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Project Report

Variation in length of alpha waves reveals how forebrain activity is organized

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Abstract

Background

The cerebral cortex is composed of functional units known as columns. The “two levels” hypothesis states that the activity in a column is either at a high level or at a normal, relatively low level. Measurements indicate that the duration of the high activity in a column is around 450 ms. The number of highly active columns is often 4–5. These data are from previous studies on alpha waves in electroencephalograms. The idea is that alpha waves are created when a regulating system keeps the number of highly active columns within proper limits. If this is true, then regulating signals determines the length of the alpha waves, which opens up for a possibility to test the hypothesis.

Methods and results

Wavelengths were measured in sequences of alpha waves, and distinctive patterns in the wavelength variation were found. The elements of these patterns were repeated at intervals that exactly matched the predicted duration of high activity in individual columns.

Conclusions

The discovery of patterns in the wavelength variation confirms the central part of the two levels hypothesis. The patterns reveal the actual number of highly active columns.

Moreover, the duration of high activity in a column can be measured. Number and duration outside the optimal ranges may lead to a variety of symptoms.

Keywords

wavelength, patterns, functional organization, repetitions, cerebral cortex, columns, epilepsy, mental disorders

Introduction

Alpha waves in electroencephalograms (EEGs) contain information about how the activity in the forebrain is organized. The most valuable part of this information lies hidden deep within the wavelength variation and is not easily retrieved. At first sight, the variation in the length of the alpha waves may seem overwhelming and unpredictable (Gibbs and Gibbs 1950, Niedermeyer and Lopes da Silva 2005, Başar 2012, Bazanova and Vernon 2014).

The present report describes part four of a project that started with a theoretical analysis of the functional organization of the forebrain (Johannisson 1984). In the first part of the project, the main concern was to ensure that the suggested hypothesis was consistent with all available evidence. The second part came as a surprise when it turned out that the hypothesis can explain how alpha waves are generated (Johannisson and Nilsson 1996).

A major prediction was tested in part three of the project. The hypothesis predicted that there must be three main groups of alpha waves, and an experimental study succeeded in verifying that these groups exist (Johannisson 2016).

Highly specific patterns in the wavelength variation are analyzed in the fourth and final part of the project. Several examples of such patterns are given in the present paper, and they provide decisive information on the functional organization of the forebrain.

Wavelength variation and forebrain activity

To explain the variation in wavelength and its relation to the activity in the forebrain, we need to better understand the mind-brain problem (Bunge 1980, Sperry 1980, Gazzaniga 2012). Here, the attention is on the physiological part of the problem, not the philosophical and religious aspects.

The same building blocks can be expected to be found in the brain of a small mammal and in a human brain, though a large brain may have many more of these building blocks. The point is that we should search for basic principles that are reasonably simple (Kuffler and Nicholls 1976, Mountcastle 1997).

Fig. 1 illustrates a hypothesis that explains how and why the alpha waves are generated. In this hypothesis, the columns in the cerebral cortex are organized in a way that allows activity in a column to be either at a high level or at a normal, relatively low level (Johannisson 1984).

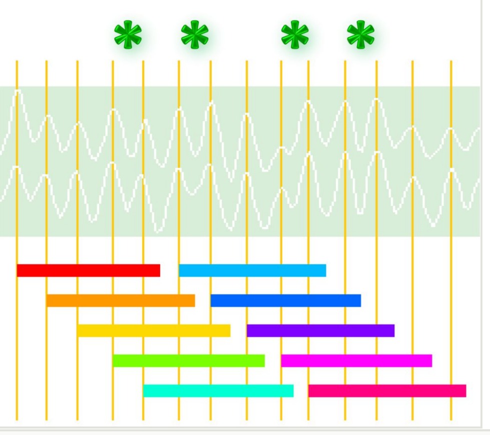

Figure 1. doi

The two levels hypothesis. The colorful horizontal lines represent the duration of high activity in individual columns. The vertical lines show the time relation to the alpha waves. The distance between two neighboring lines is the wavelength, and the green symbols indicate that some waves are a little bit shorter than other waves.

Signals from a regulating system

The number of highly active columns alternates between a lower limit and an upper limit (Johannisson and Nilsson 1996). When the number is at the lower limit, a regulating system increases the excitability until the activity in a column with low activity jumps up to the high level and the upper limit is reached.

