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International Journal of Psychophysiology 48 (2003) 263–274
INTERNATIONAL JOURNAL OF PSYCHOPHYSIOLOGY
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Vagal influence on working memory and attention

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Received 18 December 2002; received in revised form 29 December 2002; accepted 15 January 2003

Abstract

The aim of the present study was to investigate the effect of vagal tone on performance during executive and non-executive tasks, using a working memory and a sustained attention test. Reactivity to cognitive tasks was also investigated using heart rate (HR) and heart rate variability (HRV). Fifty-three male sailors from the Royal Norwegian Navy participated in this study. Inter-beat-intervals were recorded continuously for 5 min of baseline, followed by randomized presentation of a working memory test (WMT) based on Baddeley and Hitch's research (1974) and a continuous performance test (CPT). The session ended with a 5-min recovery period. High HRV and low HRV groups were formed based on a median split of the root mean squared successive differences during baseline. The results showed that the high HRV group showed more correct responses than the low HRV group on the WMT. Furthermore, the high HRV group showed faster mean reaction time (mRT), more correct responses and less error, than the low HRV group on the CPT. Follow-up analysis revealed that this was evident only for components of the CPT where executive functions were involved. The analyses of reactivity showed a suppression of HRV and an increase in HR during presentation of cognitive tasks compared to recovery. This was evident for both groups. The present results indicated that high HRV was associated with better performance on tasks involving executive function.

Keywords: Heart rate variability; Working memory; Continuous performance test

1. Introduction

Working memory has been assumed to involve moment to moment updating and rehearsal of information to prolong storage (Logie et al., 1990). Therefore, it can be viewed as a complex system used both for the storage of information and for the computational processing of that information. In that sense, working memory consists of a central control structure called the central executive, characterized by a flexible but limited capacity workspace (Baddeley and Hitch, 1974).

Baddeley (1986) suggested that the central executive is needed in planning future actions, decision-making and trouble-shooting. Executive components control response selection, such as the adoption of an overall strategy or plan, or the utilization of specific attentional inhibitory mechanisms during task performance (Robbins, 1996).

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0167-8760/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0167-8760(03)00073-4

Neural structures underlying executive function, concerned with selection and evaluation, have been assumed to be located in the prefrontal cortical areas of the brain (Luria, 1980). Executive functions are called into action when task demands are non-routine, and one way to test these functions are by tasks that involve aspects like planning, working memory, and selective and sustained attention (Robbins, 1996).

The process of sustained attention refers to an individual's ability to maintain their focus of attention and to remain alert to stimuli over prolonged periods of time (Johnsen et al., 2002). Tasks involving vigilance have come to be regarded as providing 'the fundamental paradigm' for defining sustained attention as a behavioral category (Jerison, 1977). The tasks require direction of attention to one or more sources of information in order to detect and respond to infrequent changes in the nature of the information being presented (Davies and Parasuraman, 1982).

One category of sustained attention tasks is the continuous performance test (CPT) originally developed by Rosvold et al. (1956). This type of test has played an increasing role in the assessment of attentional processes (Baker et al., 1995). One of the characteristics of a CPT is the involvement of higher mental workload levels such as memory search, choice reaction time (CRT), mental arithmetic, time estimation, simple tracking and grammatical reasoning (Warm, 1993). Parasuraman et al. (1987) suggested that the increase in working memory load might be the key factor in perceptual sensitivity or decrement during these tasks. Thus, working memory has been seen as a very general resource, which has played a role in a wide variety of cognitive tasks including sustained attention.

Since CPTs enable us to separate tasks into those involving and not involving executive function, the use of CPT makes it possible to compare the executive functions to the non-executive functions. Thus a generalized influence on performance can be separated from a specific effect related to prefrontal associated working memory performance.

One of the underlying mechanisms that has been associated with the understanding of attentional and memory processes is activity in the cardiovascular system. In the last decade increased attention has been directed to the fluctuation in the inter-beat-interval (IBI) between normal heartbeats. This has been referred to as heart rate variability (HRV). Porges and Raskin (1969) demonstrated that HRV was significantly reduced during sustained attention. The relation between attention and HRV has also been found in infants (Richards and Casey, 1991) and children (Porges, 1974).

