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EEG Alpha Rhythm Frequency and Intelligence in Normal Adults

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The electroencephalogram (EEG) reflects stable individual differences in brain function and therefore can be a powerful instrument for exploring the biological basis of intelligence. However, the question of whether the EEG, and, in particular, the alpha rhythm frequency (AF) is related to intelligence in normal adults remained unclear. We analyzed EEG spectra and performance on different intelligence tests in 101 healthy males aged 20 to 45 (*M* IQ = 119.2; *SD* = 9.4) with a special regard to brain region and specific mental abilities. Scores on Raven's Standard Progressive Matrices (SPM) correlated positively with AF in prefrontal and frontal regions. Verbal abilities factors derived from the verbal subtests of Amthauer's Intelligence Structure Test (IST) and Horn's LPS test of mental performance correlated positively with both mean and peak AF factors (r = .34 and .35, correspondingly; $p < .001$). However, AF did not show any significant relationship with the factors of general (*g* factor), spatial, and arithmetic abilities.

INTRODUCTION

The understanding of the biological bases of intelligence requires a detailed analysis of the neurophysiological processes contributing to particular aspects of mental abilities. Despite the advent of modern brain imaging techniques, the electroencephalogram (EEG) still remains the main tool for investigating brain functioning in normal healthy humans. The EEG shows a high interindividual variability, which is to a great extent genetically determined (for review, see van Beijsterveldt & Boomsma, 1994). However, the question of whether basic EEG

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characteristics are associated with intelligence in normal adults remained controversial.

In this article, we consider one of the basic measures of background human EEG, the frequency of alpha rhythm (AF). Alpha rhythm is the most prominent component of the vast majority of human EEG records and is traditionally considered to be the basic, dominant EEG rhythm. There is multiple evidence that alpha rhythm recorded from the scalp represents neurophysiological mechanisms directly related to individual differences in information processing in the human brain (Klimesch, Schimke, & Pfurtscheller, 1993; Lebedev, 1990). Compared to amplitude and power measures of the alpha rhythm, AF is less influenced by extracerebral factors such as skull thickness or conductance and therefore its variation seems to result directly from the variation in brain function. This EEG parameter showed a good test–retest reliability (Anokhin, 1988; Deakin & Exley, 1979; Gasser, Bacher, & Steinberg, 1985; Salinsky et al., 1991) and substantial heritability that has been demonstrated both on twins (Lykken, Tellegen, & Thorkelson, 1974) and on families (Anokhin, 1988).

The attempts to correlate EEG with intelligence have a long history, and AF was one of the first EEG indices tested for the possible relationship. The results of the early studies were rather inconsistent. Mundy-Castle (1958) and Mundy-Castle and Nelson (1960) reported a positive relationship, whereas in other studies no significant correlation could be found. In their review, Vogel and Broverman (1964) concluded that the available evidence supported the relationship between EEG and test intelligence in individuals with either relatively undeveloped intellectual function (children, mentally retarded) or deteriorated intellectual function (due to aging or brain damage), whereas in normal adults the relationship is very ambiguous. Ellingson (1966) argued in his review that the weight of available evidence suggested no relationship between EEG and intelligence in normal adults. In another comprehensive review, Oswald and Roth (1974) noted that most EEG studies involving normal adults did not provide evidence for an association between AF and psychometric intelligence; the positive findings available point to a possible relationship with performance rather than verbal IQ. Further studies could not clarify the issue. Giannitrapani (1969) reported a significant correlation between IQ and the average EEG frequency (over all frequency bands), as well as its asymmetry index in a relatively small group of adults (18 participants). In contrast, Vogel, Broverman, & Klaiber (1968) did not find any evidence that AF is related to general level of intelligence; however, it correlated with "automatization" cognitive style in their study. They concluded that EEG indices seem to be related to particular cognitive factors, rather than to general mental ability. In another review, Oswald and Roth (1974) concluded that most EEG studies involving normal adults failed to provide convincing evidence for the relationship between AF and test intelligence; however, the authors noted that the few positive findings available suggest a relationship with performance IQ. Gasser, Von Lucadou-Müller, Verleger, and

Bächer (1983) found a positive correlation between AF and IQ in a group of mildly retarded children, but failed to find such relationship in a group of normal children. Giannitrapani (1985) reported a significant correlation between dominant AF and Full-Scale IQ, as well as correlation of 13-Hz activity (the upper bound of the alpha band) with verbal IQ in a sample of normal 11- to 13-year-old children. The study of Juolasmaa et al. (1986) was most representative regarding sample size and methodologies and could shed more light on the issue. It involved a relatively large sample of 52 adult cardiac valvular patients. Although a portion of participants were supposed to have brain disorders due to an impaired cerebral circulation, the mean sample IQ was in the normal range. This study found significant correlations between AF and intelligence test scores, mainly with verbal and memory subtests.

