Cardiac rhythm as an indicator of normal and pathological adaptation to mental effort

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Introduction

It has been observed that an increasing number of children are unable to cope with the normal school curriculum. The impairment of intellectual development in these children may be due, apart from social neglect, to organic effects on the central nervous system (CNS). These result in a slowing down of the rate of mental development, and deficiency of spontaneous and anticipatory activity[1,2].

To find ways of correcting this defect it is necessary to understand the neurophysiological mechanisms underlying cognitive activity. One of the basic factors in the processes of organization of attention, memory, and learning ability, is the level of CNS activation. Some parameters of the work of the cardiovascular system could be used as an indicator of general adaptation of an organism to the task carried out[3-6].

The purpose of the research was to study features of the functional state regulation by examining cardiac rhythm during some mental tasks performed by children with minimal mental dysfunction (MMD) and a control group of normal children. The results are interpreted with the help of models of cardiac regulation.

The physiological background and cybernetic models

Regulation of the heart activity depends on a hierarchy of autonomous and central nervous system structures. The work of the isolated heart is determined by the sinoatrial nerve-knot. In the organism the sinoatrial knot is supplied by the sympathetic and parasympathetic systems. The chronotropism of the heart is initiated by the parasympathetic system. The purpose of the sympathetic system is to maintain this reaction pursuant to the needs of the organism[4,7].

At the level of the medulla oblongata there is a connection between the respiratory and cardiac centres which accounts for the appearance of respiratory waves in the cardiac rhythm. The cardiac centre is subject to the influence of the reticular formation and is closely connected with the work of the vasomotor centre. It is accepted that the hypothalamus participates in the regulation of heart activity[7]. Information about the cortical influence on the cardiovascular system has until now been rather general. However, changes in

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blood pressure and heart rate are marked during mental effort and emotional excitation. Rushmer and Smith[8] noted that all the CNS centres, which under stimulation cause a cardiovascular reaction, are responsible for changes of behaviour normally accompanied by cardiovascular adaptation.

Unfortunately the current state of knowledge only allows us to determine a general dependence between the behaviour of the heart rhythm and the physiology and anatomy of its control mechanisms. We can employ the hypothesis due to S.N. Braines[9] about the general structure of systems for control of physiological processes in living organisms. According to this hypothesis, all systems of biological management comprise three levels, where the higher levels drive the lower ones.

The lower level of regulation ensures constancy of the organism's main physiological parameters at definite "given" rate. On the middle level the information coming from internal organs is processed. The middle level provides the adaptation of the lower level to changes in the organism's internal environment. The higher level of regulation drives the two other levels according to the processing of information coming from the external environment. This information arrives through various receptors. The regulation at the higher level is based on conditioned reflexes; the processes of regulation at the middle level are a summation of unconditioned reactions[9].

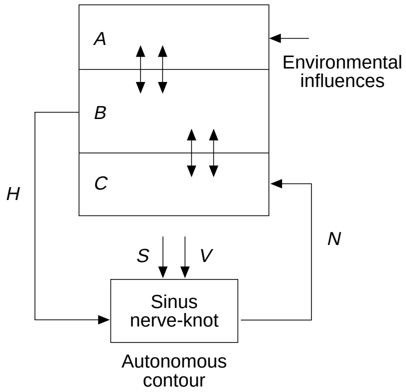
The application of this hypothesis to the cardiovascular system has been developed in the works of R.M. Baevsky *et al.*[3]. According to their theory, the system of heart regulation consists of controlled and managing sections. In the absence of physical and mental effort the controlled section (sinoatrial nerve-knot) works in its independent regime. During various tensions this section enters its forced regime, determined by the managing section.

The managing section includes three levels: A, B and C (Figure 1); respectively the higher, middle and lower levels of regulation according to the hypothesis of Braines. The activity of the A level provides, as already mentioned, the regulation connected with changes of the external environment, and it is also effective during physical or mental tension. The vascular motoric centres are attributed to the C level, and ensure general adaptation of the vascular system to changes of per minute and per contraction volumes of blood circulation[3].