At the upper limit, the regulating system decreases the excitability in columns with activity in the low-activity range. Thus, the regulating system causes small but synchronous changes in excitability in columns with low activity, and these changes can be recorded as alpha waves.

Data of the type shown in Fig. 2 indicate that the alpha frequency is determined by the number of highly active columns. As an example, if the number of highly active columns alternates between 4 and 5, then the signals from the regulating system give rise to waves where the frequency is around 10 Hz.

Three alpha groups

There are three main groups of alpha waves (Johannisson 2016). The frequencies in these groups are around 8 Hz, 10 Hz, and 12 Hz. The three groups are assumed to be seen when the limits for the number of highly active columns are 3–4, 4–5, and 5–6. Sequences of alpha waves from the groups are shown in Fig. 3.

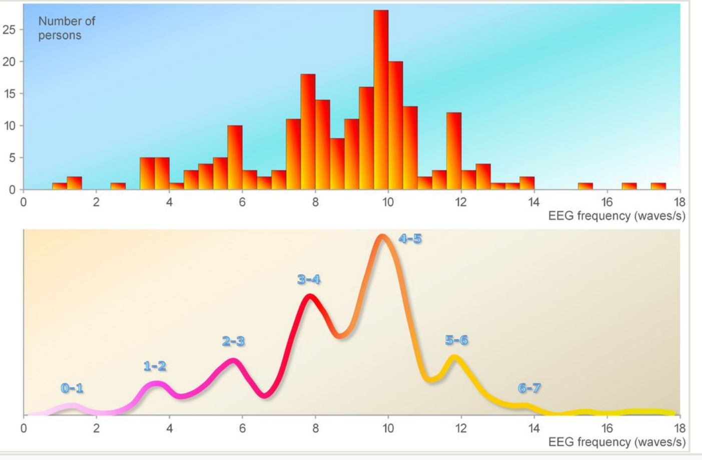

Figure 2. doi

Number of highly active columns and EEG frequency. The histogram shows the distribution of the frequency for 213 individuals. The data are from a pilot study described in another paper (Johannisson 2016). In the lower part of the figure, the data have been slightly smoothed and presented as a curved line. This makes it easier to see that there are different frequency groups. The smallest possible number of highly active columns should be found when the limits are set to 0 and 1. This may correspond to the first peak on the left. The other peaks can then be linked to higher limits in consecutive order.

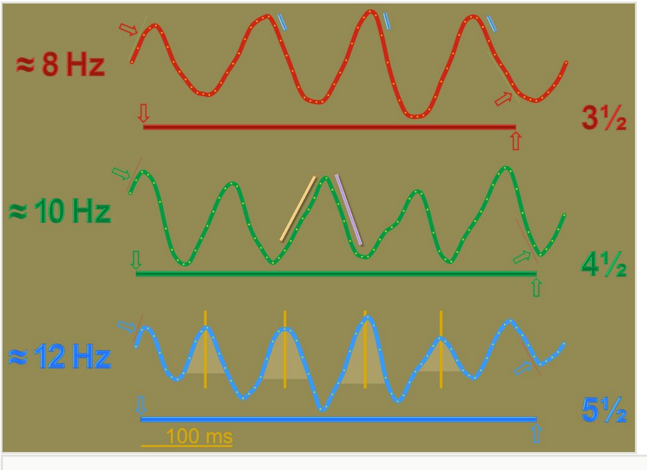

Figure 3. doi

Three types of alpha waves. The arrows indicate the beginning and the end of high activity in a column. The horizontal lines represent the duration of activity at the high level. The small blue bars indicate that the initial part of the downward slope often has a decisive start. The yellow and purple bars indicate that the upward slope is less steep than the downward slope. The vertical lines illustrate how the wavelength was measured. The EEGs are from participants 59, 51, and 149 in a previous study (Johannisson 2016).

The duration of the high activity in a column can be measured if the number of highly active columns is known. For example, in the alpha group at 12 Hz, the limits for the number are expected to be 5–6, and then the duration is approximately 5.5 times the wavelength (Fig. 3).

Patterns in the wavelength variation

The existence of the frequency groups in Fig. 2 supports the two levels hypothesis, but it is essential to find new and better evidence. The turnover of highly active columns must leave a trace of some kind, especially since there is a variation in the timing of the turnover (Fig. 3).

