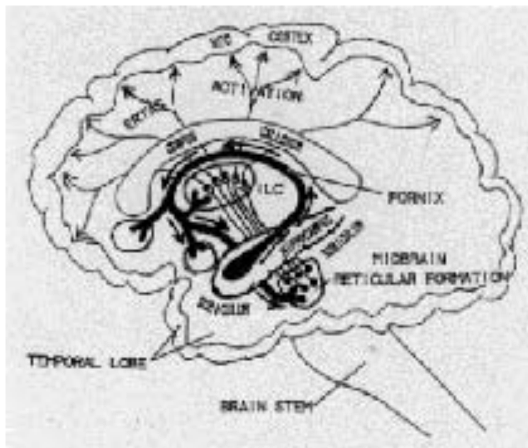
Oscillations in the Brain:



A Dynamic Memory Model

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Table of contents

Introduction………………………………………………………………………… 1

Chapter 1: The Conceptual Framework
1.1 Memory…………………………………………………………………… 3
1.2 Consciousness……………………………………………………….... 3
1.3 Rhythms…………………………………………………………………… 5
1.4 Generation of 40 Hz oscillations…………………………………... 7
1.5 From rhythm to memory……………………………………………. 8

Chapter 2: Reasons for a New Memory Model
2.1 What is wrong with neural networks?………………………………. 9
2.2 Long-range correlations…………………………….. ………….. 11
2.3 A dynamical picture………………………………………………… 12

Chapter 3: A Quantum Field Theory of Memory
3.1 Vitiello's quantum brain dynamics model………………………….. 13
3.2 Quantum brain dynamics versus orchestrated reduction model…… 13
3.3 A field influences a neuron…………………………………………. 14
3.4 The meaning of dissipation………………………………………….. 15
3.5 The model – equations………………………………………………. 15
3.6 Why would there be 40 Hz oscillations involved?…………………... 17

Chapter 4: Calculating the Field
4.1 The field without spontaneous symmetry breaking………………….. 19
4.2 The field with spontaneous symmetry breaking……………………... 20
4.3 Phenomenology: bubbles and solitons……………………………….. 25
4.4 Possible refinements of the model…………………………………… 27

Chapter 5: Possibilities for Quantitative Predictions
5.1 From neuron to EEG…………………………………………………. 29
5.2 Quantum dynamical and electrochemical level.…………………….. 29
5.3 Meaning of the parameters…………………………………………… 31

Conclusion……………………………………………………………………... 32
References………………………………………………………………………… 33

Introduction

In the field of neuroscience, the complex problem of trying to understand the brain is pursued in many different ways. The existence of so many different approaches often raises the question: how do they interrelate? In this thesis, I will study two completely different theories: one proposed by a physicist, based on oscillations of bio-molecules, another proposed by experimental psychologists, based on synchronised firings in the gamma-band range which can be found in EEG (electroencephalogram) recordings.[1] The first theory deals mainly with memory; the second is hypothesised to be related to consciousness.

Many people think that it is exactly this difficult concept of consciousness that makes humans into humans, and separates them from animals. The problem with this concept however is that it is very hard to define. In this thesis, I will restrict myself to the biological aspects of consciousness, which are distinguishable in the brain. However, it is still possible that there are components of consciousness that are non-physical and are more or less independent of the brain. Since these components cannot be caught in our physical models, I will ignore them for my purpose.

The aim of this thesis is not only to elucidate mechanisms of memory and consciousness in the brain by using a new approach, but also to see at a more general level how different sciences and approaches can improve our understanding of certain phenomena. Are the different levels of understanding reducible to each other, or can they at least be connected, or do we have to follow Kuhn in his idea of different paradigms in science, which are incommensurable? The main purpose of this thesis is thus not to give completely new and concrete results, something which would require much longer time for study, but rather to generate new ideas on how to work with models of the brain, and how to combine theories in completely different fields of studies.

For example, the calculations I will perform will not only be relevant for the study of the brain, but (hopefully) have an even wider range of applicability. The basis of my study is in mathematical terms how we can describe the effects of an oscillator bath (the quantum potentials) on a discrete lattice (the neurons). This also has its uses in 'normal' quantum field theory. For example, in the Standard Model in the case of the Higgs field, very little is known how these fields behave close to the sources. Since in our model the sources (or the neurons) are the most important, we will indeed look at how the field behaves close to them.

I will start with an analysis of how consciousness can be defined and what its relation is to different kinds of memory. The definition of consciousness should be one that is in accordance with the 40Hz theory that is being studied in relation to the model we will use. Therefore, we need a coherent description of the 40 Hz theory, as well as a discussion of some of the criticisms put forward. The definition of memory will have to be in accord with the quantum field theory of memory that we will use. Also the interrelations between memory and consciousness will be elaborated, both on conceptual and mathematical levels.