Apart from possible correlations with intelligence, there is strong evidence that AF is associated with memory performance and processing speed. Golubeva (1980) regarded alpha frequency as one of the indicators of the general central nervous system (CNS) activation factor and found significant correlation with performance on memory tasks. Lebedev (1990) proposed a theoretical model that allows derivation of an individual's limit of short-term memory span from composite electrophysiological indices, based on AF and the duration of alpha spindles. Klimesch et al. (1993) reported significant differences in alpha frequency between poor and good memory task performers, which were most pronounced when individuals actually retrieved information from their memory. Surwillo (1964) found that AF is negatively related to decision time in choice reaction task and hypothesized that the information capacity of the CNS is a function of EEG period.

Thus, although there are strong indications for the significance of AF for individual differences in mental performance, the question of whether AF is related to test intelligence in the normal adult population remained controversial. This controversy has put into doubt the value of the EEG for intelligence-related problems; and later biologically oriented studies of intelligence employed more sophisticated measures of evoked potentials rather than spontaneous EEG (for review, see Barrett & Eysenck, 1994; Deary & Caryl, 1993).

Inconsistent findings may result from a number of factors, some of which have been already mentioned by Gasser et al. (1983): (a) *small sample size:* in most studies, samples do not exceed 30 participants, which is too little for reliably detecting a correlation, which may be a priori expected to be rather modest; (b) *inclusion of participants with organic cerebral dysfunctions or/and impaired intellectual function in the sample:* associations found in such cases may result from specific impairment of brain function and therefore cannot be simply extended to the normal range; (c) *effects of age:* findings obtained on children, even if corrections for age effects are performed, cannot be extended to the adult population, because the correlation may result from the difference in developmental rate among individuals rather than from "true" individual differences, and disappear at later stages of development; (d) *gender-specific effects* may also modify the relationship; (e) *methodological problems* related to EEG evaluation and intelligence testing: a limited number of EEG derivations, insufficient length of analyzed EEG fragments, subjectivity in EEG evaluation (some of the early studies), or employment of only one intelligence scale.

This study tries to avoid these problems: It utilizes a sample of 101 normal healthy males, eight EEG recording sites, computerized evaluation of main EEG parameters, and three different tests of mental abilities, two of them containing subtests of specific abilities.

The hypothesis was that AF is positively related to mental abilities in a normal adult population, and that this relationship may vary with specific abilities and different brain regions.

The reported data are a part of a broader analysis of EEG and psychological data designed to identify relatively independent aspects of brain function contributing to both general and specific mental abilities. Special attention was paid to those aspects of electrocortical activity that has been previously shown to be genetically determined.

MATERIAL AND METHODS

Participants

We analyzed data obtained from 101 healthy males aged 20 to 45 (*M* age = 30.6 years; *SD* = 5.5), military pilots and technical personnel. All participants underwent regular medical check-ups and were in good health. The data had been collected by Vogel and coworkers in the framework of a study toward psychological differences between the carriers of inherited EEG variants (for details, see Vogel, Schalt, Krüger, Propping, & Lehnert, 1979); the material also included a large group of "average" EEG records. Because some of the specific EEG variants were overrepresented in the initial sample of 290 participants, we formed for this analysis a subsample most possibly matching the general population. The exception was that we excluded from the analysis the low-voltage records with no or very little rhythmic alpha activity, which occur at about 7% in the general population, because the estimation of alpha frequency is very problematic in these individuals.