Thus, when the high activity in a column happens to start a little bit early, it may also stop a little early. Then the next column can start its high activity slightly early. This should generate a pattern in the variation of the wavelengths, and the elements in the pattern should be repeated at an interval that matches the duration of high activity.

Such patterns were indeed found, and this discovery is reported in the present paper. Fig. 4 shows a pattern in the wavelength variation that was found when the wavelengths were measured in an EEG published 70 years ago (Gibbs and Gibbs 1950). The pattern has been there all these years, but it can be seen clearly only when using an appropriate method for the analysis.

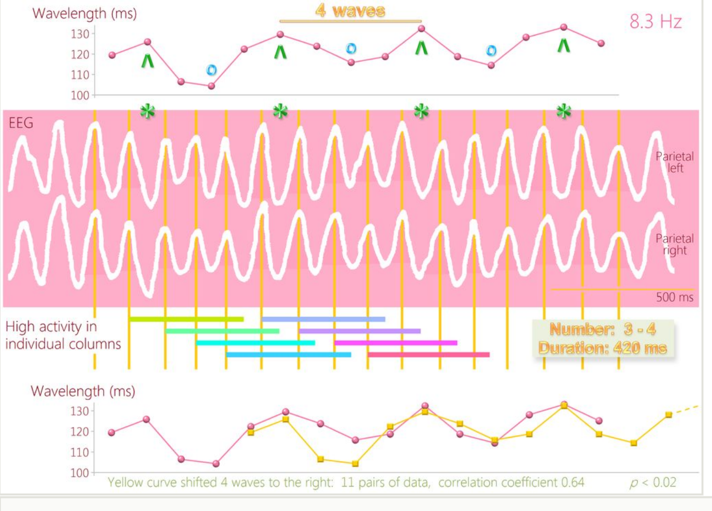

Figure 4. doi

Variation in wavelength at 8.3 Hz. The green and blue symbols indicate that there is a monophasic pattern and that the interval for the repeated elements is four waves. The *x*-axis in the upper diagram has the same timescale as the EEG. For statistical analysis, the *x*-axis in the lower diagram is a category axis. The colorful horizontal lines illustrate the hypothesis that was tested. The data are from a 22-year-old female.

Methods

The variation in the length of EEG waves is difficult to study because of disturbances and stochastic noise. Although there are methods for removing artifacts (Teixeira et al. 2006, Daly et al. 2013, Hu et al. 2017), these procedures change the shape of the waves, and this affects the measurements. Therefore, only sequences of waves with a minimal amount of disturbances and noise should be included in a study of the wavelength variation.

Approval was obtained from the Regional Ethics Board of the University of Göteborg (R627–97) and informed written consent was obtained from the participants. Sequences of alpha waves were recorded from 200 participants while they rested with their eyes closed. The recording technique has been described in a previous paper (Johannisson 2016).

The alpha waves were often asymmetrical, and the polarity was chosen so that, on average, the upward slope was less steep than the downward slope (Data S1 in Suppl. material 1). The midpoint of the area under a wave turned out to be less sensitive to disturbances and noise than the peak or the beginning of the peak.

In Fig. 4 and in the figures below, vertical lines indicate the midpoint of the area under each wave. The positions of these lines were measured, and the values can be found in the first column to the left in the five worksheets in Data S2 in Suppl. material 1. The wavelength was calculated as the distance in time between two neighboring vertical lines.

It is always possible that the elements in a pattern are repeated by chance. The probability for this can be calculated. In a diagram showing the measured wavelengths, the curve was moved sideways and compared with the original curve (Data S2 in Suppl. material 1). This procedure resulted in a series of data pairs. The correlation coefficient for these pairs was then calculated. From the correlation coefficient and the number of data pairs, a *p*-value was obtained. A one-tailed test was used because only positive correlation coefficients are of interest in the statistical analysis of the patterns.

Results

Repetitions in the wavelength variation were explored, and distinctive patterns were found. An example of such a pattern is shown in Fig. 5. When the EEG frequency was around 10 Hz, as in Fig. 5, the patterns were usually more complicated than those found at frequencies around 8 Hz (Fig. 4).

When attempting to detect a pattern in the wavelength variation, the analyzed sequence of waves must be fairly long, and every single one of the waves in the sequence must be clear and clean. For that reason, it is quite difficult to find sequences of alpha waves where the variation in wavelength can be analyzed.