Then in the computational and modelling part I will start with looking at how to model the discrete model of neuron firing that causes 40 Hz oscillations (called the

[1] Gamma-band range = 40 Hz oscillations

electrochemical level)[2] and the quantum dynamical level (i.e. arising from a quantum field). Before we do that, I will first present a justification for positing a new theory of memory. Long-range correlations and dissipation are important ingredients of that model. After the solution to the equation of motion has been found, we will discuss a number of interesting phenomena that appear from using this model of memory: bubbles and solitons. In the last chapter, I will discuss how the model could be used in the future for more quantitative or more precise predictions.

[2] Vitiello (2000), p.5

Chapter 1: The Conceptual Framework

1.1 Memory

Before I start with my analysis, it is important first to define the relevant concepts: memory and consciousness. Many forms of memory exist, and the type of memory I will consider here is dependent upon the quantum field theory model of memory I want to look at. Memory is classified according to many different criteria, the most important of which is probably retention time. Sensory memory lasts for milliseconds to seconds, short-term memory from seconds to minutes, and long-term memories have a lifetime of days to years.[3] The quantum field theory of memory, described by Vitiello is concerned with the storage of data, so that it can be recalled later on and can be associated with other information. In order to stay in memory, it has to be refreshed every once in a while. The kind of memory I consider is therefore long-term memory. Another subdivision in long-term memory is between declarative and non-declarative memory, where declarative memory relates to facts and events that can be consciously recollected, whereas non-declarative memory is rather unconscious (e.g. skills and habits, priming etc.).[4] It seems most likely that Vitiello was talking about declarative memory, because he discusses conscious recalling of memories and difficulties in that.[5] I will not consider the separation between semantic and episodic memory, because this separation cannot be made in Vitiello's model since this model concerns not the structure of memory but its contents.

Another feature of the Quantum Field Theory (QFT) of memory is that memories are rather localised in separate brain areas. It is known that the medial temporal lobe and the midline diencephalon help in the formation of new memories. The hippocampus is implicated in the consolidation of memories and the transfer from short-term to long-term memory. Yet memories are not stored there, they are hypothesised to lie in the neocortex, and consolidation takes place through the strengthening of connections between synapses and association with previously stored information.[6] In addition to that, the frontal lobes seem to be implicated in the encoding and retrieval of memories, and the temporal lobes in specific store episodic and semantic information. It is therefore clear that memory and learning are widely distributed processes.

1.2 Consciousness

Consciousness is a concept very hard to define, even though everybody has intuitively a very clear idea of what it should be (Tassi & Muzet (2001)). It is a subjective experience, which can be subdivided into the experience of oneself as a living being (self-knowledge), and one's way of perceiving the world (sentience and access to information; all perceptions are coloured by earlier experiences, and one can also perceive internal events). Consciousness defined in this way is clearly related to declarative memory, because our experience of ourselves consists mainly of memories of our personal history (biographical aspect), and also our perceptions, which are coloured by our memories (perceptual aspect). Even though also non-declarative memory

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[3] MS Gazzaniga et al.(1998), p.248-249

[4] LR Squire & S Zola-Morgan (1991) The medial temporal lobe system, Science, 253, pp. 1380-1385.

[5] G Vitiello (2000), p.16

[6] MS Gazzaniga et al. (1998), p.266-267

influences consciousness (for example in the case of priming), I will not take this into consideration in this paper for the simple reason that I here focus on a model for declarative memory.

The feeling of self-consciousness is very hard to define and research in neuropsychological terms; therefore I will not look into it. Instead, I will mainly focus on unity of perception. I will look at consciousness as an agent that makes an integrative synthesis of internal and external events and produces the appropriate behaviour in response. Thereby this consciousness allows for the formation of beliefs and it produces the narrative of our lives.[7]

It is also necessary to introduce a graded notion of consciousness, because otherwise the above conjecture would be problematic in the case of patients with amnesia: are they not conscious? The graded concept of consciousness can be enriched with a listing of features that this consciousness should have (Kahn et al.)[8], which seems to accord quite well with the 40 Hz theory I want to consider, which in short states that coherent 40 Hz oscillations bind all perceptions and cognitive processes together to a single percept.[9]:

(1) Unity of conscious experience, this could for example be achieved by the synchronising working of the 40 Hz oscillations. In the words of Llinas and Ribary: 'consciousness may arise by the resonant 40-Hz coactivation of at least these two systems, which would temporarily conjoin cerebral cortical sites specifically activated at or around 40-Hz frequency'[10] An example of cognitive processes that are synchronised by 40 Hz oscillations are memory processes, as discussed in the previous section.
(2) Graded complexity and intensity of consciousness (from the feeling of knowledge to primary processes as feelings of fatigue). Interhuman and interspecies differences can be placed here, for example a lack of long-term memory components in the case of amnesia.