The average IQ (as assessed using Amthauer's IST) surpassed that of the general population and its range of variation was somewhat restricted (*M* IQ = 119.9; *SD* = 9.4)

EEG Recording and Analysis

EEG was recorded using a Schwarzer EEG machine while the participants were sitting quietly at rest with eyes closed in a comfortable chair in a semidarkened room. Whenever possible, EEG recordings were carried out in the morning, before the psychological examination took place. Eight conventional sites of the 10–20 system electrode placement system were used: symmetric (left and right) prefrontal, frontal, central, and occipital leads (Fp1, Fp2, F3, F4, C3, C4, O1, and O2, correspondingly) referenced to ipsilateral ear; time constant was set at 0.1 sec, the upper frequencies filter at 30 Hz. The data were stored on magnetic tape using an AMPEX recorder. For each participant, at least 2 minutes of record were available.

For the purpose of this study, EEG records were digitized at the rate of 128 per sec with 12-bit precision and analyzed using MBN-Neurokartograph software. EEG records were screened for eye movements and EMG artifacts, divided into 4-sec epoches, and subjected to Fourier spectral analysis. Two parameters, peak frequency (the frequency at which maximum power occurred) and mean frequency (weighted for power) were assessed within the alpha frequency band (8–13 Hz) at each recording site averaged over 30 epochs.

Psychological Data

Psychological examinations took place on the same day as the EEG recordings. The following mental ability tests widely used in German-speaking countries were employed: (a) Raven's Standard Progressive Matrices (SPM; Raven, 1960); (b) Amthauer's Intelligence Structure Test (IST), including nine subtests measuring specific components of mental abilities (Amthauer, 1973); and (c) Horn's Leistungsprüfsystem (LPS), a mental performance battery. We used three primary subtests—L3 (logic of figures sequence), L6 (verbal fluency), and L14 (crossing out task)—and two composite subtests—LT (spatial abilities) and LR (recognition of incomplete patterns), each of the latter derived from three primary subtests (Horn, 1962).

Data Reduction and Analysis

In order to reduce the number of variables and to examine some general effects, we performed principal components factor analysis for AF and cognitive abilities measures. The first unrotated factors derived from the matrices of intercorrelations among mean and peak AF measured at different recording sites were used as integral measures of mean and peak AF in further analysis. The same analysis was performed for frontal and prefrontal sites only in order to obtain regionally specific "frontal" AF measures. Similarly, factor analysis has been performed for different sets of cognitive performance measures. First, we included all tests used in this study (nine subtests of the IST, nine individual subtests of the LPS, and the Raven's SPM score); this analysis was supposed to yield a factor of general abilities (*g* factor). Then we performed a separate analysis for subtests based on verbal material only (SE, WA, AN, and GE of the IST and L6 of the LPS), and for subtests assessing geometrical and spatial abilities (FA and WUE of the IST and L7 to L10, the four subtests comprising the LT scale of the LPS).

RESULTS

Factor analysis performed separately for the two sets of AF measures yielded the first unrotated factors whose correlations with variables ranged from .91 to .97 and from .67 to .87 for mean and peak AF, correspondingly. The first factor accounted for 90% of the total variance for mean AF measures and 61% for peak AF measures.

The correlations between initial AF measures obtained from different brain regions and the scores on individual subtests of cognitive abilities are presented in Table 1. Correlations between the factors of alpha frequency and the factors of specific abilities are presented in Table 2.

As can be seen in Table 1, there are many significant correlations ranging from .20 to .34 that are distributed unevenly with regard to brain region and specific ability. Because multiple comparisons have been performed, a question arises about whether such correlation could occur by chance. However, the inspection of the correlation matrix shows that of 256 correlations, 230 are positive, and only 26 are negative. Furthermore, negative correlations are negligible and none of them reached significance, whereas of the positive correlations 53 are significant. Thus, there is a clear overall trend toward a positive relationship. Also, some regularities can be seen in the distribution of significant correlations with regard to brain region and specific tests.

Scores on Raven's SPM showed significant correlations with both peak and mean AF, which were all but one in frontal and prefrontal regions. Multiple correlations of the SPM score with frontal peak and mean AF measures were .33 and .31, correspondingly ($p < .05$). The difference between lower and higher SPM performance groups (upper and lower 30th percentiles) on frontal AF was about 0.8 Hz, which is one SD of the latter. However, the difference between the correlation coefficients in frontal, central, and occipital regions did not reach the significance level.