More recent studies have related HRV to memory performance, mental workload and attention (Vincent et al., 1996; Middelton et al., 1999; Redondo and Delvalleinclan, 1992; Veltman and Gaillard, 1998; Backs and Seljos, 1994; Ekberg et al., 1995; Schellekens et al., 2000). Using a continuous memory task, Backs and Seljos (1994) found that as memory load increased, good performers had a small heart rate (HR) period variability decrease (i.e. higher root mean squared successive differences, rMSSD), and poor performers had a large heart period variability decrease (i.e. lower rMSSD). Furthermore, Middelton et al. (1999) found that overall HR and blood pressure variability were influenced significantly by executive and attentional tasks. Regarding the blood pressure variability, there was a significant decrease during test conditions compared to resting values. They also found lower values of HRV during attentional tasks that involved small aspects of working memory compared to executive and planning tasks. However, executive functions require higher mental load capacity, thus in accordance with Backs and Seljos's (1994) results one should expect a suppression in HRV during both these types of tasks. Thus, these issues need further investigation.

The use of physiological measures such as rMSSD have been related to the underlying autonomic activity and individual differences found in cognitive tasks. Backs and Ryan (1992) found decreased rMSSD as attention demands increased from focused to divided attention. In that experiment they manipulated the difficulty of a continuous memory task by varying the memory load, and the temporal demand. By increasing the number of target items to be counted, for the memory load, and varying the inter-stimulus interval for the temporal demand, they manipulated the difficulty of the task. Thus, vagally mediated cardiac tone could be viewed as sensitive to cognitive tasks and acting as a measure of reactivity.

Another reported factor has been the correlation between measures of cardiac vagal tone and performance data, resulting in an indication of a relationship between HRV and attention or memory processes (Backs et al., 1994). Exceptions from this correlational approach are two studies on infants and children, where cardiovascular responses were used as a predictor variable (Richards, 1987; Suess et al., 1994). The Richards (1987) study reported that infants with high respiratory sinus arrhythmia (RSA) were less distractable than infants characterized by low RSA. The Suess et al. (1994) study supported the hypothesis that high resting cardiac vagal tone was associated with good attentional capacity, and vagal tone was an index of mental effort.

One common factor for most of the studies on HRV has been the use of HRV as a dependent variable. This involves HRV as a measure of reactivity to attentional tasks that resulted in a suppression in HRV. An open question is whether resting HRV can be used as an independent variable predicting performance on cognitive tasks in adult samples.

Studies on adult samples using cardiac vagal tone as an independent variable predicting cognitive performance are scarce. Johnsen et al. (2003) investigated attentional bias in odontophobic patients, using a modified Stroop paradigm. The results showed poor attentional performance for odontophobic patients characterized by low HRV compared to patients with high HRV. This finding was evident both for identifying the color of incongruent color words and for threat words related to the phobic stimuli. The results were interpreted as the low HRV group representing a low degree of neurovisceral integration in the organism and decreased ability to organize resources to meet demands such as in an attentional task, like the Stroop-test (see also Thayer and Lane, 2000; Porges, 1992). Because the subjects have to keep in mind the instructions, in order to select the correct responses the Stroop task can be regarded as a task that utilizes executive functions. Since the study was done on a clinical population there was a problem of pre- and co-morbidity. It still remains to establish a predictive relationship between HRV and cognitive processes in healthy normal subjects.

One of the key elements in the Johnsen et al. (2003) study was the ecological validity of the situation. In order to increase this type of validity the study was performed in an odontophobic context (i.e. dental unit). Ecological validity remains a concern in experimental research on cognitive phenomenon.

In order to increase ecological validity and reduce the effect of co- and pre-morbidity one could study military personnel. Since military personnel are screened for their physical and mental health, the problem of pre- and co-morbidity is less dominant. The natural setting for military personnel operating equipment with high demands on attentional and memory processes are in teams in combat training centers. Therefore, testing cognitive functions in such a military setting would increase the ecological validity of a study.

