study and refrained from consuming stimulating substances or engaging in strenuous physical activity on the study day in order to participate. The experiment received the University Ethics Committee's approval and adhered to the moral guidelines outlined in the Declaration of Helsinki. Before the experiment began, participants read and signed an informed consent declaration. Additionally, they were made aware of their freedom to withdraw from the study at any point.

Apparatus: Measurement of Executive Function With CANTAB

All participants were seated at a comfortable seat height and handed the CANTAB iPad (Cambridge Cognition, 2006) to carry out the EF test by placing responses on the touch screen. Each test began with practice items at a basic level.

1. Delayed Matching of Sample (DMS) assesses both simultaneous and short-term visual memory. It is a four-choice recognition test of abstract patterns that share color or pattern with distractors. The outcome variables were (a) the percentage of total correct responses, which measures the total number of trials in which a correct selection was made in the subject's first response (DMSTC); (b) the percentage of correct responses (all delays), which reports the percentage of correct responses when the target and the distractors were presented after the stimulus had been hidden, with delays of 0 ms, 4000 ms, and 12000 ms (DMSTCAD); (c) the mean latency between the presentation of the response stimuli options and the subject selecting the correct box on their first attempt in simultaneous and all delays trials (DMSML); (d) the mean latency between the presentation of the response stimuli options and the subject selecting the correct box on trials containing a delay between target and response stimuli presentation (DMSMLAD); (e) the mean latency between the presentation of the response stimuli options and the subject selecting the correct box on their first attempt for trials containing a simultaneous presentation of target and response stimuli (DMSMLS); (f) the mean latency between the presentation of the response stimuli options and the subject selecting the correct box on their first attempt for trials containing a 12-s delay (DMSML12); and (g) the probability of an error occurring when the previous trial was responded to incorrectly (DMSPEGC).

2. Spatial Working Memory (SWM) is a self-ordered search test that assesses nonverbal working memory. Participants were asked to search through several colored boxes presented on the screen to find yellow tokens hidden inside. Each box contained only one token per trial. With each stage, the number of colored boxes kept on increasing. Searching a box more than once during a sequence resulted in within errors, and returning to an emptied box resulted in between errors. A double error could be categorized as both a within and a between error. The key outcome variables included (a) the total number of times a box is selected that is certain not to contain a token and therefore should not have been visited by the subject (i.e., between errors + within errors − double errors), calculated across all assessed 4-, 6-, and 8-token trials (SWMTE); (b) the number of times the subject incorrectly revisits a box in which a token has previously been found, calculated across all assessed 4-, 6-, and 8-token trials (SWMBE); (c) the number of times a box is selected that is certain not to contain a token and therefore should not have been visited by the subject in trials with 12 tokens (SWMTE12); (d) the number of times the subject revisits a box in which a token has previously been found in trials with 12 tokens (SWMBE12); (e) the strategy score for the 6-box stage of the task only, calculated based on the number of times a subject begins a new search pattern from the same box they started with previously (SWMS6); and (f) the strategy score calculated across assessed trials with 6 tokens or more (SWMSX).

3. Multitasking Test (MTT) measures the participant's ability to use multiple sources of potentially conflicting information to guide behavior and to ignore task-irrelevant information, posing a Stroop-like effect. An arrow was presented on either the left or right side of the screen, indicating the side of the arrow, or the arrow can also point either left or right, indicating the direction of the arrow. A cue was given at the top of the screen before each trial to suggest whether the participant should press the direction of the arrow (in the first set of trials), followed by the side of the arrow (in the second set of trials) using two response pads located on the left and right sides of the bottom of the screen during the single task stage. In the multitask stage, the participant had to respond based on the cue presented at the top of the screen, which could either be the side of the arrow or the direction of the arrow. As the complexity of the task grew in contrast to a single task, the multitasking task imposed a higher cognitive demand. Furthermore, in the multitasking stage, some of the task trials exhibited congruent stimuli (e.g., the arrow on the left side is pointing to the left side of the screen) or incongruent stimuli (e.g., the arrow on the left side is pointing on the right side of the screen). The cognitive demands on incongruent trials were higher than on congruent ones. The major outcomes of this task were (a) the number of trials for which the outcome was a correct response (MTTC); (b) the mean latency of response calculated across all correct trials (MTTML); (c) the mean latency of response in assessed blocks in which both side and direction rules were used (MTTMLMT); (d) the mean latency of response in assessed blocks in which a single, either direction or side, rule was used (MTTMLST); (e) the mean latency of response in congruent trails on all assessed blocks (MTTMLC); (f) the mean latency of response in incongruent trials on all assessed blocks (MTTLNOM); (g) the difference between mean latency of response on the trails that were congruent versus the trails that were incongruent (MTTICOST); and (h) the difference between mean latency of response during assessed blocks in which both rules were used versus assessed blocks in which single rules were used (MTTMTCM).