Three verbal subtests of the IST—SE (completion of sentences), WA (selection of words) and GE (conceptualization)—as well as subtest L6 (verbal fluency) of the LPS exhibited significant correlations with AF. Multiple correlation of these subtests' scores with the mean AF factor score was .40 ($p < .01$). In contrast to SPM, significant correlations were more evenly distributed over all studied brain regions. The total IST score showed significant correlations with AF indices only in occipital leads. Of nonverbal subtests, only LPS-LR (recognition of incomplete patterns) exhibited four significant correlations with both AF indices in anterior leads.

In order to examine whether the magnitude of correlation with AF may depend on differential reliabilities of individual subtests, we calculated a rank correlation (Kendall's tau) between the correlation of IST subtests with mean and peak AF factors, on the one hand, and reliabilities of these subtests (both split-half and test–retest), on the other. The tau values ranged from −.22 to .19, all nonsignificant.

TABLE 1
Correlations Between the Measures of the EEG Alpha Rhythm Frequency and Mental Abilities

Test of Mental Abilities	Peak Alpha Frequency								Mean Alpha Frequency							
	Fp1	Fp2	F3	F4	C3	C4	O1	O2	Fp1	Fp2	F3	F4	C3	C4	O1	O2
Raven's SPM	**.32****	**.26****	.19	**.29****	.18	.07	.14	**.21***	**.27****	**.24***	**.22***	**.21***	.18	.06	.16	.06
Amthauer's IST:																
SE *(completion of sentences)*	**.24***	**.21***	.16	**.26****	**.32****	**.31****	**.34****	**.34****	**.31****	**.28****	**.27****	**.27****	**.29****	**.25***	**.32****	**.34****
WA *(selection of words)*	.11	.18	.19	.12	.12	.03	.16	**.25***	**.21***	**.22***	**.20***	**.21***	**.21***	.16	**.21***	**.21***
AN *(analogies)*	.19	.11	.13	.18	.18	.11	.16	**.23***	.16	.15	.13	.13	.12	.08	.18	.14
GE *(conceptualization)*	.03	**.20***	**.28****	.05	.12	.12	.13	.18	.13	.19	.15	.15	**.24***	**.25***	**.20***	**.21***
ME *(memory)*	−.17	−.09	−.07	−.13	−.08	−.06	−.10	−.08	−.14	−.09	−.12	−.10	−.03	−.06	−.07	−.07
RA *(calculation*	.08	.09	.11	.14	.10	.12	.14	.15	.09	.10	.09	.08	.06	.07	.13	.15
ZR *(sequences of numbers)*	.07	.06	.05	.07	−.01	.03	.02	.07	.07	.05	.05	.04	.06	.06	.05	.08
FA *(selection of figures)*	.13	.08	.17	.18	.12	.20	.09	.17	.14	.16	.17	.15	.14	.10	.16	.15
WÜ *(identification of cubes)*	.07	.09	.05	.11	−.01	−.03	−.04	−.06	.02	.02	.04	.05	.02	−.09	−.03	.11
IST total score	.12	.16	.20	.16	.14	.14	.15	**.21***	.16	.18	.16	.15	.19	.14	**.20***	.18
Horn's LPS:																
L3 *(logic of figures sequences)*	.11	.03	.01	.10	.09	.01	.07	.07	.06	.04	.05	.05	.10	.02	.07	.01
L6 *(verbal fluency)*	.14	.14	.17	.14	**.26****	.18	**.24***	**.31****	.20	**.23***	.19	**.20***	**.22***	**.22***	**.26****	**.25***
LT *(spatial abilities)*	.08	−.02	.00	.04	.04	.03	−.03	−.08	.03	.03	.06	.04	.05	−.01	−.02	.14
LR *(incomplete patterns)*	.18	**.22***	.16	.19	.13	.19	.17	.18	.17	**.21***	**.21***	**.20***	.18	.13	.15	.13
L14 *(crossing out task)*	.10	.16	.05	.03	.12	.15	.15	.03	.12	.14	.11	.14	.13	.10	.17	.14

*$p \leq .05$. **$p \leq .01$.