Occasionally, a tendency for a pattern in the wavelength variation can be seen directly in a sequence of alpha waves, but most often, the variation in wavelength has to be analyzed in a diagram before the patterns become visible. It helps to know what to look for, and without the two levels hypothesis, it is unlikely that the patterns would have been found.

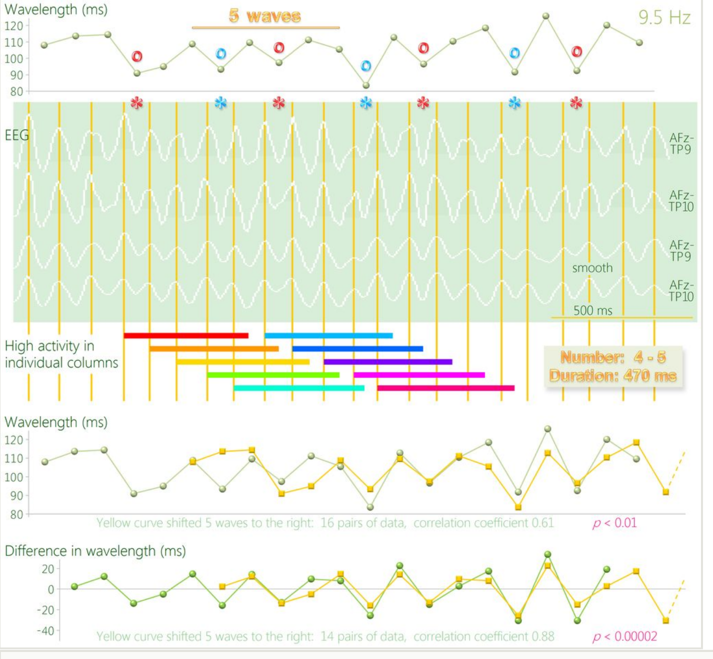

Figure 5. doi

Variation in wavelength at 9.5 Hz. The red and blue symbols indicate a biphasic pattern where the elements are repeated at an interval of five waves. The EEG is from a 26-year-old female.

About ten percent of the participants had sequences of alpha waves that were long enough and without too much of disturbances and noise. All of these sequences contained patterns, and all of the patterns had elements that were repeated at intervals that were in agreement with what can be expected from Fig. 2 and Fig. 3.

Smoothing destroyed the shape of the waves, but the elements in a pattern became a little easier to see. The smoothed curves in Fig. 5 have been included for comparison only, and they were not used when the wavelengths were measured for this figure.

To reduce the effect of slow fluctuations in wavelength, a difference in wavelength was used on the *y*-axis in the lowermost diagram in Fig. 5. This measure was calculated as the difference between a wavelength and the average of the wavelengths measured one wave before and one wave after. Further analysis of the alpha waves in Fig. 5 can be found in Data S3 in Suppl. material 1.

The interval for the repeated elements is five waves in Fig. 5 and Fig. 6. The alpha frequencies in these two figures are in the main group around 10 Hz. An interval of five waves at this frequency agrees with the predicted value.

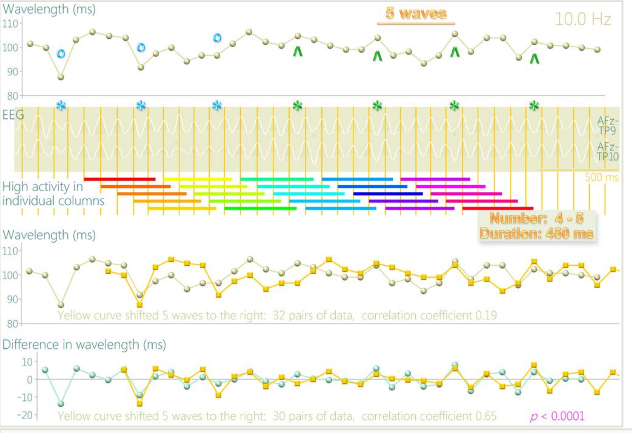

Figure 6. doi

Variation in wavelength at 10.0 Hz. The blue and green symbols indicate elements that are repeated at an interval of five waves. The pattern was not clear when there was almost no variation in wavelength, as in the middle of the sequence. Fortunately for the analysis, this period with almost no variation was not long-lasting. The letter H refers to disturbances from the heart. The EEG is from a 29-year-old male.

