

PSYCHOLOGICAL DIFFERENCES ASSOCIATED WITH INDIVIDUAL DIFFERENCES IN THE PHYSICAL PROPERTIES OF THALAMOCORTICAL OSCILLATORS

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Abstract

EEG findings and the related results of neurophysiological studies are used to demonstrate how the physical properties of thalamocortical neurons cause oscillatory electrical activity and EEG frequency response curves. These data confirm that thalamocortical circuits behave like other simple oscillators and that this behaviour can be explained by the same laws of physics that cause oscillatory activity in other material systems. One consequence of this advance in the development of theory is that it has been possible to carry out the first systematic and physically meaningful analysis of human individual differences in thalamocortical EEG activity, and to describe the results in terms of parameters that are used to describe the dynamic character of other oscillating systems. One parameter, the 'damping ratio', indicates the rate at which an oscillator loses energy. This determines the duration of oscillatory activity following a transient disturbance and also determines the sharpness of the resonance peak in an oscillator's frequency response curve. A second parameter, 'natural frequency', indicates the rate at which energy is transferred between system elements. This determines the frequency of free oscillation as well as the frequency of resonance when an oscillator is 'driven' at different frequencies. These two parameters provide a comprehensive description of the dynamic character of thalamocortical oscillator circuits, considered in aggregate, and they do so in a way that shows how this depends on 'capacitance', 'inductance' and 'resistance' effects caused by glutamatergic excitatory neurons and GABAergic inhibitory neurons. The profound psychological significance of individual differences in thalamocortical damping ratios and natural frequencies is illustrated by reference to data which demonstrate that these parameters are related in a strong, systematic, and theoretically meaningful fashion to temperament differences and to all the major and generally accepted dimensions of personality and intelligence.

My interest in oscillating brain electrical potentials began in the mid 1970s when I was searching for some way of testing the theories of Pavlov and Eysenck. These theories assert that the major differences in personality and temperament are caused by differences in the functional character of brain systems. Figure 1 shows the major dimensions of personality revealed by contemporary research (Eysenck and Eysenck, 1985; Robinson, 2009) and one can see how the two dimensions define the four classical temperament types that Pavlov studied (Pavlov, 1955). These are the fundamental dimensions and temperament types that must be explained by any theory of personality. Ideally, any comprehensive theory of personality should also explain the intelligence factors or dimensions revealed by psychometric studies (Cattell, 1987; Eysenck and Eysenck, 1985; Robinson, 2009). Finally, such a theory should suggest how normal differences in personality and cognition relate to abnormal psychological conditions (Claridge, 1995).

My ideas about brain function and personality began with Eysenck's cortical arousal model (Eysenck, 1967). At that time it had been demonstrated that the 'brain-stem ascending reticular activating system' could cause generalized cortical activation or arousal and that this arousal could be observed in the EEG (Magoun, 1963). It is self-evident that individual differences in the functional character of such a system would have a profound influence on the way in which people think, feel and act (Samuels, 1959) but Eysenck's more specific proposal was that such differences cause the introversion-extraversion dimension of personality (Eysenck, 1967). Introverts, according to Eysenck, have typically higher levels of brain-stem mediated cortical arousal than extraverts.

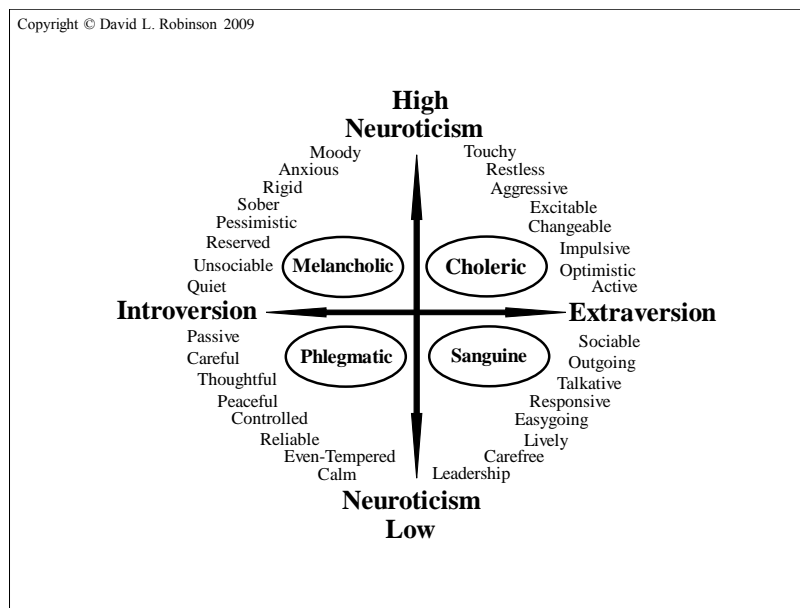


Figure 1. The relationship between personality traits, the introversion-extraversion and neuroticism dimensions of personality, and the four temperament types of antiquity.

I was drawn to Eysenck's theory because of its explanatory power and because it was testable. Initially it seemed to me that to test the theories of Pavlov and Eysenck one would only have to find out whether or not there is a correlation between EEG differences and introversion-extraversion differences. I soon discovered that others had already thought of this test and that there had been a general failure to find any consistent relationships between EEG differences and personality differences (Stelmack, 1990; Gale, 1983). Despite these negative findings I thought it highly unlikely that differences in brain activity could be unrelated to differences in personality. This view was greatly reinforced by evidence such as the general observation that all psychoactive drugs alter EEG activity whereas other drugs have no effect on the EEG. From this and other relevant information I was reluctant to reject Eysenck's theory and began to consider the possibility that failure to discover any EEG and personality relationships was due to the inadequacy of the methods and measures employed.

Further study of the literature revealed that the EEG measures used in personality studies were entirely superficial and virtually every study used different methods or experimental conditions. Since the methods and measures employed lacked any theoretical basis it was impossible to know the meaning of the results. It was very obvious that the data would confound the activity of different neural systems as well as confounding the activity of excitatory and inhibitory neurons. There was also no basis for making a distinction between

differences in thalamocortical activity or arousal that relate to intrinsic functional properties of the cerebrum, and differences in arousal determined by extra-cerebral brain systems that can alter the state of activation of the cerebrum as a function of time, internal body states, and environmental circumstances. To overcome these problems and develop adequate methods and measures I could see that it would be necessary to acquire a better understanding of the physical character of EEG activity and of the neural systems that generate the EEG.

The Physical and Neurological Significance of Oscillating EEG Activity

Since the most obvious feature of EEG activity is that it oscillates I became convinced that this brain electrical activity should be studied using the concepts and methods of physics that enable us to understand and evaluate the properties and dynamic character of other systems that oscillate. As I learned more about the nature of systems that generate oscillatory activity, and became more familiar with the neurophysiological literature, I realized that systems of interacting excitatory and inhibitory neurons have the same basic features of organization and function that characterise the elements of simple electrical and mechanical oscillators.