Thus, based on Johnsen et al.'s (2003) study, we hypothesized that subjects with high HRV would show faster mRT, more correct responses and fewer false positive responses than the subjects with low HRV on cognitive tasks that utilized executive functions. On the working memory test (WMT), more true positive responses were expected for the high compared to the low HRV group. This prediction was based on findings from Backs and Seljos (1994), since good performers showed higher rMSSD during exposure to cognitive tasks than poor performers. The same pattern was predicted concerning the CPT—faster mRT and better accuracy was expected for the high HRV group compared to the low HRV group. Furthermore, on the sub-tasks that involved executive functions, we expected that the high HRV group would show faster mRT, more true positive responses and less false positive responses than the low HRV group. Regarding reactivity, a suppression of HRV was hypothesized, resulting in a lower HRV and a higher HR during the cognitive tasks. These predictions were based on the Porges and Raskin (1969), Porges (1972), Backs and Seljos (1994) and Backs and Ryan (1992) studies.

2. Methods

2.1. Subjects

Fifty-three male sailors, with a mean age of 23 years, (range 18–34 years), from the Royal Norwegian Navy participated in this study. Four subjects were excluded from the data analysis because of technical problems. In addition to this one outlier was excluded because of extreme reaction time.

2.2. Experimental tasks

Two cognitive tests were presented using Micro Experimental Laboratory (version 2; Schneider, 1988) installed on a Fujitsu Life Book with 10×7.5 inch^2 screen. The tests were computerized versions of a WMT and a CPT. A modified version of a WMT developed by Hugdahl et al. (2000), based on Baddeley and Hitch's (1974) research, was chosen as a WMT. The test consisted of a continuous flow of digits and subjects were to detect identical digits to the one presented two trials previously. The stimuli were numbers from 1 to 9.

As a CPT, the California Computerized Assessment Package Abbreviated version (CALCAP; Norland Software, Los Angeles, CA) was chosen. CALCAP is recognized as a test of sustained attention and consisted of four sub-tests, two with non-executive components (simple reaction time (SRT) and response latencies to specific stimuli components) and two with executive components (detection of identical stimuli and a simple addition task). The test was self-explanatory and needed only minimal supervision by the investigator.

2.3. Physiological measures

Cardiovascular responses were registered using an ambulatory monitoring system (AMS; Klaver et al., 1994). The cardiac responses were measured with 8 mm Ag/AgC1 ECG electrodes (Cleartrode, Disposable Pregelled Electrodes, 150, Standard Silver). One electrode was placed over the jugular notch of the sternum, between the collarbones, another was placed 4 cm under the left breast between the ribs, and the third electrode was placed at the right lateral side between the two lower ribs. In addition, movement was recorded using an accelerometer housed in the AMS device. These data were used to exclude those epochs with excessive movement. None were excluded.

2.4. Procedure

All subjects were tested in groups in a room on the military base. There were four to six subjects in each group. This is a typical size of expert teams in the Royal Norwegian Navy. All groups were tested at the same time every day (10.00–12.00 am). Before the start of the experiment the subjects read and signed an informed consent statement. They were informed about their rights to leave the experiment at any time. No subject withdrew from the experiment.

After the AMS system was placed on the subjects, the sequence of 5 min of baseline, tests and 5 min of recovery was performed on all subjects. The cognitive tests were administered in counterbalanced order.

On the WMT the subjects were instructed to depress the spacebar when the number that was presented two stimuli previously appeared on the screen. A total of 200 stimuli, separated into four blocks, were presented for the subjects. The target probability for WMT was 33%. Frequencies of correct responses were recorded as true positive, and responses to non-targets were recorded as false positive.