The patterns in the wavelength variation changed over time. When sequences of alpha waves were relatively long, as in Fig. 6 and Fig. 7, it was possible to detect patterns even though the elements of the patterns were only partially repeated. An example of a changing pattern in a very long sequence of alpha waves can be found in Data S4 in Suppl. material 1.

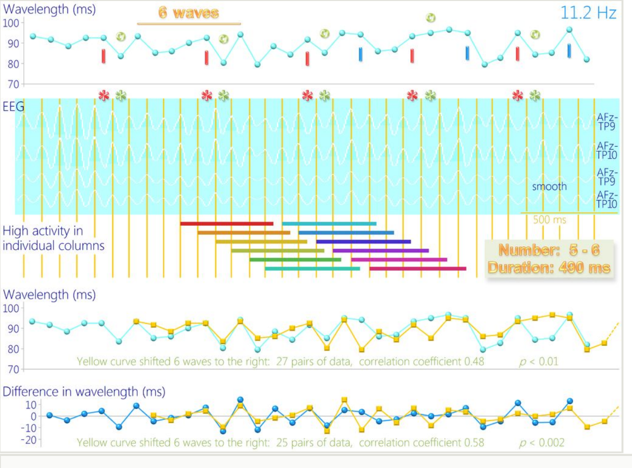

Figure 7. doi

Variation in wavelength at 11.2 Hz. The red, green, and blue symbols indicate a relatively complicated pattern wherein the elements are repeated at an interval of six waves. The EEG is from a 28-year-old female.

Discussion

The finding of highly specific patterns in the wavelength variation strengthens the two levels hypothesis. The elements of the patterns were repeated at intervals that exactly matched the predicted duration of high activity in individual columns.

In the alpha groups around 8 Hz, 10 Hz, and 12 Hz, three different intervals for the repeated elements had to be found to confirm the hypothesis (Fig. 3). These intervals correspond to four, five, and six alpha waves, respectively. All of these intervals were found, and they were found precisely in those alpha groups where they should be found.

The idea behind the two levels hypothesis

The theoretical work that led to the two levels hypothesis was published many years ago (Johannisson 1984). The hypothesis starts with the notion that some of the activity in the forebrain can observe itself from within. This activity is thus available for observation both from the inside and from the outside (Fig. 8).

Figure 8. doi

The starting point for the two levels hypothesis. A hand has an inside and an outside, and both sides are available for observation. In a similar way, the activity in some parts of the brain can be observed from two different angles.

Observations made from within the brain provide valuable clues as to how activity in the forebrain is organized. There are three clues that are particularly important (Johannisson 1984).

(1) High or low activity

The first clue concerns the degree of activity. Observations from within the brain indicate that there is a clear difference in the degree of mental activity when something is present in consciousness and when that something has disappeared from the conscious level. Therefore, activity can be found on two separate levels.

The functional units in the brain that are of interest in this context are the columns in the cerebral cortex. These units must be organized in a way that allows activity in a column to be either at a high level or at a low level.

(2) A few at a time

The second clue concerns the number of highly active columns. A very small part of all that may appear in consciousness is actually appearing there at any given moment in time. Consequently, only a few of the columns can be highly active at a time.

When the activity in one column has dropped from the high level to the low level, the activity in another column may jump up to the high level. This results in a turnover of highly active columns and gives a flow of thoughts and feelings.

(3) Functional properties = connections

The third clue is about functional properties. Anything that may appear in consciousness is characterized by its properties, and here, a property is a connection to something else that may appear in consciousness.

Thus, each cerebral column must have a set of connections with other columns. These connections have a double function. They can be used for associations in cognitive processes, and they constitute the functional properties that characterize every cerebral column.

The activity when we are thinking

The colorful horizontal lines in Figs 4, 5, 6, 7 illustrate the central part of the hypothesis. The lines represent activity at the high level in individual columns. When these lines are taken together, they may represent the activity when we are thinking.

Simplifying principles can be helpful, and as a simplification, the high activity in the cerebral columns during a sequence of alpha waves can be considered to be a thought. It is not always clear where one thought ends and the next begins. It can also be difficult to decide where a sequence of alpha waves ends and the next sequence begins. However, a sequence of alpha waves is not a thought in itself. The alpha waves just reflect the efforts of the regulating system that occur during a thought (Johannisson and Nilsson 1996).