TABLE 2
Correlations Between the EEG Alpha Frequency Factors and Mental Abilities

Factor Scores Analyzed	*r*	*p*
Mean AF vs. General Abilities	.138	*ns*
Peak AF vs. General Abilities	.162	*ns*
Mean AF vs. Verbal Abilities	.341	<.001
Peak AF vs. Verbal Abilities	.356	<.001
Mean AF vs. Raven's SPM	.190	*ns*
Peak AF vs. Raven's SPM	.266	<.01
Frontal mean AF vs. Raven's SPM	.238	<.05
Frontal peak AF vs. Raven's SPM	.304	<.01
Mean AF vs. Spatial Abilities	.083	*ns*
Peak AF vs. Spatial abilities	.081	*ns*
Mean AF vs. Arithmetic Abilities	.072	*ns*
Peak AF vs. Arithmetic Abilities	.120	*ns*

Note. Figures in this table represent correlations between the scores on first unrotated factors derived from intercorrelations within the following sets of variables. *Mean AF and Peak AF*: mean and peak alpha frequency values, respectively, across all recording sites; *Frontal Mean and Peak AF*: the same for frontal areas only (Fp1, Fp2, F3, F4); *General Abilities*: all subtests of the IST and LPS tests and the SPM score; *Verbal Abilities*: verbal subtests of the IST and the LPS; *Spatial Abilities*: spatial and geometric tasks of the IST and the LPS; *Arithmetic Abilities*: multiple correlation of the two arithmetic subtests of the IST with each of the AF factors is presented. For more detail see Methods and Results sections.

The correlations between AF indices and factors representing general and specific abilities are shown in Table 2.

The first unrotated factor derived from the correlations among all 19 individual tests (which can be supposed to represent the *g* factor in our data) accounted for 29% of the total variance. All variables correlated positively with the first factor; however, there was a significant difference among subtests regarding the magnitude of correlation: The subtests of geometrical and spatial abilities as well as arithmetic subtests showed the highest correlations (ranging from .31 for L12 of the LPS to .76 for the RA of the IST), whereas the correlations with verbal subtests were lower (from .08 for L6 of the LPS to .52 for AN of the IST). Raven's SPM score correlated at .55 with this factor. Thus, this factor is more loaded by nonverbal than verbal subtests. Table 2 shows that correlations between this factor's score and both mean and peak AF factors are insignificant.

The first unrotated factor derived from the five verbal subtests accounted for 43% of total variance; correlations between the variables and the factor ranged from .49 to .79. This factor correlated significantly with both mean and peak AF factors.

Similar factors derived from the scores on six geometrical and spatial tasks accounted for 49% of the total variance; correlations between the variables and the factor ranged from .46 to .82. As can be seen from Table 2, this factor did not show any significant relationship with AF indices. A multiple correlation calculated for the two arithmetic subtests of the IST and AF were also insignificant.

The results suggest that there are distinct differences between specific abilities with regard to their relationship with AF. The comparison of correlation coefficients showed that the correlations of AF measures with verbal abilities factors differ significantly from their correlations with "spatial" and "arithmetic" factors with the z statistic for comparison of interdependent correlations ranging from 2.09 to 2.58 ($p < .05$).

No hemispheric differences can be seen in the pattern of AF/intelligence correlations. In order to examine whether hemispheric asymmetry of the AF is related to mental abilities, we also estimated the asymmetry indices as $((L - R)/(L + R))*100$, where L and R are AF values at left and right symmetric electrode placements, correspondingly. This measure did not show any correlations with mental abilities in this study.

We also examined the effect of age on the studied variables. Raven's SPM score correlated negatively with age ($r = -.26$; $p < .01$), but there were no significant age effects on IST and AF measures in this sample.

DISCUSSION

The results of this study, obtained from a representative sample of normal male adults, provide ample evidence that the frequency of alpha rhythm, the main component of the human EEG, is significantly related to mental abilities. Of course, the portion of IQ variance explained by AF is small; however, the magnitude of significant correlations (.20 to .36) is of the same order as correlations between IQ and other measures assumed to be indicative of the biological basis of intelligence: reaction times, inspection time, variability and latency of ERP, nervous conductance velocity, and so on (McGarry-Roberts, Stelmack, & Campbell, 1992; Miller & Vernon, 1992; Reed & Jensen, 1992; Vernon & Weese, 1993).

It should be noted that the mean values for mental ability tests were elevated in our sample compared to population norms, and the range of variation was considerably restricted. (e.g., 63% of that in the general population for the total IST score). We restrained from presenting correlations corrected for the restricted range of IQ variation. However, such correction (Cohen & Cohen, 1983) would considerably increase the reported correlations: For example, a correlation of .31 between a verbal subscale of the IST and AF factor increases to .40. Thus, it should be kept in mind that the figures presented in the tables seem to be the lower bound estimate of correlations expected in the general population.