The general approach to interpretation of the heart rhythm variations is to consider the higher levels of regulation as inhibitors of lower levels' activity, and periodic fluctuations of the rhythm to be connected with the level of management.

Any physiological system of an organism should be able to mobilize an "answer" depending on activation of appropriate organs, in response to a sufficient degree of irritation. The physiological reserve of each separate system has its internal structure, consisting of various levels of functioning (base, working, reserve, utmost and pathological)[10].

The base level is associated with the rates of the physiological reactions, inherent in the system in conditions of normal metabolism. This level is



Key:
H Humoral channel of management
N Nervous channel of management
S Sympathetic nervous system
V Vagus

Source: [3]

Figure 1.
The model of heart cycle regulation

determined genetically. The working level is characterized by the parameters of the system in the conditions of usual vital activity and its main characteristics are determined genetically also. The reserve level represents the difference between the maximal and base significance of the system's parameters. The value of the reserve level is determined genetically as well as by individual features of the organism[10].

The above cybernetic model is the basis of the heart contraction sequence analysis[3],widely used in psychophysiological researches. It follows that a series of consecutive R-R intervals of the cardiogram not only contains information about the automatic action of the heart, but also reflects the nature of processes, occurring in control systems of the sinus nerve-knot.

The latter, in turn, works as an indicator of more general changes in the organism, determined by changes of functional state. Nevertheless the frequency of cardiac rhythm reflects only the final result of numerous regulatory influences on the blood circulation apparatus. The activity of the regulatory mechanisms is represented in the variations of the heart rate[3].

One of the valuable components of the heart rate is the respiration sinus arrhythmia. The significance of this phenomenon is determined by the fact that respiration fluctuation of the heart rhythm decreases with activation of high levels of management, i.e. its centralization[3]. The amplitude of respiration sinus arrhythmia is considered to be one of the parameters of vagal influence on the heart[6,11]. The amplitude of the mode of the heart rhythm intervals histogram is traditionally used as an indicator of the degree of sinus arrhythmia[3,11].

Another four central characteristics of the statistical distribution – mean, variance, skewness and kurtosis – are considered to exhaust the description of the heart rate as a probabilistic process[12]. However, to examine characteristics of the contributions of separate processes in the cardiac rhythm regulation a whole set of other parameters and integrated coefficients is used[3,11,12].

Technique

The study was carried out on 212 subjects of 12-17 years of age (110 male and 102 female) attending an average school. As a result of preliminary neuropsychological testing, the subjects were divided into two groups: those with minimal mental dysfunctions of varied aetiology – the MMD group (37 male and 31 female); and the NORM group (73 male and 71 female).

Each of the subjects was asked to perform the following tasks: a time-perception test (estimation of a one-minute time interval); tests of arithmetic calculation ability of two degrees of complexity; and a verbal task.

The personal level of attention was tested during the proofreading test. Correctness was calculated as a percentage ratio of the number of specified letters marked by the subject to total occurrences of the letter. The speed of completion was evaluated as the number of lines read in one minute. A general index of attention (AI) was calculated using the formula:

$$\mathrm{AI} = \frac{2C + 10S}{3}$$

where C is correctness and S is speed of completion.

In order to study the dynamics of cardiac activity regulation during the onset of fatigue, ten subjects from both groups were required to complete an extended task increased to 40 lines.

The electrocardiogram (ECG) was recorded in conditions of rest (the background), while having the mental task explained (instruction), and while performing the task (task). Histograms of distribution of heart rate intervals, grouped with step 0.05 seconds in range from 0.4 to 1.3 seconds were formed and the following characteristics were calculated: Mo – the mode, AMo – amplitude of the mode, Δx – range of variation. The index of intensity of regulation systems (IIRS)[3] was calculated in order to find out the contribution of different levels of CNS regulating cardiac rhythm:

$$\mathrm{IIRMS} = \frac{\mathrm{AMo}}{2 \times \Delta x \times \mathrm{Mo}}$$

where AMo, Δx and Mo are characteristic of the distribution curve of heart rate values, measured during one kind of activity.