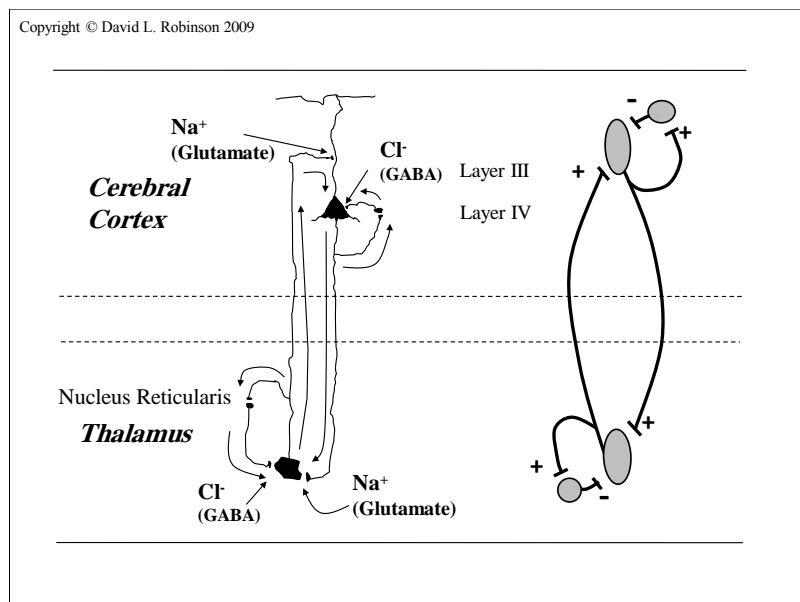


Figure 2. Drawings of thalamocortical neurons which show how ‘excitatory’ and ‘inhibitory’ neurons interact within a closed loop or circuit.

At an early stage in my research I was able to establish that thalamocortical activity could be evaluated in terms of the equations that describe the dynamics of simple mechanical and electrical oscillators (Robinson, 1983). However, it has taken many years to develop an adequate understanding of the manner in which neural circuits generate oscillatory activity. Figure 2 shows how excitatory glutamatergic neurons of the cortex and thalamus form closed loops or circuits. Another particularly important functional feature of these neural circuits is that the axons of the excitatory neurons project collateral branches to excite inhibitory neurons and, in turn, these inhibitory neurons project back to inhibit the excitatory neurons. If reference is made to the universally applicable laws of physics it becomes evident that the organization and functional properties of these circuits will cause oscillatory activity to occur in the same way as oscillatory activity is generated in other simple oscillators.

Figure 3 illustrates the analogous properties and organization of mechanical,

electrical, and neuronal oscillators that cause the physical effects which result in oscillatory activity. For the sake of clarity I have not included a resistor in the electrical oscillator. It is also usual to draw the plates of an electrical capacitor ‘back-to-back’ but here it is important to show that in simple oscillators there are always two distinct elements, or mutually exclusive states of a single element, in which potential energy is stored. These three systems all have the essential features that are necessary for oscillatory activity to occur.

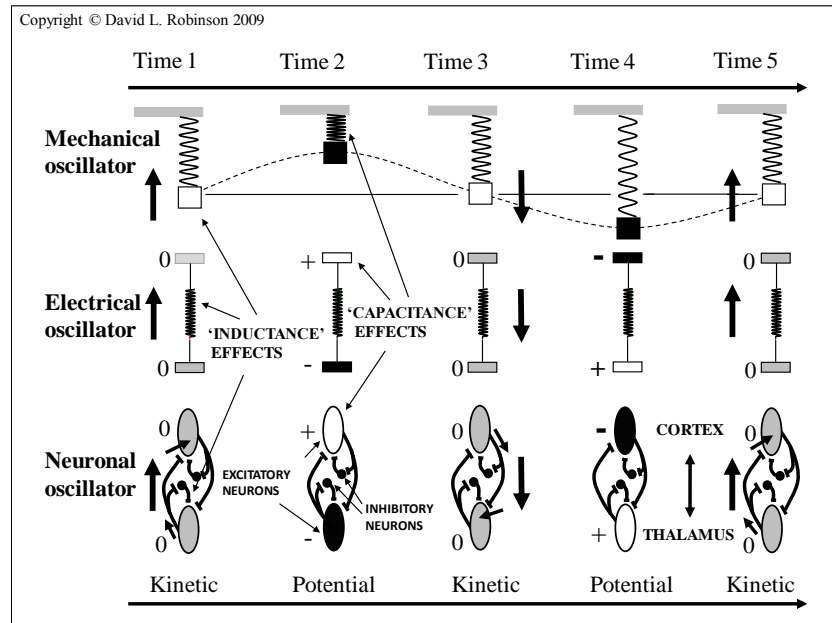


Figure 3. The analogous properties and organisation of mechanical, electrical and neuronal oscillators that are responsible for the physical effects which cause oscillatory activity.

First, there are two different elements, or two mutually exclusive states of a single element, that allow energy to be stored in a static or ‘potential’ form at two different locations. Secondly, there is a medium or substance that can move or flow between these locations so that potential energy can be converted into the kinetic energy of motion. Oscillatory activity occurs when the energy introduced by a transient disturbance is converted successively into static potential energy and into the kinetic energy of motion as it is transmitted to and fro between the elements that store potential energy. In thalamocortical oscillators the energy associated with oscillatory activity is stored in large excitatory neurons of the cortex and thalamus and the effective medium of energy transfer is the trans-membrane sodium ion current. As discussed in more detail elsewhere, the transmission of neural impulses is like an electrical relay that connects one part of a system to another but does not introduce physical effects that contribute to the generation of oscillatory activity (Robinson, 2009).

The ‘natural frequency’ of the ‘free oscillation’ of a simple oscillator is determined by the amount of time required to transfer energy from one potential energy storage element to the other. Thus frequency is directly related to transmission time within these systems. This transmission time is determined by two factors. First, there is the energy storage capacity of the elements that store potential energy. This energy storage capacity is greater in the case of more compliant springs, larger capacitor plates, or larger neurons that provide a greater volume for the distribution of charged sodium ions. When this storage capacity or capacitance is greater a longer period of time is needed in order to convert the kinetic energy of flow or movement into potential energy. For the sake of clarity I have ignored the normal

conventions and in every system the capacity for storing potential energy is indicated by the letter C.

The second factor that determines the amount of time required for the energy transfers is the 'inertia' of the medium that moves or flows. The effect of inertia is most easily explained in terms of the mass of the body appended to the spring in Figure 3. The mass of the body opposes changes in the rate of movement or flow. Thus, when mass is greater it takes longer for the potential energy of the compressed spring to be converted into the kinetic energy of the moving body. That is to say, a greater amount of time is required for the spring to move from full compression to its equilibrium position. Similarly, when the mass of the body is greater it takes longer for movement to cease after the spring passes through its equilibrium position and motion begins to be opposed by extension of the spring. The inductance of the coil in the electrical circuit causes similar inertial effects that oppose changes in the flow of current. Again, for the sake of clarity, I have represented the properties causing inertial effects in all systems by the letter L.

From the diagram one can see that in the case of the neuronal oscillator there is negative feedback through the small inhibitory cells. Initially, this negative feedback opposes an increase in the rate at which action potentials are generated by the excitatory neurons. This slows the transmission of neural impulses and, in effect, slows the 'transfer' of energy from one excitatory neuron to the other. Subsequently, however, a second effect of the inhibitory activity is to cause the hyper-polarization of intracellular potential in the excitatory neurons. This occurs just prior to the point in time when the 'inhibited' excitatory neuron in the thalamocortical circuit is re-excited by the excitatory neuron that was the target for the impulses transmitted initially by the neuron that is now inhibited. Hyper-polarization just prior to the arrival of excitatory impulses will increase the amount of time during which positively charged sodium ions can flow into the hyper-polarized neuron during the excitation phase of the excitation-inhibition cycle. Thus the second effect of the inhibitory neurons on the flow of sodium ions into excitatory neurons is analogous to that of momentum due to mass in a mechanical system or to the 'momentum' imparted by inductance in an electrical circuit.