Regarding the distribution of significant correlations across the scalp, the results are suggestive of certain topographic differences in the patterns of correlations between AF and different measures of mental abilities (Table 1). Correlations with Raven's SPM and LR of the LPS tend to aggregate in the frontal areas (11 of 12 significant correlations), whereas verbal scales of the IST and LPS show a more diffuse topographical distribution of significant correlations with AF (only 16 of 39 significant correlations with verbal subtests lie in frontal areas). Such a pattern suggests that nonverbal inductive reasoning abilities as assessed by Raven's test may be related to neurophysiological properties of the frontal areas of the brain. However, the difference between correlation coefficients (frontal vs. nonfrontal) does not reach significance. Thus, this observation is preliminary and needs to be confirmed in further studies.

The results of this study suggest a greater relationship of alpha frequency to specific rather than to general abilities (*g* factor). Correlations of both AF measures with the first factor derived from all tests used in this study did not reach significance (Table 2). However, the tests used in this study (IST and LPS) do not seem to be optimal for the assessment of *g* factor, because they had been developed based on Thurstone's primary abilities model. In our data, the first unrotated factor accounted for only 29% of the total variance of individual subtests and showed higher correlations with nonverbal than verbal subtests. Regarding specific abilities, there are distinct and significant differences in the magnitude of correlations with AF: There are highly significant correlations of both AF measures with verbal abilities factors but no significant relationship with spatial and arithmetic abilities.

The analysis did not reveal any lateral hemispheric effects regarding the correlation between verbal abilities and AF, although one might expect a higher relationship on the left side of the brain.

Prior studies could establish a reliable relationship between AF and test intelligence in individuals with undeveloped, deteriorated, or impaired intellectual functions (children, elderly, patients with brain dysfunctions), whereas most data obtained on normal adults were either insufficient or inconclusive. However, the study of Juolasmaa et al. (1986) performed on a sample of 52 cardiac valvular patients provided more definite evidence in favor of the AF–intelligence relationship in a normal adult population. Most of the significant correlations concerned verbal subtests and memory performance. The authors noted, however, that such patients are prone to disorders of cerebral circulation leading to brain dysfunctions; the rate of possible cerebral disorders was assessed to be 19.2% in this sample. Theoretically, the presence and/or severity of brain dysfunction may be a confounding variable that can give rise to the association between AF and test intelligence in a mixed sample containing neurologically healthy persons and those with organic brain disorders. However, the mean IQ of the sample was in the normal range, suggesting that this factor does not have any substantial effect. Despite this possible limitation, this study seems to be the most representative of the earlier studies involving normal adults. Although the study of Juolosmaa et al. and our study employed different tests of intelligence, different EEG montage, and samples of different mean age (46.6 and 30.6, respectively) and health status, the results seem to be very consistent with regard to both specific abilities (maximum correlations with verbal subtests) and the magnitude of the observed correlations (.30–.35).

At present, only a hypothetical explanation of the AF–intelligence relationship can be proposed based on the possible role of the alpha rhythm for information processing in cortical networks (Klimesch, Schimke, & Pfurtscheller, 1993; Lebedev, 1990) and on individual differences in cortical arousal level (Golubeva, 1980; Robinson, 1993). Alpha rhythm emerges as a result of synchronous oscillations of synaptic potentials in large populations of neurons (primarily pyramidal cells) spread throughout the cortex. Although the exact mechanisms of alpha rhythm generation and its functional meaning are not understood completely so far, there is increasing evidence that synchronized oscillatory activity in the cerebral cortex is essential for spatiotemporal coordination and integration of activity of anatomically distributed but functionally related neural elements. Recent experimental and simulation studies of information processing in neuronal networks suggest that synchronized oscillatory activity in cell assemblies plays a key role in encoding, storage, and retrieval of information in the brain. Whereas information seems to be encoded by the temporal sequence of action potentials, synchronized periodic fluctuations of membrane excitability enable temporally and spatially structured coactivation of cells in an assembly (Birbaumer, Elbert, Canavan, & Rockstroh, 1990; Buzsaki & Chrobak, 1995; Lisman & Idiart, 1995). As a consequence, the duration of the cycle of the dominant cerebral rhythm may limit the capacity for storage, transfer, and retrieval of information in individual brains.