Before presenting the CALCAP the subjects were instructed to focus on the computer and respond to the target stimuli by depressing the spacebar of the computer using their dominant hand. During the SRT task, subjects were asked to press a key as soon as possible to target stimuli. This procedure provides a basal measure of reaction time. For the CRT task for single digits, subjects were asked to press a key as soon as they saw a specific number such as seven. For the serial pattern matching 1 (SPM 1), the subjects were asked to press a key only when they saw two sequential identical numbers (i.e. a number repeated). This procedure adds a more complex element of memory since the subject must keep in mind the last number that

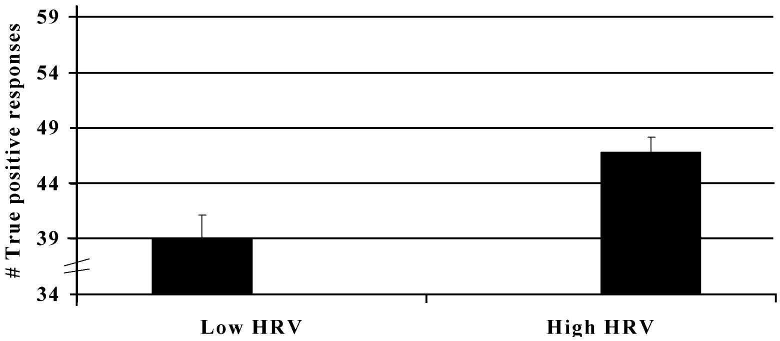

Fig. 1. Number of true positive responses to WMT (Error bars = S.E.).

was seen. For the serial pattern matching 2 (SPM 2), the subjects were asked to press a key only when they saw two numbers in sequence (increasing order; Miller, 1999). The CALCAP program presented training trials before the start of every task, and the subjects were presented a total of 315 trials. The target probability for CALCAP was 22%.

Also on this task the frequency of correct responses to target stimuli was recorded as true positive responses, and subject's responses to non-target stimuli were classified as false positives (Caretti et al., 1995). After the analysis of sub-tasks pooled together, the sub-tasks were separated and followed up for comparison of the executive and the non-executive functions.

For both tests the mRT for trials were recorded in milliseconds from stimulus onset until a manual reaction was performed by the subject, using the internal clock of the computer.

HRV was measured as the rMSSD, and also averaged over task period. Each R- to R-wave IBI in the selected period was used to calculate the average HR and the rMSSD. rMSSD is an index of vagally mediated cardiac control that correlates highly ($\sim$90) with spectrally derived measures of vagally mediated HRV (Thayer et al., 2000; Friedman et al., 2002). In addition, this measure acts as a high pass filter and thus removes the slower, blood pressure mediated variability from the signal. HR was measured as beats per minutes, based on the IBI averaged over 30 s periods.

The subjects were assigned into two groups; high HRV and low HRV, based on the median split of rMSSD during baseline. This resulted in 24 subjects in the high HRV group (i.e. high rMSSD) and 25 subjects in the low HRV group (i.e. low rMSSD).

2.5. Design and statistics

Differences between the high and low HRV groups on the measures of test performance were investigated by separate one-tailed *t*-tests for independent samples. This was done because of the specific directional hypotheses (Ferguson and Takane, 1989; Voght, 1999). In order to examine the magnitude of these differences between the independent means, effect sizes were calculated as point-biserial correlations (Wilkinson and The Task Force on Statistical Inference, 1999). This was calculated on the performance data only, because of the use of one-tailed tests.

Spearman rank order correlation coefficients were used to estimate the relationship between individual cardiovascular activity and performance on the cognitive tasks. To test the significance of the correlation coefficients, one-tailed tests were used.