The data obtained were averaged over all tasks for each subject and over each group.

Results

The frequency of cardiac contractions (FCC) in condition of rest decreases "wavily" with age in both groups (Figure 2). The curves relating FCC to age in the NORM and MMD groups have a similar form, but are displaced relative to

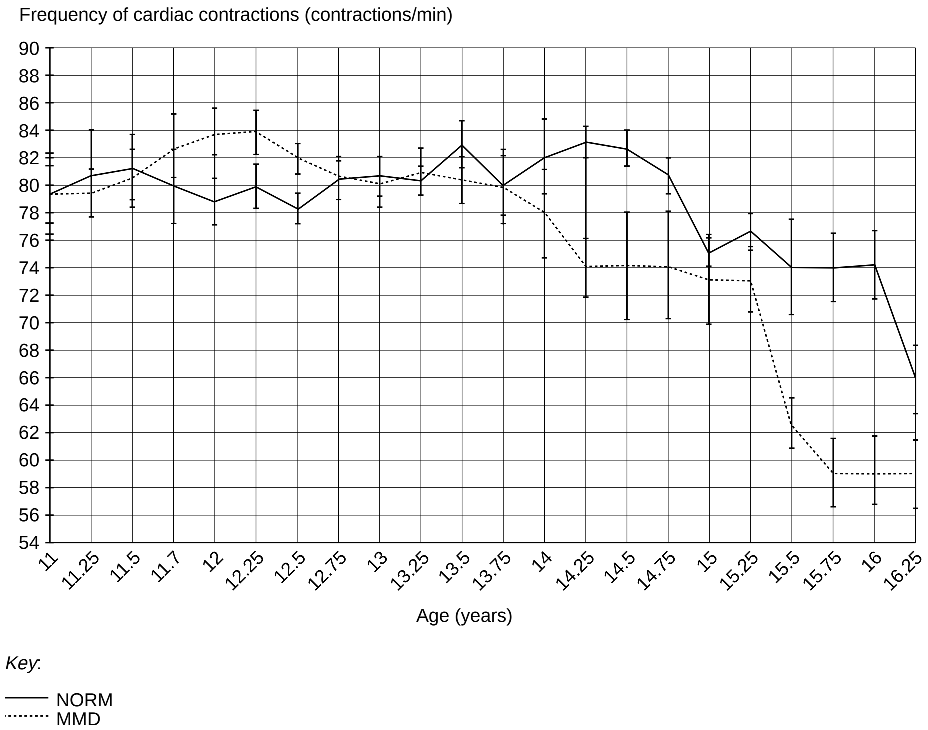


Figure 2.
The dependence of FCC on the subject's age in the NORM and MMD groups (females)

each other. To check this, the cross-correlation function was calculated over a range of time displacements. The coefficient of correlation reaches its maximum (0.927 for female and 0.548 male subjects) at displacement of the curve of the NORM group by 0.75 year backwards. At the age of 14-16 years the average FCC in condition of rest is significantly lower in the MMD group.

During mental activity the range of changes of cardiovascular parameters is much lower in children with MMD, than in children without deviations in mental development (Table I).