In the case of the neuronal oscillator shown in Figure 3, 'C' represents the volume of distribution of charge within the bodies of excitatory neurons and 'L' represents the inertial effects due to inhibitory neurons on transmission between the excitatory neurons. In less formal terms, $1/C$ represents the effectiveness of excitatory neurons, while L represents the effectiveness of the inhibitory neurons.

The constant R relates to dissipation or loss of energy – as in the case of friction in a mechanical system or resistance in an electrical circuit. In the neuronal oscillator, R can be related to membrane resistance and any other factors which dissipate the energy of an input and cause an impedance effect that is not frequency-dependent. This caveat is important since the capacitance and inductance effects associated with excitation and inhibition also cause impedance effects but in both cases these impedances vary as a function of frequency. Since neuronal oscillators are active rather than passive systems that are energized by their environment it is important to note that any effective gain in energy will reduce the value of R. Thus, negative values of R are possible but this would result in something like the activity recorded during epileptic seizures with the growth of high-amplitude oscillations that would be sustained until the metabolic resources of the system are exhausted.

From the formulae shown in Figure 4 one can see how the excitation and inhibition constants determine the natural frequency (NF) of the system. When the product of L and C is greater the natural frequency is lower. Alternatively, we can say that when the quotient of L (inhibition) divided by $1/C$ (excitation) is greater natural frequency will be lower. From this it should be evident that *natural frequency is a direct index of the relative influence of*

inhibitory and excitatory neurons. In fact, natural frequency is the reciprocal of the inhibition-excitation ratio such that a high natural frequency indicates predominance of excitation over inhibition whereas inhibition is predominant when the natural frequency is low.

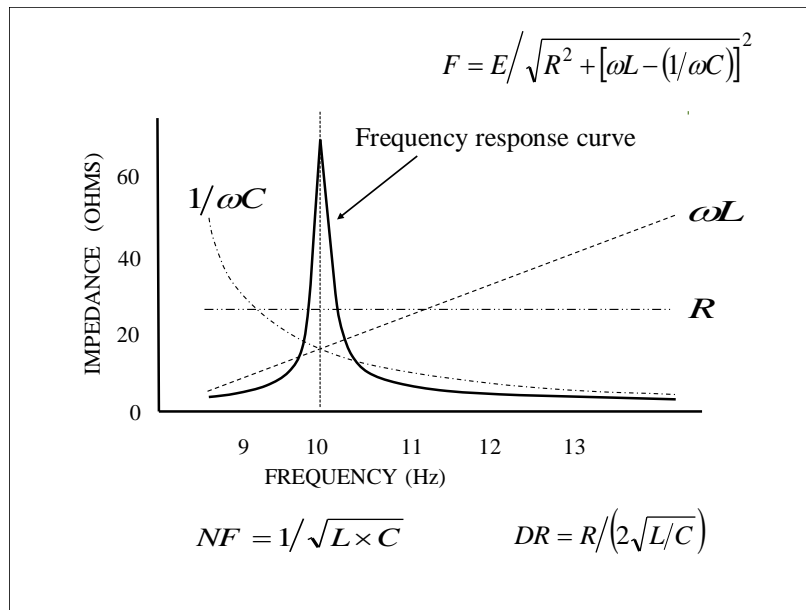


Figure 4. The diagram illustrates how the ‘capacitance’, ‘inductance’ and ‘resistance’ properties of a simple oscillator determine differences in natural frequency and damping ratio. The equation in the figure is a steady-state solution for the equation for forced harmonic motion where E is a driving ‘effort’ variable and F is an output ‘flow’ variable. This equation shows how the impedances due to the L, C and R parameters in combination determine the shape of an oscillator’s frequency response curve (ω = Frequency in Radians/Sec; Radians x 0.1591 = Hertz).

There is an impedance due to capacitance ($= 1/\omega C$) which reduces as frequency (ω) increases. An impedance due to inductance ($= \omega L$) increases as frequency increases. A resonance peak occurs at the specific frequency where the opposed impedances due to capacitance and inductance cancel out. The amplitude of the steady-state response to a driving sinusoidal input at this ‘natural frequency’ is only limited by the impedance due to resistance (R). The sharpness of the resonance peak depends on the damping ratio (DR) of the system. This is determined by the rate at which the system loses energy and depends on the values of R, L and C as shown in the Figure. From this, one can see how the natural frequency and damping ratio parameters provide a comprehensive description of the frequency response curve that is characteristic of a particular oscillator. It should also be emphasized that the dynamic character of a simple oscillator is immediately evident from observation of its behavior following any transient disturbance. First, there is the frequency of the oscillatory activity and secondly there is the persistence or duration of this activity. The former is determined by the system’s natural frequency and the latter by its damping ratio. From this it should be evident that the behavior of a simple oscillator should be evaluated in terms of these two parameters. In doing so there also is the great advantage that the observed behavior can be related in a meaningful way to the functional properties of the components that constitute the system.

Figure 4 also shows that the impedance caused by resistance does not alter as a function of frequency. The impedance caused by capacitance is greatest at low frequencies

because there is more time in each cycle of an oscillation for potential energy to accumulate and oppose the movement or flow in a system. The impedance due to inductance is greatest at high frequencies because the inertial effects that oppose changes in the rate of flow are greater when changes in motion are more frequent and occur faster.

Again referring to Figure 4, there is one particular frequency where the impedances due to capacitance and inductance are equal. Since these impedances are opposed they cancel out. At this particular frequency the amplitude of the steady-state response to a driving input builds up to a higher value because it is only limited by the impedance due to resistance. That is why the frequency of resonance is entirely determined by the capacitance and inertial properties represented by the constants C and L. The frequency of resonance alters as a direct consequence of differences in the L to 1/C ratio and in the case of thalamocortical oscillators this means that the frequency of the resonance peak is another indicator of differences in the ratio of inhibition to excitation

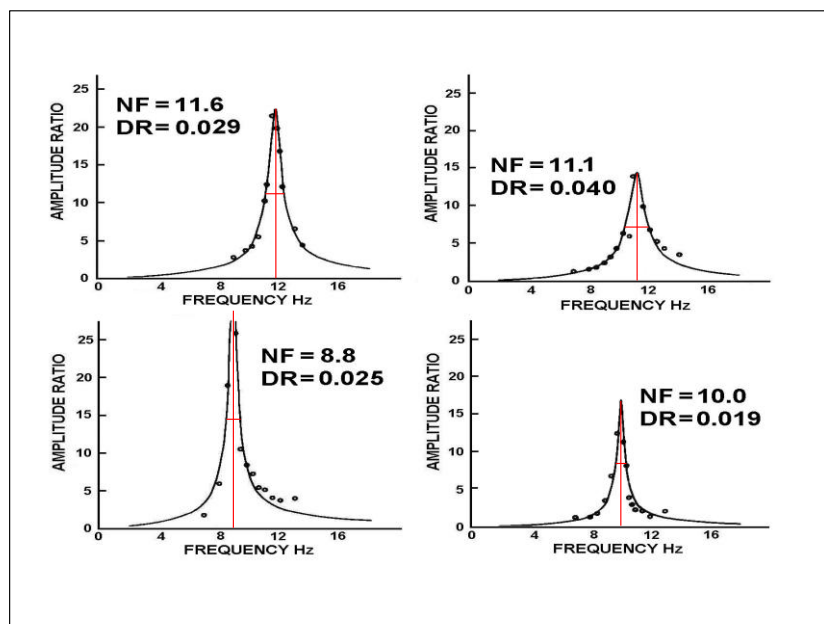


Figure 5. The fit of the simple harmonic oscillator model for EEG frequency responses from four different individuals. Across these four individuals one can see how the natural frequency and damping ratio parameters vary from person to person.