IPAQ questionnaire

The 27-item long-form IPAQ was used to measure domain-specific physical activity for each intensity group, including physical activity at work, home, during transit, during leisure, and for the duration of inactive hours. Adults from the Indian Subcontinent have also demonstrated modest construct validity and test–retest reliability for items of the modified IPAQ-LF (Wani & Nabi, 2020).

Measurement of Heart Rate Variability

Participants were fitted with an EQ02 (Equivital EQ02, Hidalgo, U.K), a wearable Lycra sensor belt with a fitted pocket for a Bluetooth device measuring multiple physiological parameters such as heart rate, HRV, respiratory rate mean, ECG, and chest expansion mean. A polar wristwatch was also worn by the participants for measuring the saturation of oxygen (Sp02) levels. Data acquisition and postprocessing of the recorded data were conducted using the LabChart software. The processed data was further analyzed in another software, the Kubios HRV software (v.3.0.0, HRV analysis, University of Eastern Finland). It includes a modified algorithm for detecting QRS as well as tools for noise reduction, trend removal, and analysis sample selection (Brennan et al., 2001).

HRV indices obtained included mean RR interval, root mean square of the successive differences (RMSSD), standard deviations of RR intervals (SDNN index), and PNS index that evaluated the activity of the PNS. HRV indices for sympathetic activity included mean HR, SNS index, and stress index (SI) were the referred parameters. The PNS index computed in Kubios HRV software is based on Mean RR, RMSSD, and HF power; and the SNS index is based on the mean heart rate, SI, and LF power (Cakir et al., 2019). SI in the Kubios software is computed by calculating the square root of Baevskey's stress index formula. This formula was developed using a histogram based on the 50 ms interval mapping of the RR intervals to calculate the stress levels (Baevsky & Chernikova, 2017).

Procedure

Participants were asked to sit down comfortably on a chair with closed eyes after the EQ02 wearable device to measure HRV was strapped on. A resting HRV was measured for a duration of 5 min. The seated participants were then handed the CANTAB iPad to carry out the EF test by placing responses on a touch screen. Simultaneously, HRV data was recorded while each participant performed EF tests (DMS, SWM, and MTT). Further, recovery data of HRV for a span of 5 min was recorded, once all the EF tests were completed. At the beginning of each EF task, all the participants had a familiarization period. They received verbal video graphic instructions and, after that, each task incorporated a demonstration before the beginning of the task. The sequence of the cognitive task was kept random to avoid any bias in the performance of the tests.

The time duration of the start and end of each task was noted for further analysis of HRV. During the experiment, the participants were seated in a well-illuminated room and isolated from external noise. Comfortable temperature (17.9 ± 0.5 ˚C) and relative humidity (64.9 ± 6.75%) values were maintained throughout the experimental session.

Statistical Analysis

A priori power analysis was conducted before the study (G*power), which estimated that the minimal sample size needed was 130 participants (effect size = 0.15, α err prob = 0.05, power $1-\beta$ err prob = 0.90). Five participants were excluded during the time of analysis including two YA and two MA due to incomplete experimental procedure (four participants) and a data outlier (one participant).

HRV parameters were non-normally distributed, namely SDNN, RMSSD, and SI; therefore, they were converted into logarithmic values (lnRMSSD, lnSDNN, and lnSI, respectively). Pearson analysis and linear regression were used to investigate the possible correlations and interdependence with EF test scores as the outcome variable and resting HRV parameters as the predictor variable. EF scores were compared amongst participants with high HRV versus low HRV using a *t*-test. An independent *t*-test was also applied for the comparison of HRV indices according to age at rest, during EF tests, and during recovery. In order to analyze changes in HRV across each EF test and with its increasing complexity from the resting state, a repeated measure ANOVA analysis was performed. Therefore, recorded HRV data was taken at different time points (i.e., during resting state, during DMS, during SWM, during MTT-single task, during MTT-multitask task, and during recovery). A mixed model ANOVA design was performed to analyze interactions of independent variables in the study (i.e., age, the difficulty of task, and gender) on the dependent variable of HRV. A regression analysis was also applied to investigate EF test scores and HRV indices as the outcome variable and physical activity levels (IPAQ METS) as the predictor variable.

Results

Out of 148 participants, 143 were suitable for analysis. Table 1 shows their descriptive characteristics.