It was found that AI increased with age in the subjects of the NORM group (female – from 75.3 at 12 years old to 84.0 at 16 years old; male – from 76.5 at 12 years old to 84.2 at 16 years old). The growth of AI is mainly due to increase in correctness. In the MMD group at the age of 12 the AI is approximately the

Table I.
Average estimates of heart parameters in the NORM and MMD groups

	Background			Instruction			Task fulfilment		
	IIRS	AMo	FCC	IIRS	AMo	FCC	IIRS	AMo	FCC
NORM group	163.3	48.2	87.4	243.9	53.9	95.5	347.5	60.1	101
Standard error	16.5	1.8	2.5	27	2.2	3.1	53.1	3.4	3.8
MMD group	111.7	44.8	77.2	178.7	50.6	82.3	193.7	53.2	82.1
Standard error	10.5	1.4	2.6	21.2	2.7	2.6	15.1	1.3	2.7
Level of significance	–	–	$p<0.01$	$p<0.05$	–	$p<0.01$	$p<0.01$	$p<0.05$	$p<0.05$

same as for normal children (73.1 in female, 72.9 in male). After 12.5 years in male and 13 in female subjects, the AI decreases and at 16 years is significantly lower than in the NORM group (74.4 and 64.1). The decrease of AI with age in the MMD group, and the differences between the groups, are partly due to differences in speed, as well as in correctness.

On completion of the extended proofreading test designed to examine the effect of fatigue, children of the NORM group showed reduction of FCC (from 96.1 to 92.3), of AMo (from 54.9 per cent to 39.9 per cent) and of IIRS (from 208.0 to 101.3). These results agree with data in the literature[13,14]. The dynamics of the parameters of cardiac activity were different in the MMD group. In this group the FCC increased from 74.1 to 80.2, IIRS from 59.1 to 101.6 and AMo from 36.9 per cent to 44.2 per cent.

Children of 11-15 years of age, on average, understate the minute time interval during the time-perception test. The error in the time measurement decreases with age in the NORM group subjects. At the age of 14-15 years the male subjects, on average, make an error of 0.57 seconds, and females of 2.48 seconds. The children of the same age from the MMD group, on the other hand, make substantially larger errors: males – average 6.1 seconds, females – average 20.4 seconds. At the age of 14-15 years the distinction between the test results in the groups became significant, both for male and for female subjects.

Discussion

In ontogenesis an FCC reduction in the condition of rest takes place. The great FCC significances in children, in comparison with adults, are explained by high intensity of metabolism, hormone reorganizations and reduced vagal influences[15,16].

It is difficult to indicate precisely the physiological background of bradycardia in children with MMD because they are considered as practically healthy and do not pass through a full clinical examination. Presumably, the oscillatory nature of the changes of the FCC is connected with an uneven increase with age of sympathetic and parasympathetic influences on the heart.

The mental activity success depends on the conformity between internal resources mobilization and the complexity of the soluble task[11]. The degree of internal resources mobilization depends on the level of CNS activation. The success could be associated with the adequate redistribution of specific activation or general level of non-specific activation, pursuant to the task conditions. Normally, these mechanisms are perfected with maturation of the CNS[11,17].

The parameters of cardiac rhythm (including IIRS, FCC and AMo) depend on the degree of intensity of mental activity which, in turn, depends on the general level of the subject’s tenseness[18]. At low significances of mental work the intensity of the direct dependence between IIRS and tenseness was observed, while at high significances the increase of tenseness and the decrease of IIRS were observed. The authors[18] considered it to be connected with the decrease of the sympathetic nervous system tone in conditions of dangerous levels of stress. Such parameters of cardiac rhythm as AMo and FCC vary in a similar way with increase of intensity of mental activity.

From this point of view it is interesting to compare the characteristics of the heart work in the groups during mental tasks, because the performance of arithmetical and verbal tasks is poor in the MMD group.

At the transition from the background to the instruction, FCC and IIRS increased in both groups approximately by the same amount (Table I), but at the transition from instruction to the task fulfilment the degree of the increase is considerably higher in the NORM group. In the MMD group these parameters change only slightly. The difference in AMo between the two groups becomes especially high during task fulfilment. The FCC and IIRS are significantly higher in the NORM group.

In the condition of rest the distinction in AMo between the groups is insignificant (Figure 3). The scale of the sinus arrhythmia (indicated by AMo value) in the condition of rest is determined by the work of the sinus nerve-knot, i.e. the independent management contour and medulla oblongata centres[3,5,6]. It explains the close significances of sinus arrhythmia in somatically healthy subjects of both groups in the background conditions.