The height of the resonance peak is inversely related to the value of R. Less obviously, the values of L, C and R all help to determine the sharpness of the resonance peak. This is so because the impedance due to R limits the height of the resonance peak and at this resonance frequency the impedances due to L and C cancel out. However, at frequencies above or below the resonance peak the impedances due to L and C are not equal and the impedance difference depresses the amplitude of oscillatory activity. From the Figure it can be observed that the magnitude of this impedance difference at any given frequency depends on the ratio of L to C. It is also evident from the diagram that the magnitude of the impedance attributable to the difference between L and C increases as frequency either increases above the resonance frequency or reduces below it. This is consistent with the fact that the L to C ratio appears as the denominator in the expression used to calculate damping ratio.

To test my thalamocortical oscillator theory I used sinusoidal modulation of the luminance of a large-field visual stimulus to generate corresponding sinusoidal EEG

responses. A full account of the methodology and the conditions necessary to control for non-linearity of the visual system is provided in Robinson (2009). Here it will suffice to state that in 48 independent tests of the oscillator theory there was confirmation that the curves generated by the oscillator equation shown in Figure 4 could account for variation of the peak-to-peak amplitudes obtained at different frequencies of stimulation in the alpha range. In other words, thalamocortical oscillators can be described and understood in terms of the same laws of physics that govern the behavior of other simple oscillators.

Examples of the frequency response curves obtained from four individuals are shown in Figure 5. One can see that the theoretical oscillator curves fit the data very well. More generally, the curves generated by the oscillator equation were able to account for over 95% of the amplitude variance in 45 out of the 48 individuals studied. The resonance peak occurs at the natural frequency of the system. In this case the alpha-frequency thalamocortical system. Differences in damping ratios are indicated by differences in the sharpness of the peaks. These data do not relate to individual thalamocortical oscillators but to the aggregate activity of many thalamocortical circuits being driven in a synchronised manner by the light stimulus.

The Neurological Basis of Personality and Intelligence Dimensions

Mapping Relationships between the Thalamocortical Oscillator Parameters

It was evident from the beginning that the oscillator parameters were strongly related to personality and intelligence differences (Robinson, 1982) but initially much was obscured because of the complex nature of the relationships existing between the oscillator parameters. Since these relationships were unknown and difficult to unravel it was only very recently that I could claim to have a more or less complete understanding of the data. Previously I had not been able to achieve a full understanding because it had never occurred to me that I should treat the numerator and denominator of the damping ratio as separate variables. When I did so, and when I developed a multivariate mapping technique which allowed me to see all relationships simultaneously, it was immediately evident that the oscillator parameters can account for most of the variance of all the major dimensions of personality and intelligence. In addition, it was evident that these data provided answers to many questions concerning the neurological and psychological significance of the various dimensions. For example, it is particularly useful to have a clear picture of the manner in which conjunction of the dimensions determines the basic psychological profiles of a small number of particular personality types; and to understand why some of these types are emotionally unstable and vulnerable to the development of particular psychiatric disorders.

Despite a relatively small sample size of 48 individuals the two multivariate maps in Figure 6 provide a clear and unambiguous picture of the relationships between the oscillator parameters and there are solid reasons for believing that the full range of variation in the general population is represented in these maps (Robinson, 2009). The X axis is natural frequency and it will be recalled that this is inversely related to the ratio of L (inhibition) to 1/C (excitation). The Y axis is the denominator used in the calculation of the damping ratio and since this is the product of L and 1/C the plotted points account for the total variance of the excitation and inhibition parameters. Notably, higher values of natural frequency signify *both* greater ‘arousability’ and predominance of glutamate mediated thalamocortical excitation over GABA mediated thalamocortical inhibition. Higher values on the Y axis also signify greater ‘arousability’ since this axis represents the combined excitability of both excitatory and inhibitory neurons.

Considered solely in terms of the X and Y variables arousability would be greatest in

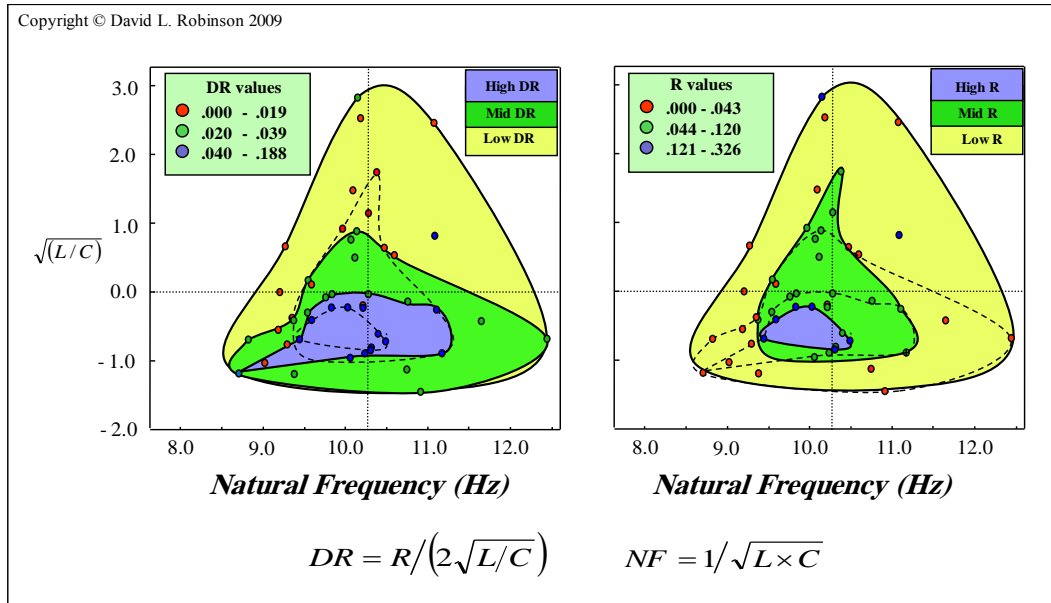


Figure 6. In both graphs the points have been plotted with natural frequency (inhibition-excitation ratio) on the X axis and the L to C ratio (= L x1/C, the product of excitatory and inhibitory excitability) on the Y axis. In the left graph high values of damping ratio occur in the blue area, moderate values in the green area and low values in the yellow area. The right graph is identical to that on the left except that the blue, green and yellow areas show areas of high, moderate and low values for R, respectively. These two graphs show how the oscillator parameters vary from person to person and they also show their complex inter-relationships.