Table 1
Descriptive Statistics of the Population (N = 143)

Age group (years)	Middle aged adults (n = 65, mean age = 45.5 ± 5.3 years) Young adults (n = 78, mean age = 24.1 ± 2.1 years)
Gender	Males (n = 69, mean age = 37.4 ± 13.2 years) Females (n = 74, mean age = 33.2 ± 12.1 years)
IPAQ METS (MET/week)	Mean: 4813.8 ± 232.8 Minimum: 677 Maximum: 12552

Relationship of EF Scores With Resting HRV

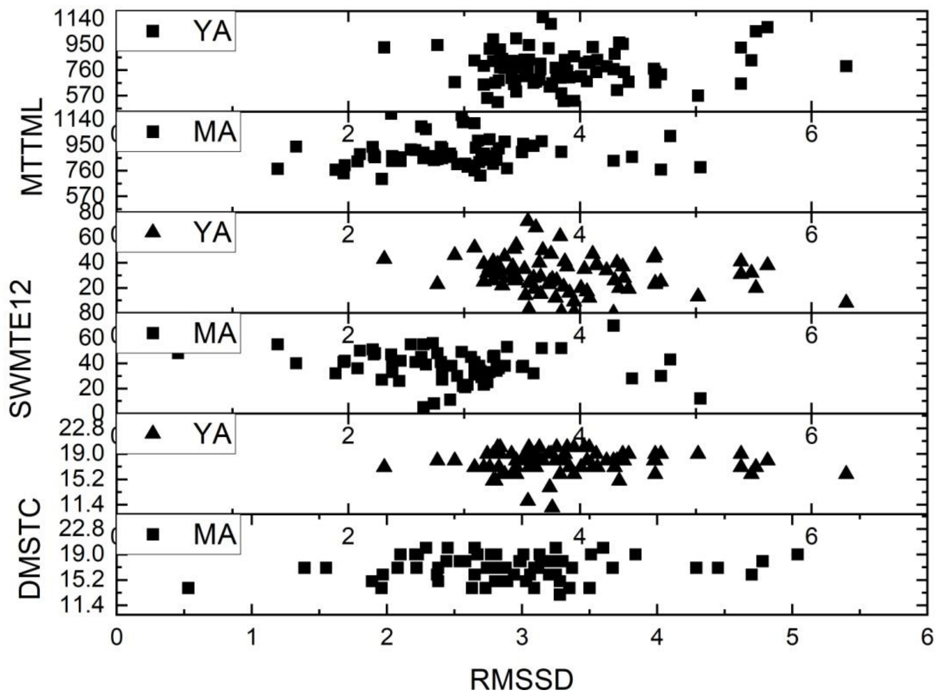
As multicollinearity was found in the parasympathetic indicators of HRV, we chose to represent only lnRMSSD. Logarithmic values of RMSSD were able to predict key parameters in EF tests. In the DMS task, regression trends were found in DMS correct score at R^2 = 0.03, F(1,142) = 3.54, p = .06. In the SWM task, SWM total errors at the 12-token stage at R^2 = 0.001, F(1,142) = 13.16, p < .001; and SWM between errors at the 12-token stage at R^2 = 0.001, F(1,142) = 14.53, p < .001. In the MTT task, overall reaction latency at R^2 = 0.007, F(1,142) = 6.14, p < .05; reaction latency during multitask at R^2 = 0.001, F(1,142) = 9.39, p < .05; reaction latency during the congruent task at R^2 = 0.006, F(1,142) = 6.5, p < .05; reaction latency during the incongruent task at R^2 = 0.011, F(1,142) = 5.29, p < .05 and multitasking cost at R^2 = 0.009, F(1,142) = 5.78, p < .05 (refer to Table 2, Figure 1).

Table 2
Regression Analysis of Resting LnRMSSD as Predictor Variable (N = 143)

Outcome measure	Correlation Coefficient R	p value	Adjusted R^2	Degree of freedoms	F stats	p value
DMS						
DMSTC	0.15	.03*	0.018	(1,142)	3.54	.06*
DMSML	−0.07	.21	−0.002	(1,142)	0.67	.41
DMSMLAD	−0.06	.21	−0.003	(1,142)	0.61	.43
DMSMLS	−0.05	.24	−0.004	(1,142)	0.48	.49
DMSPEGC	−0.11	.08	0.007	(1,142)	1.944	.16
SWM						
SWMTE468	−0.11	.11	0.004	(1,142)	1.57	.21
SWMBE468	−0.09	.11	0.003	(1,142)	1.40	.23
SWMTE12	−0.29	.001**	0.079	(1,142)	13.16	.001**
SWMBE12	−0.31	.001**	0.087	(1,142)	14.53	.001**
SWMS	−0.07	.18	−0.001	(1,142)	0.79	.37
SWMSX	−0.10	.11	0.003	(1,142)	1.48	.22
MTT						
MTTC	0.06	.23	−0.003	(1,142)	0.55	.45
MTTML	−0.20	.007*	0.035	(1,142)	6.14	.014*
MTTMLMT	−0.25	.001*	0.050	(1,142)	9.39	.003*
MTTMLST	−0.12	.07	0.008	(1,142)	2.12	.14
MTTMLC	−0.21	.006*	0.037	(1,142)	6.50	.012*
MTTLNOM	−0.19	.011*	0.029	(1,142)	5.29	.023*
MTTICOST	0.04	.30	−0.005	(1,142)	0.27	.60
MTTMTCM	−0.19	.009*	0.033	(1,142)	5.78	.017*

Note. Refer to Methodology section for explanation of acronyms; $*p < .05$; $** p < .001$.