To examine the effect of reactivity to the cognitive tests on HR and HRV 2-way (High vs. Low HRV × Baseline vs. CPT vs. WMT vs. Recovery) analyses of variance were used. The analyses were corrected for sphericity using the Geisser-Green-

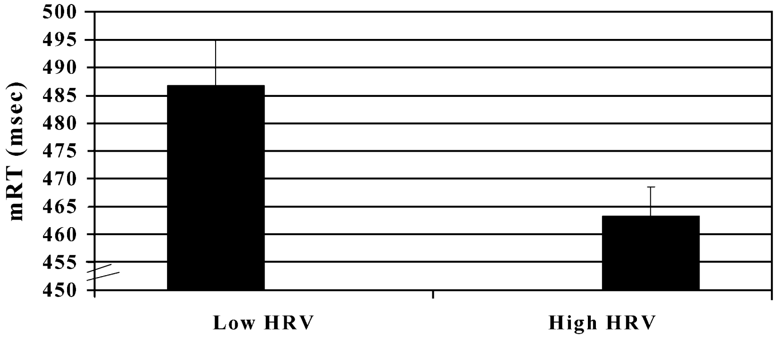

Fig. 2. Mean reaction times (mRT) in milliseconds (ms) to sub-tests pooled together on CPT (Error bars = S.E.).

house procedure (Vasey and Thayer, 1987), and followed up with LSD tests.

3. Results

3.1. Heart rate variability and task performance

When looking at specific contrasts a group difference on the WMT was found. The high HRV group showed more true positive responses than the low HRV group, $t(46) = 2.24$, $P < 0.02$ ($r = 0.31$; see Fig. 1).

The results from the CPT (all sub-tests pooled together) revealed faster mRT for the high HRV group compared to the low HRV group, $t(45) = 1.73$, $P < 0.04$ ($r = 0.25$; see Fig. 2).

True positive data for all the sub-tests pooled together showed that the high HRV group had more true positive responses than the low HRV group, $t(46) = 1.75$, $P < 0.04$ ($r = 0.25$; see Fig. 3). A borderline difference was found for false positive responses when all sub-tests were pooled together. The high HRV group (S.E. = 0.14) showed less false positive responses compared to the low HRV group (S.E. = 0.25), $t(46) = 1.47$, $P < 0.07$ ($r = 0.21$).

In order to follow up the sub-tests involving executive functions and non-executive functions, separate *t*-tests were performed for each sub-test of the CALCAP. The results showed faster mRT on the SPM 1 for the high HRV group (S.E. = 7.83) compared to the low HRV group (S.E. = 16.52), $t(46) = 1.63$, $P < 0.05$ ($r = 0.23$). This trend was also evident for accuracy data where the high HRV group (S.E. = 0.15) had more true positive responses compared to the low HRV group (S.E. = 0.66). This comparison was borderline $t(46) = 1.55$, $P < 0.06$ ($r = 0.22$). No other comparisons reached significance. Importantly, there were no

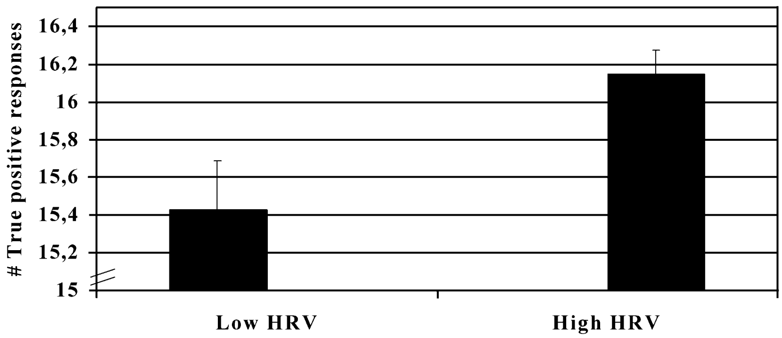

Fig. 3. Number of true positive responses on sub-test pooled together on CPT (Error bars = S.E.).

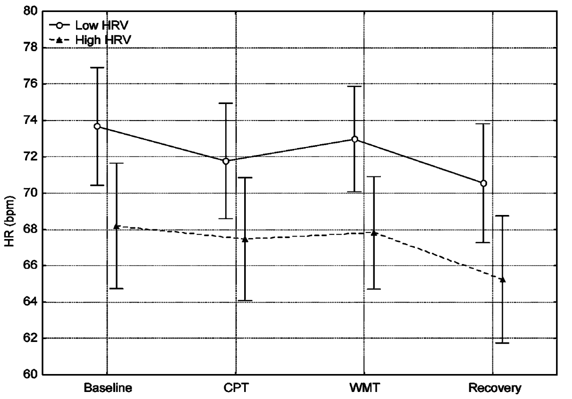

Fig. 4. Means for HR, measured as beats per minute (bpm) for low HRV and high HRV group. The means are separated for recordings during baseline, CPT and WMT and recovery (Error bars = S.E.).

differences on the SRT or CRT tasks thus supporting the specificity of the effects to those involving aspects of executive function.