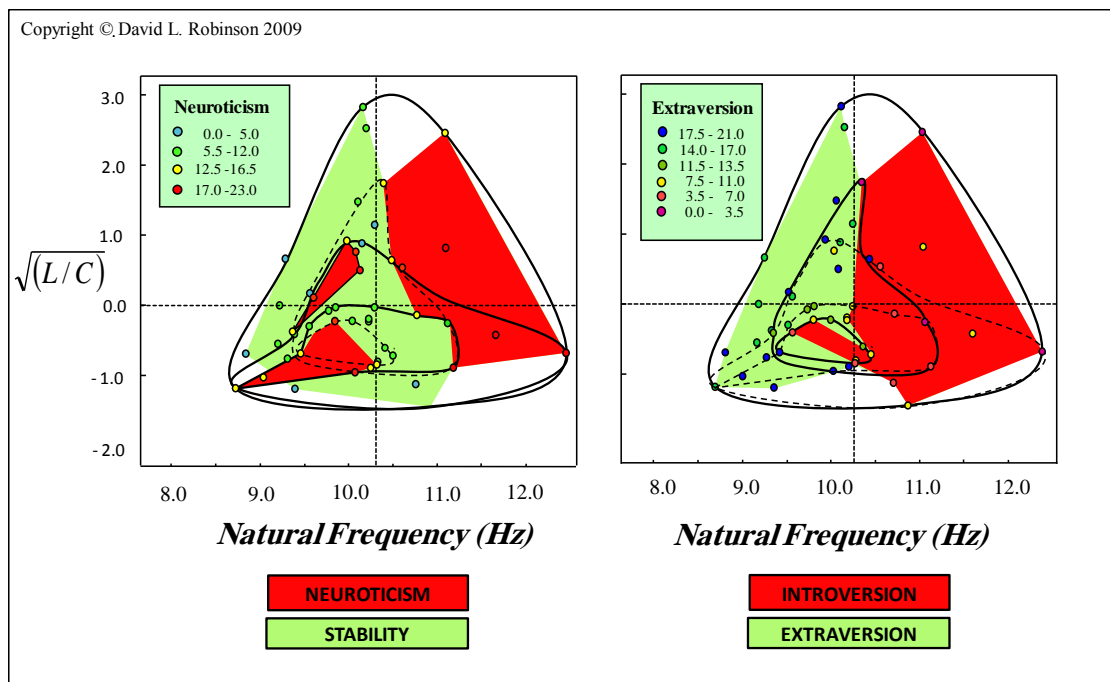


Figure 7. The points in the two graphs are plotted as in Figure 6. The red areas on the left graph include all individuals with high neuroticism scores. The green area includes all individuals with low neuroticism scores. With just one exception, the red area on the graph on the right includes all introverted individuals. Again with just one exception, all individuals in the green area are extraverted. The dashed and continuous lines are explained in the text.

the top right area of the maps and least in the bottom left areas. Since the term ‘arousability’, like ‘excitability’, refers to the ease with which a state of activation or arousal can be generated, or to the potential for activation, one would expect, all else equal, that differences in arousability would be strongly correlated with differences in the state of actual activation or arousal. Since R is thought to be an index of the general state of thalamocortical activation it follows that R should be greatest in the bottom left low arousability region of the maps and highest in the top right region. However, as shown in the map on the right side of the Figure, R is greatest in the middle region of the map and becomes lower with movement towards the periphery.

An explanation for this, proposed in the author’s theory (Robinson, 2009), is that low thalamocortical arousability means weaker inhibition of the brain-stem arousal system by descending projections from the thalamocortical system. This disinhibition of the brain-stem arousal system must result in greater ascending excitatory activity with the result that there can be very high brain-stem mediated thalamocortical arousal when thalamocortical arousability is very low. Thus, there is high *intrinsically determined thalamocortical arousal* when thalamocortical arousability is very high and high *brain-stem mediated thalamocortical arousal* when thalamocortical arousability is very low. It is also probable that an exact balance between thalamocortical excitation and inhibition will prevent the synergistic lateral spreading of activity so there is an additional reason why very high values of R would be expected in the central region of the maps. This view is supported by the observation that there is a very marked and steep increase in the values of R in the central region of the maps which indicates that in this region a corresponding disinhibition of the brain-stem arousal system is unable to increase thalamocortical activation and reduce R. In other words, thalamocortical oscillators in the central region are relatively inert and difficult to excite because the balance of excitation and inhibition prevents synergistic activity.

Finally, it is important to consider the distribution of damping ratio values. It will be recalled that R is the numerator of the damping ratio so it is not surprising that the distribution of damping ratio shown on the map on the left is similar to that of R. However, there is a difference since damping is also determined by the L to C ratio, which is to say by the Y axis of the graph. Lower values on the Y axis mean higher damping ratios and lower arousability and we can see that, as a consequence, damping is generally greater in the lower half of the map and that the region of very high damping extends down towards the bottom left of the map. Notably, in this bottom left region high damping can co-exist with low values of R and high thalamocortical arousal. Here the high damping ratios are due to low values on the Y axis (low values for the damping ratio denominator) and since natural frequency is low and damping is high – both contributing to low arousability – the low values of R must be attributed to disinhibition of the brain-stem arousal system and to the fact that an imbalance of thalamocortical excitation allows or does not prevent synergistic activity.

It will soon be evident that although R and damping are related they have distinct psychological consequences. It is also noted that near the centre of the maps there is a region where R and damping are both very high and this means that the thalamocortical system is least active and least excitable. Towards the bottom left there is very low natural frequency in combination with high damping so again arousability is low. However, in this region there can be high arousal mediated by the brain-stem arousal system. Finally, it is noted that there is an exact balance of thalamocortical excitation and inhibition at about 10.3 Hz and this frequency is indicated by the vertical line drawn on the graph.

Thalamocortical Oscillator Properties Causing High and Low Neuroticism

Turning now to Figure 7, the concentric dashed and continuous lines are used to show the distributions of R and damping ratio as already indicated by the coloured regions in Figure 6. The map on the left side of the Figure shows the distribution of high and low neuroticism scores and here the continuous concentric lines show the distribution of damping ratio since it is the combined influence of natural frequency and damping that accounts for the variance of neuroticism rather than the variation of arousal indicated by variation of R. On the right side of the map, and above the 10.3 Hz frequency where there is a balance of excitation and inhibition, it can be seen that high neuroticism is invariably associated with either high values of natural frequency, or very low values of damping, both indicating high arousability, and with low values of R indicating a correspondingly high level of thalamocortical activation or arousal that is a consequence of this high arousability. It is also evident that the area of high damping, which extends above the 10.3 Hz frequency and counteracts high arousability due to high natural frequency, is associated with low neuroticism scores. In effect, all individuals with natural frequencies above 10.3 Hz have high neuroticism scores except in the specific area where high arousability due to high natural frequency is countered by low arousability due to high damping so that there is an intermediate degree of overall arousability.

The situation is a little more complicated when we come to consider the distribution of neuroticism below the 10.3 Hz frequency because there are two distinct areas where neuroticism is high. However, if we turn first to the larger area where neuroticism scores are high, at the bottom left on the map, we can see that this area is quite clearly the region where there is a combination of very low natural frequency and high damping. The combination of parameters that indicates very low thalamocortical arousability. However, as already discussed, there are also very low values of R which in this case indicates high arousal due to disinhibition of the brain-stem arousal system and more effective ascending excitatory projections from the brain-stem into the thalamocortical system. These results provide confirmation of the hypothesis that neuroticism will be higher when arousability is either very high, or very low, and the thalamocortical system is functioning at the extremes of its normal operating range. At first glance one might conclude that it is the high arousal and low R values associated with high and low arousability that is the common cause of high neuroticism scores. However, inspection of the map shows that it is the distribution of high damping and not the distribution of R that defines the region of high neuroticism under discussion. That is to say, there are other areas in the region below 10.3 Hz where R is low, and even very low, and neuroticism scores are not high.

As already noted, in the low natural frequency region the situation is complicated by the occurrence of a second smaller area where there are high neuroticism scores. In this case, the values of natural frequency are low and overlap to a considerable extent with those of the high neuroticism group just discussed. Damping is at the low end of mid-range values and R is at the high end of mid range values. Thus, in this case we cannot draw any very definite conclusions concerning the cause of the high neuroticism scores. Arguably, the marginally low natural frequency values of most individuals in the group are not sufficient to counter the low damping ratio values. This would mean that high neuroticism in the low natural frequency region below 10.3 Hz is mostly due to low arousability but in a minority of cases may be due to high arousability if natural frequency is not too low and this is accompanied by low damping ratios.