Figure 1. *Scatter Plot Demonstrating Key Parameters of EF Tests in Relation to Resting lnRMSSD Levels in YA And MA.*



Since lnRMSSD was able to predict EF scores, its median value was calculated to classify the population into high HRV versus low HRV group, and EF scores were compared similarly to a previous study (Hansen et al., 2003). A median value of 3.37 was obtained; the high HRV group was comprised of 67 individuals (8 MA, 59 YA), and the low HRV group was comprised of 76 individuals (57 MA, 19 YA). In comparison, it was found that the high HRV group performed significantly well in all EF tasks with more correct scores (DMSTC, $t = 2.1$, $p < .05$), lesser errors (SWMTE12, $t = -2.69$, $p < .05$; SWMBE12, $t = -3.24$, $p < .05$), and faster processing speed during the tasks (MTTML, $t = -3.88$, $p < .001$, MTTMLMT, $t = -4.35$, $p < .001$; MTTMLST, $t = -2.74$, $p < .05$; MTTMLC, $t = -3.81$, $p < .001$; MTTMLNOM, $t = -3.76$, $p < .001$ and MTTMTCM, $t = -2.52$, $p < .05$) in comparison to their counterparts with low HRV (refer to Table 3).

Table 3
Comparison of EF Scores Between High HRV and Low HRV Adults

EF test parameters	High HRV ($n = 67$)	Low HRV ($n = 76$)	t value	p value
DMS				
DMSTC	17.6 ± 1.7	17.1 ± 1.8	2.1	.037*
SWM				
SWMTE12	30.4 ± 16.2	36.7 ± 10.7	−2.69	.008*
SWMBE12	27.6 ± 14.9	34.7 ± 10.3	−3.24	.002*

Table 3
Comparison of EF Scores Between High HRV and Low HRV Adults

EF test parameters	High HRV (n = 67)	Low HRV (n = 76)	t value	p value
MTT				
MTTC	151.2 ± 14.4	147.3 ± 18.5	1.39	.16
MTTML	784.7 ± 134.1	868.5 ± 1622.6	−3.88	.001**
MTTMLMT	876.2 ± 146.6	984.7 ± 150.9	−4.35	.001**
MTTMLST	693.5 ± 139.2	754.6 ± 125.3	−2.74	.007*
MTTMLC	762.8 ± 138.8	847.3 ± 123.8	−3.81	.001**
MTTLNOM	806.6 ± 133.1	889.9 ± 131	−3.76	.001**
MTTMTCM	182.7 ± 99.1	230.1 ± 126.4	−2.52	.013*

Note. Mean, standard deviation, and t-test values of the high HRV and low HRV group; *$p < .05$; ** $p < .001$. Refer to Methodology section for explanation of acronyms.

Changes in HRV During the EF Tests

The sympathetic activity was significantly high (lnSI, $t = 8.81$, $p < .001$; SNS index, $t = 4.71$, $p < .001$), and parasympathetic activity was significantly low in MA at resting (lnSDNN, $t = −7.41$, $p < .001$; lnRMSSD, $t = −7.97$, $p < .001$; PNS index, $t = −3.79$, $p < .001$) in comparison to YA. During EF tasks, sympathetic activity was raised in both groups but was higher in MA in comparison to YA, with the highest peak seen during MTT multitask. Significantly early recovery was observed in YA in comparison to MA with higher parasympathetic indicators (lnSDNN, $t = −5.93$, $p < .001$; lnRMSSD, $t = −6.96$, $p < .001$; PNS index, $t = −3.80$, $p < .001$).

As MTT multitask was found to be the most challenging task across the EF test, differences in percentage change of HRV parameters (resting value of HRV parameter − the value of HRV parameter during MTT multitask / resting value of HRV parameter) were also investigated. Mann Whitney U test was used for the comparison of percentage differences between MA and YA. It was found that the percentage change in stress index was significantly higher in YA in comparison to MA (refer to Table 4).