A more technical definition of how this really works is put forward by Picton and Stuss, who hypothesise that 'conscious experience involves a modelling process'.[11] This modelling would occur at the level of the neocortex, and may be associated with oscillatory field potentials. Thereby consciousness becomes again a reflection 'of the brain's representation of the world and ourselves'.[12] Consciousness is that process in the brain which creates our experience of the world, it is a very dynamical process.

Employing this definition of consciousness – which is the phenomenal consciousness – it is important to know which kinds of consciousness are excluded from this analysis. First there is the relation dichotomy between conscious and unconscious. This type of consciousness has more to do with attention or awareness, and this is not what I will consider here, in particular because a strict dichotomy between the conscious and unconscious cannot be made.[13] The last relation I need to discuss is that between consciousness and attention. We could say that consciousness in fact creates access to

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[7] MS Gazzaniga et al. (1998), p.543
[8] described in P. Tassi & A. Muzet(2001), p.179
[9] described in P Tassi & A Muzet(2001). p.177, I will discuss this theory further in section 1.3
[10] Llinas and Ribary (1993), p.2081
[11] described in P Tassi & A Muzet (2001), p.177
[12] ibid. p.177
[13] ibid. p.178

unconscious resources (e.g. perceptions, memory), whereas attention controls the access to consciousness. Attention is thus a more specific process, most pronounced in perception, which works through consciousness. Here, we will study memory processes and consider unity of perception, how perception itself works, and will therefore not be concerned with it in this paper.

This approach to consciousness is also clearly different from the approach to consciousness by studying sleep and dreaming, as studied for example by Hobson. In my definition, both consciousness during waking, and during REM-sleep (dreaming) are forms of consciousness, because both have these integrative features.

Instead of considering the question of whether there *is* awareness, I will consider the question of how the perceived reality is turned into a single whole. In short: with consciousness I mean the ability to integrate internal (e.g. memories) and external inputs into the perception of the world as a whole and as a continuous picture.

1.3 Rhythms

When studying the EEG, one can distinguish different rhythms for different states of wakefulness. It has been conjectured that the frequencies in the gamma range (35-45 Hz) are related to unity of conscious experience, because they arise in waking state and REM sleep. These 40 Hz oscillations have also been found (by Llinas and Ribary) in MEGs (magnetic encephalograms).

Moreover, recently it has been found that gamma oscillations can be related to the formation of memories (J Fell et al.(2001)). In epileptic patients, a depth-EEG was recorded, in which they found that successful memory formation was characterised by first a rhinal-hippocampal gamma synchronisation, followed by a desynchronisation. In the case memory encoding was not successful, this was because the background gamma-activity interfered. The 40 Hz oscillations have also been implicated in other cognitive processes, for example perception (consider for example Engel & Singer, who claim that synchronization has a major role in visual consciousness – JW Singer 2001)). The clear binding character of 40Hz oscillations has also been demonstrated by OW Sakowitz et al. (2001), who found that bisensory evoked potentials in perception showed significantly greater amplitudes in gamma waves than visual and auditory evoked potentials.

By assuming that consciousness is not the result of one specific faculty, but rather an integrative function, it seems likely that it arises from an interaction of different brain systems, rather than from just one of them (as is presupposed in the search for a localised neural correlate of consciousness (NCC)).[14] The 40 Hz theory, which is essentially non-localised, has thus been implicated in consciousness, but it is still a debated topic.

The idea behind the 40 Hz theory is that ‘collective oscillation creates unity from a multiplicity of input sources which makes it possible for the brain to connect or correlate activity from different neuronal groups’.[15] If you have inputs in different parts of the brain, they are temporarily joined by these oscillations, and the brain can connect or correlate activity form these different areas. A possibility however is that these oscillations are only related to cognition and perception, and not consciousness in specific. However, it has been shown that absence of consciousness can be related to an

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[14] P Tassi & A Muzet (2001), p.179
[15] ibid. p.179

interrupted pattern or burst suppression of gamma waves.[16] Moreover, the gamma oscillations become synchronised only after a relevant stimulus or focused attention.[17] In this situation of focused attention, the power density of the gamma spectrum (that is, distribution of the amplitudes of the gamma oscillations) is surmised to be a determinant of whether consciousness has been reached (and to what level: perceptions can be more or less conscious).