The problem with a neural correlate to a thought

It is tempting to say that the colorful horizontal lines in Figs 4, 5, 6, 7 represent the neural correlate to a thought, but that would not be correct pursuant to the hypothesis. The problem with a correlate is illustrated in Fig. 8. It is not a good idea to describe the outside of a hand as a correlate to the inside. A hand can be observed from two different angles, but it is still the same hand. To describe the outside and the inside of the hand as two entities that correlate with each other is unnecessarily complicated.

In a similar way, it is not a good idea to search for a correlate to a thought. When high activity in the columns is observed from the inside, this activity can be described as the mental activity that constitutes a thought, and when high activity is observed from the outside, the activity can be described as neuronal activity. However, it is still the same activity in the brain, not two correlates.

Number and duration

The discovery of patterns in the wavelength variation makes it possible to determine the actual number of highly active columns. Moreover, the duration of high activity in individual columns can be measured in a reliable way. Fig. 9 shows an overview of the values for number and duration that may appear in various situations.

Figure 9. doi

Overview for number and duration. The values in the center of the figure are thought to be optimal and associated with good health. Slightly suboptimal values may lead to anxiety and depression. Values clearly outside the optimal ranges are expected to cause mental disorders. Optimal values for children are not the same as those for adults. During epileptic seizures, number and duration are changed in a special way.

The values for number and duration shown in the center of Fig. 9 are found among healthy individuals. Differences in number and duration within these ranges have been linked to differences in personality traits and temperament types (Johannisson 2016).

In Fig. 5 and Fig. 6, the elements in the patterns are repeated at an interval of five waves. As can be seen from the colorful horizontal lines in these figures, this interval means that, at any moment in time, the number of highly active columns was either 4 or 5. Because the number alternated between 4 and 5, it cannot be given as a single integer. In Fig. 9, the number is given as 4–5 when it alternates between 4 and 5.

Epilepsy

The actual number of highly active columns is usually the same as the limits used by the regulating system. For example, when the limits are 4–5, the number should be 4–5. If the regulating system makes a mistake, the number can end up outside the limits. It has been suggested that the number alternates between the upper limit and one step higher during grand mal seizures (Johannisson 2016).

In petit mal seizures, the number may alternate between the lower limit and one step lower (Fig. 9). This can be tested, because the EEG pattern during a petit mal seizure is a remarkably clear example of a pattern. Therefore, the actual number during a seizure is possible to measure, and this number is expected to be one step lower than the number representative of the individual under normal conditions.

How duration was measured

The values for the duration of high activity given in the center of Fig. 9 are optimal in the sense that these values are associated with low levels of anxiety and depression (Johannisson 2016). The duration was calculated as the wavelength multiplied by the mean number of highly active columns. This way of calculating the duration is illustrated in Fig. 3.

As an example, the mean number of highly active columns is approximately 4.5 when the number alternates between 4 and 5. The value cannot be exactly 4.5 because alpha waves are somewhat asymmetrical. The true value is probably slightly less than 4.5, but this value is difficult to measure in an accurate way (Figs 3, 5, 6). In view of that, 4.5 can be a reasonable approximation and is used in this paper.

The start of high activity

The colorful horizontal lines in Figs 4, 5, 6, 7 are drawn as if high activity starts at the midpoint of the area under a wave. The midpoint is close to the upward peak, but actually, high activity starts a little bit earlier. In Fig. 3, the horizontal lines start at the beginning of the upward peaks, and this is an attempt to indicate that high activity starts earlier than at the peaks. Although the beginning of a peak is closer to the actual start of high activity than the peak itself, it is often problematic to determine precisely where the peak begins (Fig. 3).

In Figs 3, 4, 5, 6, 7, the beginning of an upward peak can be taken as the first sign that the activity in a new column has jumped up to the high level. However, there is a small delay between the actual start of high activity and the beginning of a peak. Information about the start of high activity in the new column is expected to be mediated via corticothalamic fibers (Johannisson 1984). They are myelinated and fast-conducting, but it does take a little time. Then, there is a short processing time in the thalamic complex as well as a short time for the conduction of the regulating signals in the thalamocortical fibers. Thus, the actual start of high activity occurs a little earlier than the start of the horizontal lines in Fig. 3.