Table 4
Difference in Percentage Change in HRV Indices in MA and YA

% Change	MA (n = 65)	YA (n = 78)	p value
lnSDNN	0.015 ± 0.52	0.074 ± 0.19	.72
lnRMSSD	−0.078 ± 0.9	0.075 ± 0.17	.98
SI	−0.04 ± 0.16	−0.17 ± 0.39	.01*
PNS index	−0.34 ± 2.18	0.17 ± 2.84	.30
SNS index	−0.41 ± 1.7	0.17 ± 5.74	.67

The repeated-measures ANOVA with the within-participants factors of EF tasks showed statistical significance reached in all HRV indices namely in RR interval, $F(1,141) = 29.9$, $p < .001$, η $partial^2$ = 0.17; mean HR, $F(1,141) = 21.9$, $p < .001$, η $partial^2$ = 0.13; lnSDNN, $F(1,141) = 9.12$, $p < .001$, η $partial^2$ = 0.06; lnRMSSD interval, $F(1,141) = 5.82$, $p < .001$, η $partial^2$ = 0.04; lnStress index, $F(1,141) = 18.5$, $p < .001$, η $partial^2$ = 0.11; PNS index, $F(1,141) = 15.53$, $p < .001$, η $partial^2$ = 0.09; SNS index, $F(1,141) = 27.2$, $p < .001$, η $partial^2$ = 0.16. All parasympathetic indexes showed the lowest values in the MTT Multitask, all $p \leq .01$. All sympathetic indexes showed the highest values in the MTT Multitask, $p < .005$. The between-subject effects, as per age group, revealed significantly different HRV indices in response to the same EF tasks, lnSDNN, $F(1,141) = 78.9$, $p < .001$, $\eta\ partial^2 = 0.35$; lnRMSSD interval, $F(1,141) = 67.3$, $p < .001$, η partial^2 = 0.32; lnStress index, $F(1,141) = 97.9$, $p < .001$, $\eta\ partial^2 = 0.41$; PNS index, $F(1,141) = 12.38$, $p < .001$, $\eta\ partial^2 = 0.8$; SNS index, $F(1,141) = 22.4$, $p < .001$, $\eta\ partial^2 = 0.13$. Parameters indicating sympathetic activity were found to be higher and parameters indicating parasympathetic activity were lower in MA in response to EF tasks (Refer to Table 5 and Figure 2).

Table 5
Repeated Measure ANOVA Analysis

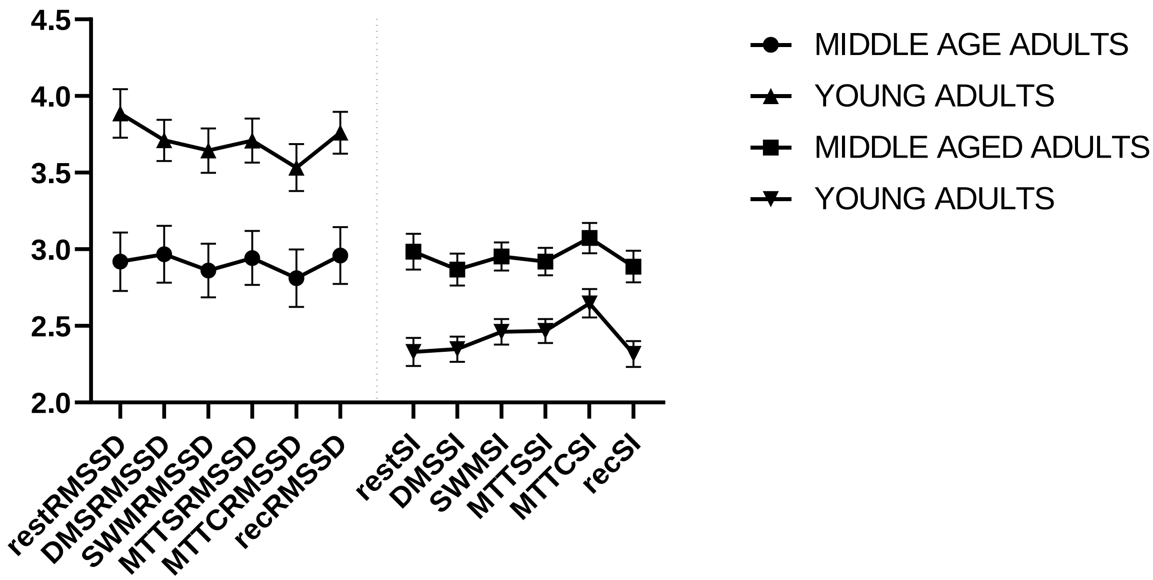
HRV indices	Within subject's effect	Between subject's effect	Pair wise significance
RR interval	29.91; (1,141); 0.001*; 17.5%	2.23; (1,141); 0.13; 1%	Level 1 vs. Level 2 Level 1 vs. Level 3 Level 1 vs. Level 4 Level 1 vs. Level 5 Level 2 vs. Level 6 Level 3 vs. Level 5 Level 3 vs. Level 6 Level 4 vs. Level 5 Level 4 vs. Level 6 Level 5 vs. Level 6
Mean HR	21.91; (1,141); 0.001*; 13.5%	1.43; (1,141); 0.23; 1%	Level 1 vs. Level 2 Level 1 vs. Level 5 Level 2 vs. Level 6 Level 3 vs. Level 5 Level 3 vs. Level 6 Level 4 vs. Level 5 Level 4 vs. Level 6 Level 5 vs. Level 6
lnSDNN	9.12; (1,141); 0.001*; 6.1%	78.9; (1,141); 0.001*; 35%	Level 1 vs. Level 5 Level 2 vs. Level 5 Level 3 vs. Level 5 Level 4 vs. Level 5 Level 4 vs. Level 6 Level 5 vs. Level 6
lnRMSSD	5.82; (1,141); 0.001*; 4%	67.37; (1,141); 0.001*; 32%	Level 1 vs. Level 5 Level 2 vs. Level 5 Level 4 vs. Level 5 Level 5 vs. Level 6