There are also some indications that AF is related to the level of cortical arousal both in state and trait aspect. AF increases with mental activity compared to rest. Increasing cognitive task difficulty leads to right hemispheric as well as bilateral alpha acceleration (Earle, 1988); a decrease in individual alpha frequency is always related to a drop in performance on memory tasks (Klimesch, Schimke, & Pfurtscheller, 1993). Resting AF is higher in persons with a higher level of tonic cortical arousal regarded as a stable individual trait and assessed using other EEG and evoked potentials measures. Moreover, it correlates positively with indices of mental activity level, academic performance in high school students, as well as performance on some memory tasks (Golubeva, 1980). It can be supposed that individuals with a higher level of cortical arousal would also show a better performance on intelligence tests. However, such explanation in terms of a linear relationship is not quite consistent with the theory of Robinson (1993) based on evoked potentials data, according to which high IQ is associated with an intermediate degree of cerebral arousability.

The question arises what elementary cognitive abilities can mediate the relationship between AF and intelligence. Recent analyses (Miller & Vernon, 1992) suggest that there are at least two main constituents of general intelligence on the level of elementary cognitive functions: speed of information processing and short-term memory. Moreover, the general factor score derived from short-time memory measures appeared to be a better predictor of IQ than RT. Interestingly, as already mentioned in the introduction, AF was shown to be related to both these measures (Golubeva, 1980; Klimesch, 1993; Lebedev, 1990; Surwillo, 1964). Weiss (1992) proposed a model linking these two basic parameters to predict the individual capacity for information processing. To gain further insights into the pathways linking AF and higher mental abilities, the structure of interrelationships among AF, short-term memory, processing speed, and intelligence should be experimentally explored in more detail.

It should be noted that the IST "memory" scale did not correlate with AF in this study; however, this scale is not an experimental short-term memory test in a strict sense, and the way of its presentation as a group test (Amthauer, 1973) does not seem to allow an accurate assessment of memory capacity.

Regarding hypothetical neuroanatomical features underlying stable individual differences in AF, the degree of myelination could play an important role. Alpha rhythm results from cyclic excitations in cortico-cortical and thalamo-cortical circuits involving certain numbers of interneurons. It can be supposed that the duration of a cycle would be shorter with a greater axonal and dendritic conduction velocity (given the same or a similar number of interneurons) and, hence, the frequency of the resulting rhythm would be higher. Recently, R. Miller (1994) provided evidence that axonal conduction delay in cortico-cortical connections, rather than synaptic delay, is the major factor limiting EEG propagation velocity. In turn, conduction velocity in cortico-cortical connections is mainly determined by the degree of axonal myelination. It is noteworthy in this connection that ontogenetic changes of these interconnected parameters (myelination, alpha frequency, processing speed, and short-term memory span) go in parallel. This interpretation of the alpha frequency–intelligence relationship also seems to be consistent with the brain myelination hypothesis of intelligence (E.M. Miller, 1994).

On the whole, we can conclude that the EEG is an important tool of exploration of the biological basis of intelligence. Its advantage is that it is more closely related to basic cerebral processes than behavioral measures such as, for example, reaction time; another advantage is that the EEG is an involuntary measure, which is important in view of critical arguments that IQ–RT correlations may be attributed to the individual's ability to concentrate on the boring task, rather than to causal relationship between these measures (Mackintosh, 1986). It seems therefore reasonable to incorporate EEG assessment into experimental studies of the biological bases of intelligence, along with processing speed and memory assessment.

In the context of behavioral genetic research, identification of basic neurophysiological factors contributing to intelligence may shed the light on the pathways and mechanisms of the genetic influences on mental abilities and thus point to possible sites of gene action in the brain. The latter may be useful for genetic linkage studies aimed at the identification of single genes involved in the determination of mental abilities and their impairment.

It should be mentioned that this analysis was performed on an entirely male sample. In females, the pattern of relationship may differ, although we suppose that only quantitative differences would occur.

The data reported here deal with only one basic EEG property, the frequency of the dominant rhythm, and represent a part of a broader analysis of the relationships between EEG and mental abilities. Another EEG aspect we are currently focusing on is the cross-correlation and coherence between EEG activity at distant recording sites at rest and during cognitive tasks, the measures presumably representing the speed and efficiency of functional integration of different brain areas in ongoing activity.

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