Asymmetrical waves

The regulating system must react as quickly as possible when a new column starts its high activity. This is a critical moment, and if the system is not successful, the number of highly active columns may exceed the upper limit, which may lead to a grand mal seizure (Johannisson 2016). In order to reduce the risk of a mistake, the gradual increase in excitability in columns with low activity must proceed at a restrained speed. Then, as a rule, there will be enough time for the regulating system to react.

When the activity in a new column jumps up to the high level and the upper limit is attained, the decrease in excitability in columns with low activity must begin decisively (as illustrated by the small blue bars in Fig. 3). Moreover, the rate of change in excitability during the latter part of the decrease phase is not as delicate as it is during the increase, so the decrease in excitability can proceed somewhat faster than the increase. This may explain why alpha waves can be asymmetrical. For this reason, the polarity of the EEGs in Figs 3, 4, 5, 6, 7 was selected so that, on average, the upward slope is less steep than the downward slope. Then, an upward slope in these figures indicates an increase in excitability, and this makes it easier to interpret the curves.

Duration disorders

A previous study found high scores on anxiety and depression when the duration was either slightly too long or slightly too short (Johannisson 2016). Thus, suboptimal duration can explain some anxiety syndromes and some depressions (Fig. 9).

Within the optimal range, a long duration gives reliable associations when we are thinking (Johannisson 2016). However, if the duration becomes too long, the variation in the associations will be very small or almost none (Johannisson 1993a). The consequence can be repetitive thoughts, as in obsessive-compulsive disorders, and rumination, as in major depressions.

Short duration can be linked to impulsive thinking and behavior (Johannisson 2016). Thus, a spectrum from impulsive to compulsive can be explained by a wide range of different durations. Long-lasting conditions with somewhat too-short duration may perhaps account for some personality disorders, such as borderline personality disorder.

If the duration is more than slightly outside the optimal range, the result will be disorders that are more serious (Fig. 9). Too-long duration may cause major depression with reduced psychomotor speed, and too-short duration can result in a manic state (Johannisson 1993a). The degree of severity is determined by how far the duration is outside the optimal range.

Number disorders

When looking at the colorful horizontal lines in Fig. 7, it becomes clear that the regulating system has a difficult task when the limits for the number are relatively high. Very few people have limits of 6–7, probably because a high number requires that the regulating system and other parts of the nervous system are exceptionally well ordered and fine-tuned. It also helps if the duration is somewhat prolonged because this gives the regulating system additional time for the delicate adjustments of the excitability.

A high number may lead to complicated thoughts. If the number is too high, one can imagine that very complicated associations in thinking processes could be difficult to handle. The result would be incoherent thinking and other problems (Johannisson 1993b). Thus, an overload in the regulating system or having overly complicated thoughts may explain some of the symptoms present in the schizophrenic spectrum (Fig. 9).

Disorders during childhood

The limits for the number changes stepwise and the duration changes gradually. Babies may start with 1–2 as the limits for the number (Johannisson 2016), and during early childhood, the limits can increase to 2–3. When the number is small, the duration can be relatively short.

For normal development, it is necessary that both number and duration increase, but not too early and not too late. This gives four main alternatives for what can go wrong with number and duration during childhood.

Why measurement before treatment

A medication or other treatment that shortens the duration can be helpful if depression is the result of a duration that has become too long. On the other hand, such a shortening treatment would worsen the symptoms if given to a patient where the duration is already too short.

Thus, the outcome of an antidepressant medication may depend on whether depression is caused by a duration that is too short or too long. This is of crucial importance when testing a medication. If we have a mixed group of patients with different types of depression, we will most likely get a mixed outcome. An effective treatment that can shorten or prolong the duration will probably be dismissed as ineffective because of the mixed results. This mistake can be avoided if there are duration measurements before and after treatment.

How to find the best treatment

The data in Figs 4, 5, 6, 7 are from healthy individuals without medication. Fig. 10 shows a pattern in the wavelength variation that was found in an EEG from an individual who had a mental disorder and was taking medication (Koshino 1989).