Table 5
Repeated Measure ANOVA Analysis

HRV indices	Within subject's effect	Between subject's effect	Pair wise significance
lnSI	18.59; (1,141); 0.001*; 11%	97.96; (1,141); 0.001*; 41%	Level 1 vs. Level 5 Level 2 vs. Level 3 Level 2 vs. Level 4 Level 2 vs. Level 5 Level 3 vs. Level 5 Level 3 vs. Level 6 Level 4 vs. Level 5 Level 4 vs. Level 6 Level 5 vs. Level 6
PNS INDEX	15.53; (1,141); 0.001*; 9.9%	12.38; (1,141); 0.001*; 8.1%	Level 1 vs. Level 2 Level 1 vs. Level 3 Level 1 vs. Level 4 Level 1 vs. Level 5 Level 2 vs. Level 6 Level 3 vs. Level 4 Level 3 vs. Level 6 Level 4 vs. Level 5 Level 5 vs. Level 6
SNS INDEX	27.23; (1,141); 0.001*; 16.2%	22.44; (1,141); 0.001*; 13.7%	Level 1 vs. Level 5 Level 2 vs. Level 5 Level 2 vs. Level 6 Level 3 vs. Level 5 Level 3 vs. Level 6 Level 4 vs. Level 5 Level 4 vs. Level 6 Level 5 vs. Level 6

Note. Level 1: Resting; Level 2: DMS; Level 3: SWM; Level 4: MTT single task; Level 5: MTT multitask; Level 6: Recovery.

Figure 2. *Parasympathetic and Sympathetic Parameter Changes Across EF Tests.*



Note. Within subject difference in lnRMSSD values at $F(1,141) = 5.82$, 0.001* and between subject effects at $F(1,141) = 67.37$, 0.001*. Within subject difference in stress index at $F(1,141) = 18.59$, 0.001* and between subject effects at $F(1,141) = 97.96$, 0.001*.

Mixed model design ANOVA was applied to analyze changes in HRV with respect to age (MA and YA), the difficulty of condition (MTT single task and MTT multitask), and gender. It was found that lRMSSD was significantly low ($F = 75.3$, $p < .001$) and stress index was significantly high ($F = 90.2$, $p < .001$) in MA in comparison to YA with the MTT task. Parasympathetic activity indicated by lRMSSD and sympathetic activity indicated by Stress index were also inversely changed as the complexity of the task increased ($F = 4.01$, $p < .05$; $F = 14.2$, $p < .001$ respectively). It is interesting to note that gender differences were also visible where high parasympathetic activation in females during the MTT task ($F = 9.02$, $p < .05$).

Association of Physical Activity Levels With EF and HRV

Physical activity levels were able to predict DMS correct score at $R^2 = 0.029$, $F(1,142) = 4.25$, $p = .04$ and MTT correct score at $R^2 = 0.021$, $F(1,142) = 3.09$, $p < .001$, however not in SWM task. In relation to resting HRV parameters, physical activity levels were correlated with mean RR, $r = 0.14$, $p = .04$ and mean HR, $r = -0.15$, $p = .03$. A correlation was also found with recovery HRV parameters, with mean RR, $r = 0.21$, $p = .004$ and mean HR, $r = -0.24$, $p = .002$. Regression analysis revealed physical activity levels predicted recovery HRV parameters namely mean RR at $R^2 = 0.048$, $F(1,142) = 7.04$, $p = .009$ and mean HR at $R^2 = 0.06$, $F(1,142) = 9.05$, $p = .003$.

Discussion

The present study investigated the relationship between the autonomic function via short-term HRV assessment and executive performance via the administration of a neuropsychological test battery, CANTAB in MA and YA. In order to meet the broader aim, the study was further classified into three objectives: (a) association of EF task scores with resting HRV parameters; (b) analyzing HRV reactivity in response to three different EF tests: DMS for measuring short-term memory, SWM for measuring visuospatial working memory, and MTT; and (c) determining the role of physical activity in influencing autonomic function and EF of the adult population. In the forthcoming sections, we discuss each objective separately.