During functional effort the management of heart rate is executed by higher levels of CNS. The brain cortex begins to play an active role in cardiac rhythm regulation. At the transition from background to instruction we can see an approximately identical increase of AI in the groups. Thus it is possible to say that the children with MMD demonstrate the adequate reaction on low mental

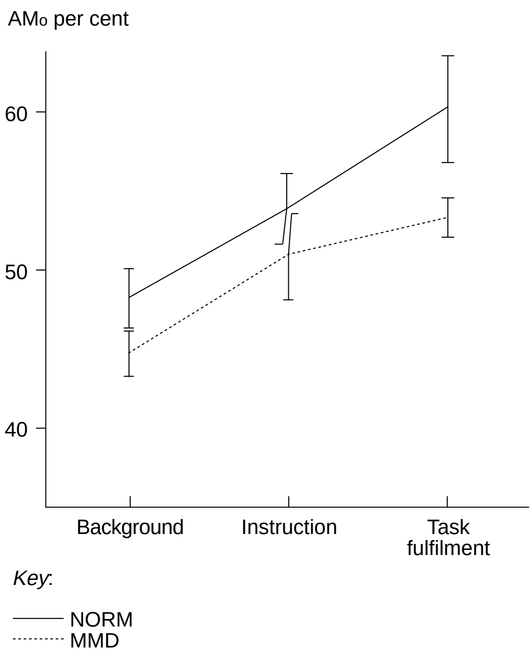


Figure 3.
Dynamics of AMo in the experiment

effort. It means that the functional reserve of the regulation system in children of both groups has sufficient size for successful completion of simple activity at the “working” level of functioning.

The increase of AMo from instruction to task fulfilment (Figure 3) in the NORM group is considerably higher than in children with MMD ($p < 0.05$). The size of AMo and IIRS is proportional to degree of activity of sympathetic regulation of the heart work and grows at activation of higher levels of management[3]. In the MMD group this increase is expressed more weakly, and this appears to reflect the lack of functional mobility and infringement of CNS higher regulation mechanisms. At the same time, the low levels of the heart rate management work properly. If in the NORM group the dynamics of all parameters indicates the increase of activation during adaptation to the task fulfilment, in the MMD group the small changes of parameters indicate the weak differentiation of the instruction listening from subsequent activity.

The low attention test scores in the MMD group could also indicate the inadequate level of the CNS activation in these subjects during the test fulfilment. As far as the fatigue process is accompanied by the decrease of general level of intensity, it is possible to suggest that children with MMD demonstrate inadequate reaction to a mental task. The intensity of systems, regulating the functional state and the cardiac response to the activity in these subjects easily reaches the critical level of functioning. It entails the increase of FCC, AMo and IIRS, instead of their decrease in the presence of expressed symptoms of fatigue.

The low range of changes of cardiovascular parameters during mental activity in children with MMD could also indicate the low functional reserve of the central regulation system.

In this connection it is interesting to analyse the age-related dynamics of time interval measurement in the NORM and MMD groups. The measurement of the time interval is one of the specific typological characteristics of the individual CNS. For each subject the length of the “individual minute” is constant for some years[19].

From the electroencephalography data[19], it is known that the subjects who understate the time interval (children with MMD in our case) have a low level of CNS activation. As far as low attention level could also indicate the deficit of the CNS structures activation, the dynamics of the time measurement and attention could correspond to the age-related changes of CNS activation management in the groups studied. The received data showed deficit of general activation of the brain structures in 15-17-year-old subjects from the MMD group. At the age of 11-17 years the deficit of activation intensifies and entails the decrease of attention level and the increase of the time measurement error, seen in the experiments.

Conclusions

We can assume that children of the NORM group demonstrate adequate vegetative reaction to mental effort, necessary for successful completion of the task. The functional reserve of central regulators of functional state appears sufficient for maintenance of this reaction. The regulating systems in this case continue to function on the “working” level (Figure 4).