3.2. Correlations

For the WMT there was a positive correlation between resting HR before the experiment and mRT on false positive responses, ($r = 0.24$, $P < 0.05$). There was also a borderline positive correlation between resting HRV before the experiment and true positive responses ($r = 0.23$, $P < 0.06$), and false positive responses ($r = 0.22$, $P < 0.06$). In addition there was a negative correlation between resting HRV and non-responses, ($r = -0.24$, $P < 0.04$).

For the CPT there was a negative correlation between resting HRV before the experiment and the false positive responses on SPM 1, ($r = -0.23$, $P < 0.05$). These correlational results support the findings based upon the median splits and show that the effects were specific to those tasks that involved executive function.

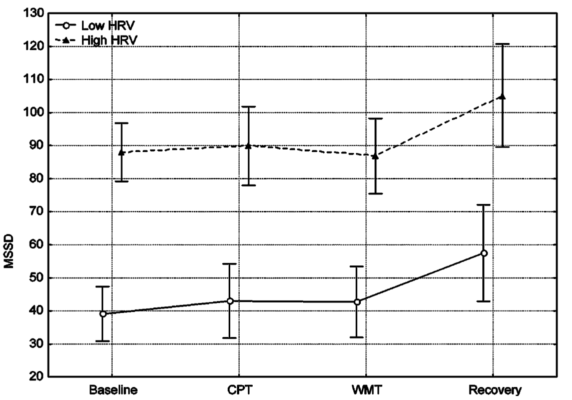

Fig. 5. Means for HRV measured as rMSSD. The means are separated for recordings during baseline, CPT, WMT and recovery (Error bars = S.E.).

3.3. Heart rate and heart rate variability reactivity to the tasks

A main effect of groups was found with the high HRV group showing lower HR compared to the low HRV group, ($F(1.45) = 5.64$, $P < 0.02$). A main effect of task conditions was also found, ($F(3.135) = 7.39$, $P < 0.001$; $\varepsilon = 0.92$). Follow-up LSD tests revealed an increase in HR for all tasks relative to recovery (all $P < 0.05$; see Fig. 4).

The HRV data showed a main effect of groups with lower rMSSD for the low compared to the high HRV group, ($F(1.45) = 46.97$, $P < 0.001$). A main effect of task conditions was also found, $F(4.180) = 8.08$, $P < 0.001$ ($\varepsilon = 0.56$). Follow-up LSD tests in this case, revealed that rMSSD were suppressed during all tasks relative to recovery (all P's < 0.01; see Fig. 5).

4. Discussion

The results from the present study showed that the high HRV group performed better on both the WMT and the CPT compared to the low HRV group. This was evident on accuracy measures on the WMT as well as mRT measures and accuracy measures on the CPT task, taxing executive functions. The correlation analysis from this study showed that there was a relationship between resting HRV and cognitive performance. Furthermore, the results showed an increase in HR during baseline and task conditions compared to recovery. An inverse pattern was found for the rMSSD data, with a decrease in rMSSD during baseline and task conditions compared to recovery. This indicated a suppression of rMSSD during the cognitive tasks.

The results from the performance data showed better performance in the high HRV group compared to the low HRV group. On WMT, that taxed executive functions, the high HRV group showed higher numbers of true positive responses compared to the low HRV group. This finding was in line with Backs and Seljos (1994) who found that when memory load increased, good performers had a higher HRV than poor performers.