Association of EF Task Scores With Resting HRV Parameters

It was found that individuals with higher resting parasympathetic indicator (i.e., RMSSD in the adult population) had better EF in comparison to their counterparts with lower parasympathetic tone. Individuals with lnRMSSD values ranging from 0.53

to 3.37 were considered lower parasympathetic activity, and those with higher values ranging above 3.37 to 6.3 were considered high parasympathetic activity. DMS correct score was higher, SWM errors, and reaction latencies during the MTT task were lower, indicating better EF performance in individuals with higher resting lRMSSD, a major indicator of parasympathetic activity. Our findings are supported by previous literature where higher RMSSD, a reflection of the vagal tone (Shaffer & Ginsberg, 2017), has been found to be associated with better cognitive performance (Hansen et al., 2003; Stenfors et al., 2016).

Studies have been conducted to find the relationship between HRV and memory functionality (Frewen et al., 2013; Gillie et al., 2014; Shah et al., 2011; Zeki Al Hazzouri et al., 2014). Although these studies have focused on long-term memory (Gillie et al., 2014) or verbal memory (Frewen et al., 2013; Shah et al., 2011). In the present study, the DMS task was used as a task which is specifically designed to challenge short-term memory at various levels of the task; spontaneously, immediate recall, at a 4-s delay after the abstract pattern is shown, and finally at a 12-s delay. We found that subjects with high HRV demonstrated better performance in short-term memory task with more correct scores at all levels tested.

The relationship between HRV and working memory, though investigated previously, has used different tasks by Hansen et al. (2003) and Frewen et al. (2013), with differing results in both. Hansen et al. (2003) showed an association of high HRV with correct responses in numerical-based working memory task, whereas Frewen et al. (2013) found no association in global cognitive function, comprising visuospatial function as one of the components. Our study differs from the previous studies in the fact that this is the first study to analyze the visuospatial component of working memory through SWM task. The task required the individual to search for hidden yellow tokens through several colored boxes, with the yellow token appearing in all the boxes once during the task, with the chances of committing an error increasing with each ascending stage (4-, 6-, 8-, and 12-token stage). It is intriguing to note that individuals with high HRV were able to demonstrate high visuospatial working memory in the advanced stage of the task (at the 12-token stage) with lesser errors in comparison to their counterparts with low HRV. Thus, it seems that the influence of HRV on measures of SWM may depend on the perception of the task difficulty with visuospatial tasks and numerical tasks requiring more composure for task performance.

During the performance of the MTT task, a computerized version of the spatial Stroop task (Sahakian et al., 1988), lower reaction latencies were exhibited by individuals with high HRV. A similar finding was reported by Mathewson et al. (2010), suggesting vagal cardiac control was associated with faster response times for a group of 81 healthy adults aged 17–55 performing pictorial Stroop task. Another cohort study conducted on middle-aged adults (CARDIA) demonstrated a significant correlation between higher quartile SDNN and improved EF and processing speed (Zeki Al Hazzouri et al., 2017). Mahinrad et al. (2016) found that individuals with lower HRV performed worse and saw a greater loss in processing speed, independent of cardiovascular risk factors and comorbidities, as part of the Prospective Study of Pravastatin in the Elderly at Risk.

Our findings propose that a higher resting parasympathetic state can ensure better EF performance even in MA despite the deteriorating effect of age seen previously (Hughes et al., 2018; Singh-Manoux et al., 2012). This notion can be validated by the results demonstrating 8 MA in the high HRV group performed significantly better in EF tasks in comparison to the low HRV group which also comprised 19 YA along with 57 MA. Conversely, studies have suggested that cardiovascular risk factors found in early to middle adulthood are associated with poor cognitive performance in midlife (Anstey et al., 2014; Yaffe et al., 2014). Therefore, it can be perceived that maintaining a high parasympathetic state during MA not only lowers the risk of cardiovascular morbidity and mortality but also contributes to better executive performance. Indulging in activities like physical activity and meditation can benefit middle-aged adults in achieving higher vagal tone and consequently improved executive functioning.

HRV Reactivity in Response to EF Tests

Resting HRV in MA was found to be significantly poor in comparison to YA, proving our hypothesis. It is well established that a decrease in parasympathetic regulation over heart rate poses as a primary mechanism due to which age-related decline in autonomic function is seen (De Meersman & Stein, 2007; Umetani et al., 1998; Zhang, 2007). However, changes in sympathetic activity with age remain unclear (Byrne et al., 1996; Grässler, Dordevic, et al., 2021; Umetani et al., 1998). In the present study stress index, an indicator of sympathetic activity, was found to be significantly higher in MA than in YA. The population of middle-aged individuals included in our study was mostly educated working class; hence, it is a possibility that they were in stress due to their jobs. Job stress has been linked to dementia and cognitive performance as well as CV risk factors and cardiovascular disease (Fishta & Backé, 2015; Jarczok et al., 2013, Theorell et al., 2016). Also, it has been discovered that midlife job stress is a strong predictor of cognitive performance (Andel et al., 2011; Stenfors et al., 2016).