The last but nevertheless important observation is that high neuroticism scores are much less in evidence when natural frequency is below 10.3 Hz as compared with individuals having natural frequencies above 10.3 Hz. In fact the average neuroticism score for individuals with low natural frequencies is lower than for individuals with high natural frequencies despite similar average values for damping ratio and R in the high and low frequency domains. It is also difficult to attribute this neuroticism difference to natural frequency, *as a*

contributor to arousability differences, because we have seen that high neuroticism is associated with either high or low arousability. However, it will be recalled that *differences in natural frequency signify differences in excitation-inhibition balance as well as differences in arousability*. Thus, it can be suggested that predominance of excitation above the 10.3 Hz frequency increases neuroticism while predominance of inhibition below 10.3 Hz reduces neuroticism – and that this effect is additional to any variation of neuroticism scores caused by differences in arousability.

Thalamocortical Oscillator Properties Causing Introversiion-Extraversiion

The red and green colours of the multivariate map on the right side of Figure 7 show the distribution of introversion-extraversion scores. In all other respects the map on the right side of Figure 7 is identical to that on the left side except that the continuous concentric lines indicate different levels of R rather than different levels of damping. The reasons for this should be obvious from comparison of the neuroticism and introversion-extraversion maps. In the neuroticism map it is immediately evident that high damping reduces neuroticism in the high natural frequency domain whereas high damping increases neuroticism in the low natural frequency domain. In contrast, there is no similar effect of damping on introversion-extraversion scores and it is only the very high values of R in the central region of the introversion-extraversion map that can cause a few exceptions to the very obvious general principle that individuals with natural frequencies above 10.3 Hz are introverted and those below this frequency are extraverted. In fact there are only two exceptions to this rule that are not accounted for by the very low values of R in the central region of the map.

The fact that damping ratio seems to have little influence on introversion-extraversion indicates that introversion-extraversion differences are not determined by differences in thalamocortical arousability - and this would rule out natural frequency as a causal agent *if natural frequency is considered only in terms of its contribution to differences in arousability*. However, as already emphasized, natural frequency is not just a contributor to arousability differences *it is also an index of the relative influence of glutamate mediated excitation and GABA mediated inhibition*. Thus, what the data indicate is that introversion is largely determined by predominance of thalamocortical excitation over inhibition, as indicated by natural frequencies above 10.3 Hz, and that extraversion is largely determined by predominance of inhibition over excitation as indicated by natural frequencies below 10.3 Hz. A particularly striking feature of the introversion-extraversion map in Figure 7 is that there is an abrupt change from extraversion to introversion at the particular frequency of 10.3 Hz where there is an exact balance between thalamocortical excitation and inhibition. This would not be expected if introversion-extraversion was determined by differences in arousability that depend on various different combinations of natural frequency and damping as in the case of neuroticism. One would not rule out some minor modification of introversion-extraversion scores as a consequence of differences in arousability but it is very clear from the data that it is almost always the case that differences in the balance of excitation and inhibition determine whether one is introverted or extraverted. As already noted, the only significant exception to this rule is when the value of R is extremely high and arousal extremely low.

Thalamocortical Oscillator Properties Determining Different Temperament Types

For over 2000 years the most eminent physicians and philosophers described personality in a wholistic manner and their direct observation of people led them to conclude that there were four distinct personality or temperament types. The modern emphasis on personality

dimensions was originally motivated by the aspirations of early psychologists who thought it important to identify dimensions that could be measured using graduated scales. For example, Wundt proposed two dimensions to account for the personality differences of the four temperament types. Notably, Wundt did not challenge the existence of personality types since his dimensions were conceived as a way of describing and measuring the differences between these types.

In the intervening period the application of powerful methods of statistical analysis has revealed the existence of the introversion-extraversion and neuroticism dimensions. The same methods have been used to construct reliable questionnaire measures that can provide quantitative information in terms of introversion-extraversion scores and neuroticism scores. Unfortunately, many personality psychologists have become so preoccupied with the study of questionnaire data that they have forgotten the temperament types. This is unfortunate since to understand personality one must first describe and classify different personalities and then seek to understand why they differ.

However all is not lost since a particularly important but unrecognized outcome of the modern research is that it confirms the existence of the temperament types. Thus, when the introversion-extraversion and neuroticism dimensions are used as coordinates, as illustrated in Figure 1, they identify the four classical temperament types. It is these types that correspond to actual people and actual personalities. The dimensions are only useful when this fact is recognized and they are used in conjunction with each other to specify actual personalities that can be studied in a meaningful manner. For example, a high neuroticism score is not very useful since melancholic and choleric individuals both obtain high neuroticism scores - despite the fact that they are opposites in terms of many features of the way in which they think, feel and act.

In Figure 8 high and low scores for introversion-extraversion and neuroticism have been used as illustrated in Figure 1 to define the four classical temperament types. The expectation from theory was that the emotionally stable sanguine and phlegmatic types would have an intermediate degree of thalamocortical arousability – as defined by the combined values of natural frequency and damping ratio – and that the emotionally unstable melancholics would have high arousability whereas the emotionally unstable choleric would have low arousability (Robinson, 2009).

The map on the left side of Figure 8 shows that individuals in the four temperament categories are clustered in quite specific areas. The data are very precise and unambiguous and the only possible interpretation is that these personality types are determined by specific combinations of the thalamocortical oscillator parameters. Beginning in the high natural frequency domain on the right side of the map on the left one can see that virtually all individuals are either melancholic or phlegmatic. The melancholics (introversion and high neuroticism) occur in the region shown in earlier figures where high natural frequency is associated with lower values of damping ratio and there is therefore greatest arousability. Phlegmatics (introversion and low neuroticism) occur in the region where high natural frequency is associated with high damping - such that there is an intermediate degree of arousability.

When one considers the region below 10.3 Hz where natural frequency is low it is evident that the sanguine temperament (extraversion and low neuroticism) occurs when low values of natural frequency are compensated by low values of damping so that there is again an intermediate degree of arousability. Choleric individuals (extraversion and high neuroticism) appear at two locations. Those in the area closer to the bottom of the figure have low natural frequencies in association with high damping so there is low arousability but notably this area is also associated with high arousal attributable to disinhibition of the brainstem arousal system. An interesting and revealing deviation from theoretical expectations is