In children from the MMD group the vegetative reaction to the mental effort has appeared insufficient for successful completion of the task. It indicates the small size of the reserve of functional state regulating systems of the organism, indicated by the inadequate cardiovascular system reaction on mental effort. In

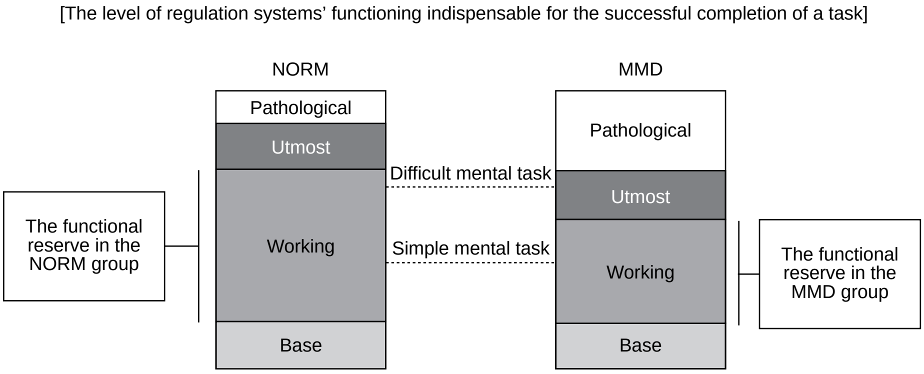


Figure 4.
The functional reserve of the heart regulation system in the NORM and MMD groups

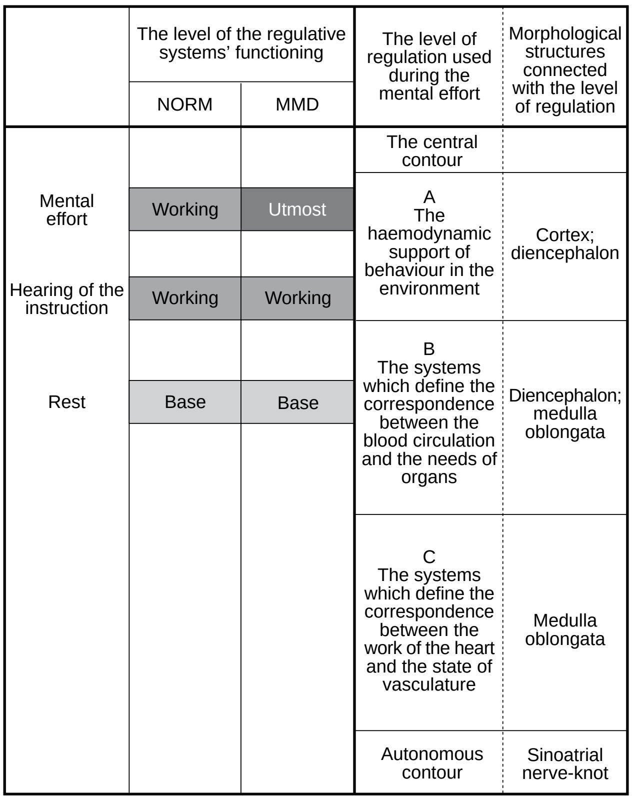


Figure 5.
Scheme of heart rate control during the mental effort in the NORM and MMD groups

these subjects, during difficult mental tasks fulfilment, the regulation of cardiac activity was executed on the "utmost" level. This is confirmed by the dynamics of cardiac activity parameters during the fatigue process. At the same time the inadequate level of functioning of regulating systems is observed during types of mental activity, when the regulating process is at the higher level, including the brain cortex (Figure 5).

The dynamics of time measurement and attention shows the strengthening of changes in functional state regulation in children with MMD during ontogenesis. These changes are connected with a general pathological process which could be connected with traumas in early ontogenesis.

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