An increase in sympathetic indicators (mean HR, stress index, and SNS) reflected autonomic responsiveness to the demands posed by the EF tests in both groups. These results are in coherence with the neurovisceral integration model proposed by Thayer et al. (2009) which state that both the EF and ANS indexed by HRV are under prefrontal cortical activity; hence, a sympathetic hyperactivation, with consequent prefrontal hypoactivation, would facilitate the disinhibition of the central nucleus of the amygdala (i.e., an adaptive response); the amygdala would promote a decrease in HRV and an increase in heart rate as shown in our study, with decreased HRV as the cognitive demands imposed by EF task increases.

Amongst the EF tests, HRV was the most reactive during the MTT task. Previous findings support performance-related reductions found in autonomic responsiveness in classic color Stroop paradigms (Boutcher & Boutcher, 2006; Delaney & Brodie, 2000; Wright et al., 2007) and pictorial strop task (Mathewson et al., 2010). However, a contradictory finding also exists (Hoshikawa & Yamamoto, 1997). This indicates that HRV does index some forms of executive effort, perhaps those that require assessing a rapid series of discrete stimuli while processing and responding in a speeded manner with a relatively high density of responses (Thayer et al., 2009), as in the case of MTT task in the present study. The remaining EF tests, DMS, and SWM were not a time-based task; therefore, the sympathetic activation was seen but not to higher extents. Byrd et al. (2015) proposed that slower, self-paced cognitive tasks involving multistep responses may require a form of executive functioning not indexed by HRV, which were the task characteristics of DMS and SWM in our study. This infers that HRV suppression is sensitive to a specific form of attentional control requiring vigilance to a rapid change course of stimuli not under the participant's control rather than a largely stationary stimulus where responding is under the participant's control.

MTT task was further classified into MTT single task and MTT multitask and, interestingly, within the task sympathetic activation was higher in response multitask stage in comparison to the single task stage. As task demands alter, HRV is significantly variable and responsive to cognitive processing (Luque-Casado et al., 2016). A novel finding of our study indicated females had better parasympathetic control as the difficulty of task increased in MTT. It is well established that females exhibit a higher vagal and a lower sympathetic modulation than men at resting levels (Agelink et al., 2001; Voss et al., 2015). However, demonstrating higher parasympathetic activity during the MTT task suggests that females were under less stress in handling multitasking stimuli in comparison to males. This maiden finding indicates further research on gender differences during executive performance focusing on all the domains.

It was fascinating to note that even though MTT multitask posed acute mental stress in both of the groups of the population, the percentage change in stress index levels of YA was higher (17%) in comparison to MA (4%). These results affirm the findings of Thayer et al. (2009)**,** suggesting sympathetic activation in response to imposed cognitive demands. The lower percentage change in MA also gives an impression of the poor autonomic flexibility in them in response to higher demands.

Role of Physical Activity in Influencing HRV and Executive Function

Adults with high levels of physical activity demonstrated higher HRV at resting and recovery HRV consistent with the previous literature (Albinet et al., 2010, 2016; Hansen et al., 2003). Association was also found between high levels of physical activity and DMS as well as MTT correct score. Physical activity is known to have a significant positive impact on cognitive function, and in particular EF (Daly et al., 2015; Liu-Ambrose et al., 2010). Since middle-aged population are at risk of declining EF and autonomic dysregulation as a function of age, poor autonomic function may develop due to stress (Dishman et al., 2000), depressive symptoms (Nahshoni et al., 2004), cardiovascular disease risk factors (Yaffe et al., 2014) such as type-2 diabetes (Carnethon et al., 2008), and hypertension (Singh et al., 1998), acting as a precursor to decline in EF abilities in later stages of life. Physical activity can be characterized as having a cardioprotective and brain-protective role in accordance with previous literature (Albinet, Boucard, et al., 2010), and its adoption in middle age is highly recommended.

Limitations of the study include that the cross-sectional design of the study could not allow causal inferences in the longer stages of life between age-related change in autonomic cardiac adjustments and EF tests performance. The population of middle-aged adults included in the study were at clerical or academic posts in the university; hence, we did not anticipate the stress levels of the individuals which could be one of the limitations. Future studies are recommended to include scales to measure stress in the case of working adults.

In summary, the present study showed individuals with high HRV at rest perform well in executive performance, even in middle age. HRV reactivity was highest during the multitasking task in comparison to short-term memory and visuospatial memory abilities. Although middle-aged adults had high sympathetic activity at rest, young adults demonstrated higher sympathetic activation to imposed demands of multitasking and better task performance in comparison to the middle-aged with poor autonomic flexibility. High levels of physical activity might play a role in influencing HRV and consequently EF.

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Author Declaration

The authors declare no conflict of interests. There is no funding to report.

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