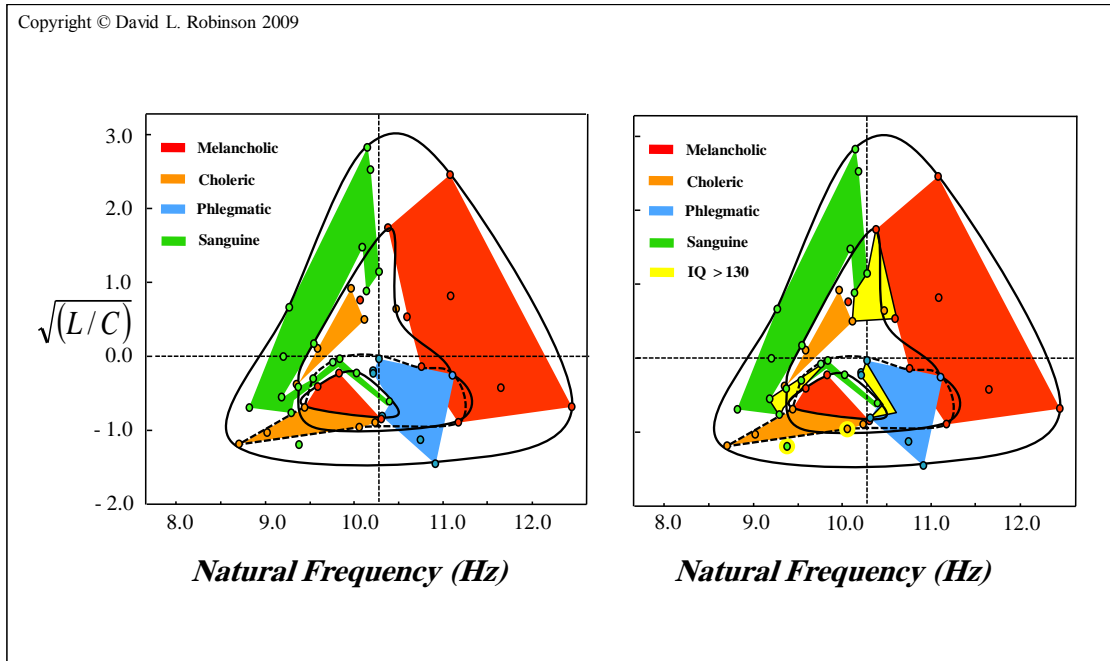


Figure 8. The four combinations of high and low introversion-extraversion and neuroticism scores define four different personality or temperament types as illustrated earlier in Figure 1. In the two maps shown in the Figure different colours are used to indicate combinations of oscillator parameters that determine the different temperament types. The yellow areas on the map on the right side of the Figure show where high IQ occurs. These specific areas embrace all individuals with WAIS IQ scores greater than 130.

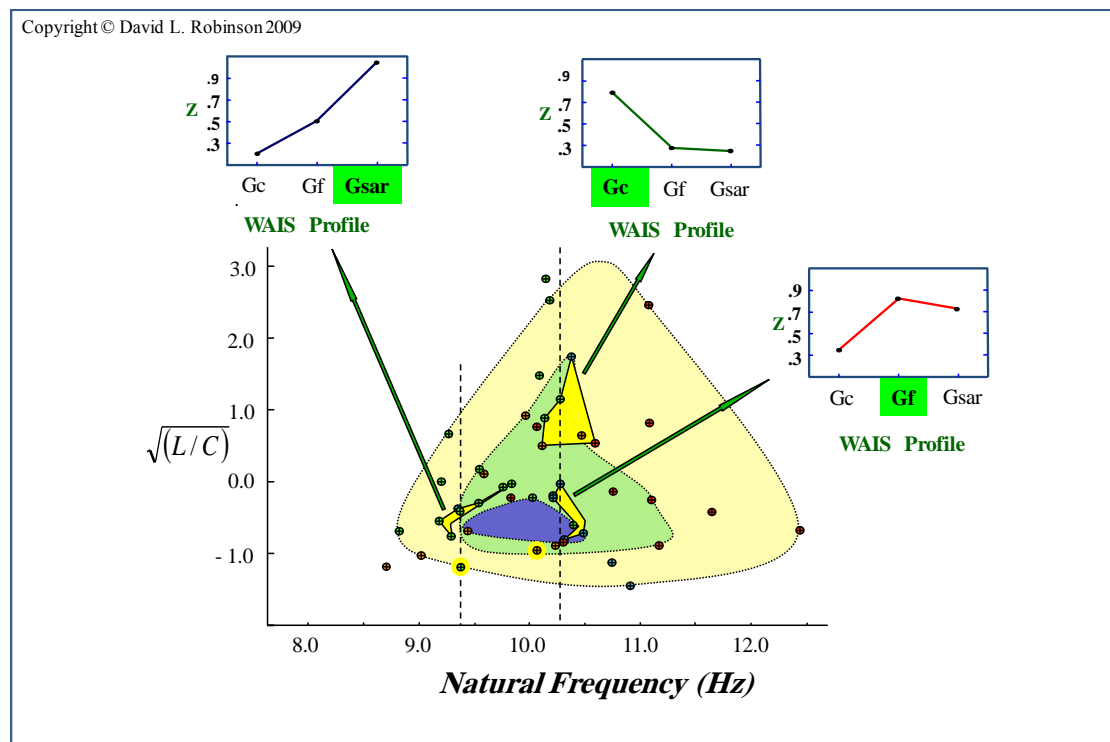


Figure 9. Multivariate mapping of thalamocortical oscillator parameters showing how different combinations of these parameters cause the Gf, Gc and Gsar intelligence dimensions.

that immediately adjacent to the choleric area just described there is a second small and circumscribed area where individuals have the melancholic combination of scores. In terms of the thalamocortical oscillator parameters these ‘melancholics’ are exactly opposite to the main group of melancholics. That is to say, they coincide exactly with the area where there is maximum damping and the highest values of R in association with low natural frequency. The only major difference between these individuals and the adjacent choleric is that they have the highest values of R – indicating the lowest thalamocortical arousal level – whereas the choleric have very low values of R indicating very high arousal (as distinct from their very low thalamocortical arousability).

This is not the place to dwell at length on the psychiatric significance of these data, and there are some who would ridicule conclusions drawn from such a small number of individuals. Nevertheless, it is important to note that all the personality and EEG variables used in the study span the full range of variance in the general population. It is also important to emphasize the precision of the measures employed, and to point out that one is not dealing with small effects that can only be detected using powerful statistical methods. The effects are very strong indeed and there is only a vanishingly small possibility that the complex and theoretically meaningful pattern of results so far described could occur by chance. On this basis it seems reasonable to expect that useful insights can be obtained from the observation that a small number of individuals obtain the melancholic combination of introversion and high neuroticism in the low frequency region where all other individuals have high extraversion scores.

From Figure 7 we already know that it is the very high values of R and the very low level of arousal that causes the small pocket of introversion in the extraversion domain and it is this that results in the ‘atypical’ group of melancholics. Another theoretically important consideration is that these melancholics are adjacent to a group of choleric and from careful inspection of the data one can see that there is a very abrupt transition from extreme introversion and neuroticism to extreme extraversion and neuroticism. The only thalamocortical parameter that can be responsible for this abrupt transition is R. This also changes very abruptly such that the extreme introversion is associated with very high R and very low arousal whereas the extreme extraversion is associated with very low values of R and high arousal.

The important point to be made here is that in this particular region it only requires a very small change in the arousability parameters to produce a very large change in the level of arousal and a correspondingly dramatic change in personality. It has long been known that very dramatic changes in personality are a feature of some psychiatric conditions and the observation of such changes are obviously related to the concepts of cyclothymia, manic-depressive illness, and bi-polar affective disorder. As Freud has pointed out, it is a very remarkable experience to observe cyclic alterations in personality during the course of psychiatric illness. Referring to ‘melancholiacs’, he notes that after some months the critical voice of the superego is silent and something exactly the reverse takes place. The ego finds itself in an ecstatic state of exaltation and gives itself up in a really uninhibited fashion to the satisfaction of all its desires. This contrast is simply an exaggerated reflection of the normal distinction between the melancholic and choleric temperaments.