Also the results from the CPT showed that the high HRV group performed better compared to the low HRV group. This was evident for both speed and accuracy, with faster mRT, higher numbers of true positive responses and fewer false positive responses, for the high HRV group compared to the low HRV group. These results were consistent with studies on infants and adults (Suess et al., 1994; Porges, 1972). Suess et al. (1994) found that baseline measures of RSA using regression analyses predicted sustained attention on a CPT for infants. Furthermore, Porges (1992), predicted and found that high levels of resting cardiac vagal tone indexed good attentional capacity in infants, and Lacy and Lacy (1958) reported a relationship between spontaneous autonomic fluctuations and reaction time. Yet, another study showed that subjects who have high pretrial rMSSD and who tended to inhibit their lability by decreasing r-MSSD during a variable foreperiod also showed fastest mRT (Porges, 1972). The present study expands this knowledge by using the rMSSD as an independent variable on healthy adult subjects, in relation to a sustained attention task. These tasks included both executive functions and non-executive functions.

In the present study the relevance of executive functions was further evident since a pattern emerged with better performance for the high HRV group when tasks involved executive components. When followed up on sub-tests involving executive and non-executive functions, differences between high and low HRV group occurred only during tasks involving executive functions. No differences were found for sub-tests with non-executive components. These findings were strengthened by the results on the WMT that only taxed central executive functions. This showed that subjects characterized by increased vagally mediated cardiac control had superior performance on WMT with executive aspects. On the other hand, subjects low on vagal tone showed less ability to match their cognitive abilities to environmental demands. Thus, two out of three tests of executive functions showed better performance for the high HRV compared to the low HRV group. At the same time no non-executive tasks showed any differences. The effect sizes of the group differences were in the medium range (Cohen, 1992). This adds to the argument for the ability of HRV to differentiate between good and poorer performance on cognitive tasks.

The correlation analysis showed that there were relationships between resting HRV and performance. These results were in line with the findings from the median split analyses using separate *t*-tests for independent samples.

Looking at the reactivity, the results from the present study were in line with Middelton et al. (1999) who found decreased HRV during presentation of attentional tasks that involved aspects of working memory. Performance tasks that involve planning, working memory, response control and attentional shifting reflects aspects of executive functions (Robbins, 1996). Although, Middelton et al. (1999) found HRV to be sensitive to an attentional task involving small aspects of working memory, he found no such effect on a visual planning task. This could lead to a speculation of HRV as a predictor of more basic executive functions like working memory, but not for higher executive functions like planning. But the results from our study expanded this knowledge by showing a suppression in HRV and an increase in HR during all the conditions, except from the significant changes to recovery. Given that these differences in HRV during different cognitive tasks exist, more investigation is needed.

Decreased rMSSD during increasing working memory load has also been reported by Backs and Seljos (1994). Vagally mediated cardiac tone could be viewed as sensitive to cognitive tasks and acts as a measure of reactivity (Backs and Seljos, 1994). This is in line with the results from the present study that showed suppression in rMSSD and an increase in HR in groups characterized by both high and low initial HRV during the cognitive tasks compared to the recovery. This suppression in rMSSD and increased HR are consistent with a reduction in vagal tone (Backs et al., 1994). During sustained attention there is a marked withdrawal of vagal tone to the periphery. These effects are manifested in the disruption of normal homeostatic function. Thus, as the duration and intensity of sustained attention increases, so do the costs to the organism (Porges, 1992).

rMSSD is an index that is highly correlated with vagal sources of HRV (Hayano et al., 1991), and spectral power in the high frequency range (0.18–0.35 Hz), calculated with an autoregressive algorithm. The rMSSD measure reflects the relatively fast respiratory modulation of cardiac parasympathetic activity (Colombo et al., 1990). Despite this high correlation it has been argued that time based measures such as rMSSD have features that may confound an assumed linear relation with the amplitude of RSA and thus violate the assumed mapping into the individual differences of vagal chronotropic influences to the heart. Traditionally two problems have been raised regarding quantifying HRV. The use of a statistical filter has been a question in the literature about the 'time domain'. Another criticism has been raised against the frequency analysis of the HRV. In a recent paper Friedman et al. (2002) confronted these issues. 'Event based' registering correlated approximately 0.98 with 'time based' registering. Furthermore, Friedman et al. (2002) found that HRV registered during conditions that did not satisfy the stationarity condition correlated approximately 0.99 with measurements where stationarity was met. Friedman et al. (2002) concluded that the questions around 'stationarity' and 'time' vs. 'event based' registering while having theoretical interest may have little practical meaning for some data. In a reanalysis of the present data, rMSSD and spectrally-derived HRV were significantly correlated; $r=0.93$, $P<0.01$. Therefore our use of rMSSD seems well justified.