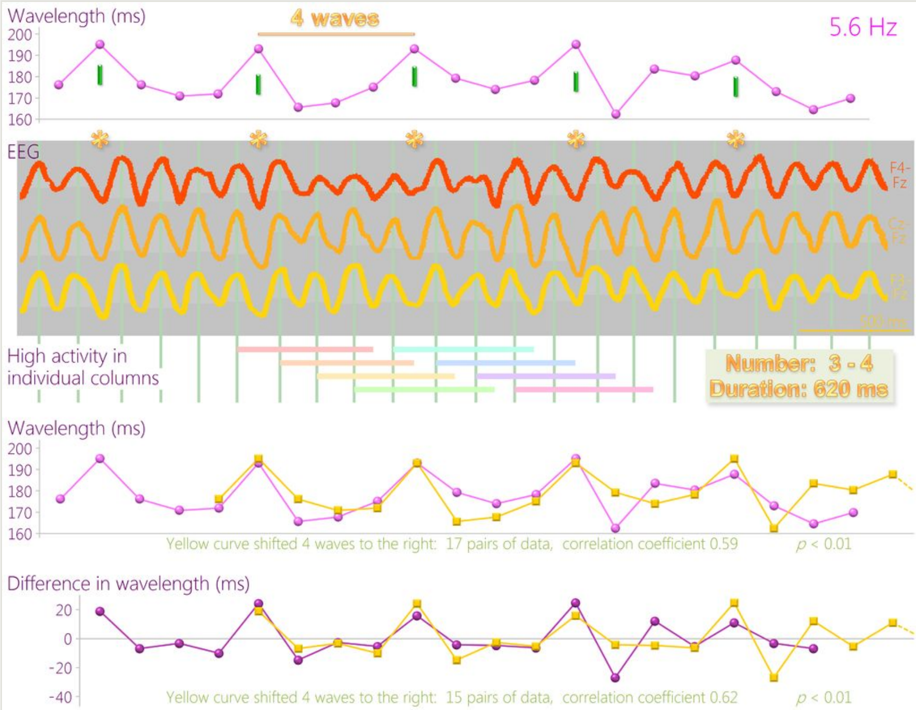

Figure 10. doi

Variation in wavelength at 5.6 Hz. The green and yellow symbols indicate a pattern where the elements are repeated at an interval of four waves. The data are from a 25-year-old male.

Fig. 10 may serve as an example that highlights the importance of measurements of number and duration. The sequence of waves analyzed in this figure indicates that the duration was far outside the optimal range. Such a long duration can be anticipated when there is severe melancholic depression. However, the patient had a different diagnosis, schizophrenia.

The number 3–4 and the duration 620 ms in Fig. 10 suggest that the medication can be improved. Without measurements of number and duration before the treatment started, it is hard to say to what extent the unusually long duration and the slightly low number were caused by the antipsychotic medication.

It is possible that a too-high number and a normal duration existed before the medication was started. At a later stage, due to overtreatment or something else, the duration became too long. Another possibility is that the duration was too long from the beginning and that this unusually long duration caused psychotic symptoms.

To find the best treatment is less problematic if we know the cause of a mental disorder. Imprecision in old diagnoses is often an impediment. When measurements of number and duration are available, we may instead talk about *number and duration disorders.*

Conclusions

1. Patterns in the wavelength variation confirm the two levels hypothesis.
2. The number of highly active columns and the duration of high activity in individual columns can be measured.
3. There are implications in areas such as personality, childhood development, epileptic seizures, and mental disorders.

Open science

In the discussion section, an attempt is made to explore various alternatives when number and duration are suboptimal. All of the suggestions can be tested, but this will require collaboration and help from open science (Senderov and Penev 2016, Penev 2017, Monachino et al. 2018).

The present report describes highly specific patterns in the wavelength variation. These patterns are important because they confirm a hypothesis that explains how forebrain activity is organized. The data collected so far support the hypothesis, but more data would be most welcome.

If anyone has a recording with a reasonably long sequence of alpha waves where the amount of noise and other disturbances is minimal, please send a copy of the waves to me (email: tomas.johannisson@outlook.com).

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Conflicts of interest

The author has declared that no competing interests exist.

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Supplementary material

Suppl. material 1: Zip-folder containing Data S1–4 doi

Authors: Tomas Johannisson
Data type: Images, tables, and diagrams
Brief description: Data S1. EEGs for Figs. 4–7 and 10.
Data S2. Tables for the measurements and analyses behind Figs. 4–7 and 10.
Data S3. Additional methods for measurement and analysis of the EEG in Fig 5.
Data S4. A sequence with 70 alpha waves and different measurement methods.
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