There remains the second small group of choleric. These individuals cannot be associated with any very extreme values, or combinations of values of the thalamocortical parameters. Their natural frequencies are similar to those of the other choleric group but they differ in terms of both R and damping. Their values of R are moderately high indicating low but not very low arousal and their damping ratios are at the low end of the range. Their extraversion can be attributed to their low natural frequencies but there is no very obvious explanation for their high neuroticism scores. A tentative proposal is that their natural

frequencies are not low enough to compensate for their low damping ratios and consequently their level of arousability is too high. This would mean that there are both ‘low arousability’ choleric and ‘high arousability’ choleric. One would not anticipate identical personality profiles and they are only given the same ‘choleric’ label because high neuroticism scores can be due to either very high or very low arousability. An important insight provided by the thalamocortical data is that even when the dimensions of introversion-extraversion and neuroticism are used in conjunction with each other there is still some ambiguity in the identification of personality types. In this review we have seen already that the melancholic combination of scores can be obtained by two groups that differ greatly in terms of the thalamocortical parameters. Now also we see that there is a similar ambiguity with respect to the choleric combination of scores. One imagines that similar ambiguities exist with respect to psychiatric diagnoses based on the classification of superficial observations and the subjective reports of patients.

Thalamocortical Oscillator Properties Determining the Intelligence Dimensions

The initial idea that led me to expect that differences in the thalamocortical oscillator parameters should relate to intelligence differences was that an intermediate level of arousal should be optimal for information transmission by neural processes, for working memory, for the regulation of attention, and for learning. In this short article I cannot elaborate further and the interested reader will have to refer to my recent book for a more detailed account of the theoretical issues (Robinson, 2009). Here it will suffice to draw attention to some empirical results which complement the personality data already discussed and show how the thalamocortical parameters determine the major dimensions of intelligence identified in psychometric studies. An important result is that it is now possible to explain the dimensions of personality and intelligence within a common theoretical framework.

Spearman (1927) was the first to provide psychometric evidence to support the notion that there is a single dimension of intelligence – his ‘g’ factor. With the development of more sophisticated and powerful methods of statistical analysis it has been shown that a single statistical factor or dimension can account for a very large proportion of the variance in any diverse set of cognitive tests. For example, over 50 per cent of the variance of the 11 subtests of the Wechsler Adult Intelligence Scale can be represented by a single dimension or factor. It is clearly important to seek to identify the cause of this common variance and the strategy that I adopted in my data analysis was to ascertain whether all high IQ individuals have something in common. There are many reasons why an individual might obtain low IQ scores so it is only in very high IQ individuals that one can expect unambiguous identification of the specific neurological properties that are essential for exceptional performance on cognitive tests. Also, as already noted, there are theoretical grounds for supposing that an intermediate degree of thalamocortical arousability might result in generally good performance across a wide range of psychometric tests and it was this idea that directed my analysis of the data.

If reference is made to the map on the right side of Figure 8 one can see that the selection of individuals with IQ scores greater than 130 resulted in the identification of three specific subgroups. These subgroups are shown in yellow and it is immediately evident that they do tend to occur in those regions of the map where there is an intermediate degree of arousal. As elsewhere, different levels of R and arousal are indicated by the concentric continuous lines and although the yellow areas are not completely confined within the mid arousal region there are only a few individuals that fall outside, but still close to, the boundary. This appears to be the only common denominator across all three groups but there are two other features of the data that are associated with high IQ scores.

First, it can be observed that the two groups in the bottom half of the map fall in the

phlegmatic and sanguine areas where there is an intermediate degree of arousability and emotional stability. Not all sanguine individuals have very high IQs and the distinguishing characteristic of those that do is that they fall in a narrow region where a progressive reduction in natural frequency is compensated very exactly by a progressive reduction in damping. There is an exactly similar balancing of natural frequency and damping in the case of the high IQ phlegmatics. Again the high IQ individuals occur in a very narrow and circumscribed region and in this case increases in natural frequency are countered by increased damping. Finally, it can be observed that these two groups lie just outside the boundary of the area of very low R and very low damping – so much so that if the two groups were joined up they would form a narrow ribbon encircling the area of very low arousal and very high damping.

The second interesting feature is that two of the groups straddle the 10.3 Hz frequency where there is a balance of excitation and inhibition. In fact, most individuals that lie close to this frequency have high IQs. This suggests that middle arousal, middle arousability, and a balance of excitation and inhibition are all features of thalamocortical function that enable enhanced cognitive performance. Finally it is noted that none of these very high IQ individuals occur within the high neuroticism zones although a few of those in one of the groups do fall at the boundaries of high neuroticism zones and do have high neuroticism scores. Thus, the personality and thalamocortical data are consistent in that both suggest an intermediate degree of arousability.

It remains to state that although all three high IQ groups perform at above average levels on all 11 WAIS subtests there are also marked differences in their performance profiles. This is illustrated in Figure 9 where the profile differences are presented in terms of composite scores for those WAIS subtests that are considered ‘markers’ for Cattell’s ‘fluid’, ‘crystallized’ and ‘short-term memory and recall’ dimensions. The opposite profiles for the two groups that are aligned with the 10.3 Hz frequency of excitation-inhibition balance are particularly striking. Both groups have almost identical mean values for natural frequency but differ greatly in terms of damping ratio.

Members of the uppermost group have relatively low damping ratios and it is suggested that in this group the greater persistence of thalamocortical activity enhances associative learning and synthesis and that ultimately this facilitates performance on verbal tests evaluating the capacity for abstract thought. Members of the lower group have high damping ratios and it is suggested that this favours performance on tests of perceptual analysis and enhances comprehension of the operation of material systems and processes. Finally, it is suggested that the third group with lower natural frequencies have that combination of thalamocortical parameters which ensures an optimal balance between the thalamocortical system and brain-stem processes. For reasons that will not be considered here this is thought to enhance the capacity of working memory and enhance performance on measures such as the WAIS Arithmetic and Digit Span subtests.

The fact that the three groups have quite distinct performance profiles, and that these profiles are so clearly related to the tests that are markers for the fluid, crystallized and SAR dimensions, leaves little doubt that it is the corresponding differences in thalamocortical parameters that give rise to the three psychometric dimensions. Notably, the explanation suggested by the present findings is very different from that proposed in Cattell’s theory of intelligence (Cattell, 1987). There are also important implications concerning the nature and significance of intelligence tests, and implications concerning the character of the intelligence dimensions, but these cannot be discussed in this article.

Conclusion

In conclusion, the results that have been reviewed provide a complete and systematic description of the manner in which parameters that determine the oscillatory alpha band activity of the thalamocortical system relate to all the major dimensions of personality and intelligence. In science one can never claim absolute certainty concerning any conclusions and weaknesses can always be identified in any particular study. Thus the special value of the results that have been discussed is not that they prove anything beyond dispute but that they provide many new insights that have refined and greatly extended the foundation theories of Pavlov and Eysenck (Robinson, 2009). Nevertheless, given the clarity and strength of the complex and meaningful relationships that have been observed there are good grounds for believing that the results provide valid information, that variation of the thalamocortical parameters does cause the most obvious differences in normal temperament and cognition, and that extreme parameter combinations could cause the different forms of neurotic and psychotic disorders. With the techniques described in this account one would expect to be able to diagnose different psychiatric disorders and to monitor the therapeutic effects of different drugs either in drug research trials or during the treatment of patients. An important implication of the findings that have been described is that different forms of psychiatric illness cannot be related uniquely to the specific effects of particular drugs on particular neurotransmitters. That is to say, the implication is that it is the combined influence of excitatory and inhibitory neurotransmitters that would be important and the manner in which these transmitter substances together determine the natural frequency and degree of damping in the thalamocortical system. Ultimately, it is the manner in which drugs affect the physiology of neural systems that is important not the specific effects of drugs on particular neurotransmitter substances.

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