An explanation of why HR and HRV did not change from baseline to the cognitive tasks in this study, could be that the subjects who participated were used to work in teams and to be tied to a particular team goal (Driskell and Salas, 1996). In this case the goals were tied up to individual performance. This together with another factor that might have influenced the reactivity during baseline, could be the experience of worry. Worry could have been associated with a lack of controllability and predictability, which has been positively and significantly correlated with anxiety (Gronich, 1995). One could argue that, recovery could be viewed as a better measure of resting cardiac activity since there is no anticipation effect confounded in the recording of resting cardiac vagal tone. The present results indicated this, with a decrease in HRV and an increase in HR during baseline and cognitive tasks compared to recovery.

According to Luria (1980) executive functions can be identified and are likely to reflect different brain mechanisms. Neural network studies in humans have reported increased activity in prefrontal cortex during working memory tasks (Goldman-Rakic, 1997). Compte et al. (2000) have proposed that the prefrontal cortex holds sensory information temporarily online through sustained activity. This continued activation of a neural network is essential for the linking of 'input' with 'output' to achieve flexible responding to changing environments. As such, optimal prefrontal functioning is necessary for the formation of associations and the representation of acquired relationships between disparate pieces of information, including information separated in time (Miller, 2000). Direct and indirect pathways by which the frontal cortex modulates parasympathetic activity via subcortical inputs have been identified, (Ter Horst and Postema, 1997; Ter Horst, 1999). A number of researchers have hypothesized inhibitory cortical-subcortical circuits (Mayberg et al., 1999; Benarroch, 1993, 1997; Masterman and Cummings, 1997; Spyer, 1989). However, Thayer and Lane (2000) have been the first to tie these circuits to HRV. The present results fit with Thayer and Lane's results (2000), and one can speculate whether executive functions and HRV are tied up to prefrontal mechanism. This interpretation is based on the observation that the high HRV group performed better than the low HRV group on tasks that involved executive function. It is well established that CPT utilize executive functions (Robbins, 1996), and that this functions is located in prefrontal cortex (Luria, 1980).

In a recent experiment, Johnsen et al. (2003) examined inhibitory responses in an emotional Stroop paradigm. Dental phobics were first exposed to recorded scenes of dental procedures and then administered the emotional Stroop-test. In addition to the traditional color congruent and color incongruent words, they also were asked to respond to neutral words and dental-related words such as drill and cavity, which were threatening to these patients. All subjects exhibited longer reaction times to the incongruent color words and the dental-related threat words, and thus, displayed a difficulty in inhibiting pre-potent responses. However, greater HRV was associated with faster mRT to these words, consistent with the link among vagally mediated HRV, inhibitory ability, and frontal lobe function. These results also supported the idea that vagally mediated HRV has been associated with efficient attentional regulation and greater ability to inhibit pre-potent but inappropriate responses. In the context of the model of neurovisceral integration, parasympathetic nervous system control of cardiovascular function (as well as activity of the prefrontal cortex) is associated with these inhibitory processes.

Thus, the present study has for the first time established a link between HRV and performance tasks that taxed executive function in normal healthy subjects. Further, the results showed that the differences attributed to qualitative differences between task demands could be predicted by the subjects' cardiac vagal tone.

Acknowledgments

The present research was supported by grants from the Norwegian Ministry of Defense and the Meltzer Foundation University of Bergen, Norway.

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