However, the idea described above has not gained universal acceptance. Vanderwolf (2000) believes that neocortical gamma activity can never be proven to be a basis for subjective awareness. Gamma waves have also been found in people who were anaesthetised or in deep sleep, but in that state, the temporal distribution of these waves differs.[18] A lack of consciousness might be associated with an interrupted sequence of gamma waves (burst-suppression pattern). However, during the waking state, there are also large amplitude slow waves, and maybe the 40 Hz oscillation temporal distribution is related to that instead of to the waking state itself (since we are not sure about the exact causal relations between the processes involved)? We should keep in mind that the definition Vanderwolf uses of consciousness is different from my definition, because he considers consciousness to be the production of appropriate behaviour and maintenance of a posture (which is not present in sleep). He found that the temporal distribution of gamma waves is not related to the dichotomies sleeping-waking or waking-comatose (where comatose means the absence of consciousness as defined above), and the same is true for cortical activation. However, Vanderwolf did find that when rats were waking and immobile, they showed a burst-suppression pattern. Even though they responded to stimuli and kept up their posture, the temporal and spatial distribution of their behaviour was completely deranged. When one considers consciousness as an integrative function, then indeed consciousness is disrupted here, in contrast to Vanderwolf's conclusions. Another critical remark that should be made here is that one cannot really be sure that rats are good candidates for drawing conclusions about human consciousness, since the consciousness of animals is clearly different from that of human beings (in particular in terms of capabilities for reflection).

Another problem with the connection between consciousness and gamma activity is that during anaesthesia, people show continuous gamma activity, and it has been shown that they are aware (e.g. of pain) in this state, yet they are also amnesic. The latter poses a serious problem for determining whether consciousness is present or not. It would be necessary to elucidate the connection between consciousness and memory, which is indeed the subject of this paper. Maybe consciousness is indeed present in amnesiacs, yet there is no memory formed, the subject lives in a continuous present, which makes it quite different from our normal, more reflective state of mind. Gamma oscillations might be a necessary but not sufficient precondition for memory formation and retrieval, which for example also requires involvement of the hippocampus and other brain areas.

Furthermore, gamma oscillations are controversial is their ubiquity. Gamma activity can be subdivided into: (1) spontaneous gamma-activity (present without intentional stimulation), (2) induced gamma-activity (initiated by a stimulus but not tightly locked to it), (3) evoked gamma-activity (elicited and strictly time-locked to a

[16] ibid., p.179
[17] ibid. p.180
[18] CH Vanderwolf (2000), p.217

stimulus) and (4) emitted gamma-activity (not bound to a stimulus but to an internal process).[19] It is clear from this that even though some gamma activity is always spontaneously present, other forms of gamma activity can be specifically linked to cognitive processes. These cognitive processes range from perception to very high order processes, such as the representation and experience of the self (D Lehmann et al. (2001)). In connection to memory, the fourth type of gamma oscillations is most important, because the gamma activity is related to the internal process of memory formation. It is this gamma activity that I will mainly discuss in this paper. I will also consider the third type, evoked gamma activity, to see how memory relates to perception and consciousness (in the sense of integration). This evoked gamma activity might have quantum field theoretical sources, as I will propose in my model. When a stimulus is perceived, and a person becomes conscious of it, that means that its pattern of brain activation oscillates synchronously with the quantum field. That means that it is related to memory of earlier times which constitutes the context of the perception. Because a field has long-range correlations, it connect memories in all brain areas together.

Finally, we should distinguish between necessary and sufficient conditions for consciousness. It might still be the case that 40 Hz oscillations are required to have any form of consciousness, yet other conditions have to be met as well. This has not been proven adequately so far, but it is not the subject of this paper. In addition, not only 40 Hz oscillations seem to be related to cognitive processes. It has also been found that successful encoding and retrieval of spatial memory (in maze learning) is correlated with theta oscillations (4-8 Hz), yet decision time is again correlated with gamma oscillations (JB Caplan et al. (2001)). In short, 'oscillations of varying frequencies may act together to perform multiple complex cognitive functions'.[20] The goal of this thesis is to elucidate some of the workings of these oscillations in the formation of consciousness and memory.

1.4 Generation of 40 Hz oscillations

Gamma rhythms can be generated by pools of excitatory neurons, networks of inhibitory neurons or networks of both excitatory and inhibitory neurons (OW Sakowitz et al. (2001)). However, only in networks of inhibitory and excitatory neurons, the synchronisation will be a property of the network itself (as opposed to being caused by the action of pacemakers in the network). Since this paper is occupied with the study of dynamical and emergent properties of networks, we will focus on the latter case. The most important feature that is required of these neurons is that they have so-called 're-entrant loops'. That is, the neurons have to be reciprocally connected.

1.5 From rhythm to memory

I already mentioned that memories are known to be stored in the neocortex. The hippocampus is involved in this storing of information, and it is the recipient of inferotemporal outputs. In order to store information successfully, it has been shown (J fell et al.(2001)) that the rhinal cortex, which is the coupling between perceptions and the hippocampus, has to be synchronised with the hippocampus by gamma oscillations. The problem with this experimental result was that it is hard to find, since the hippocampal

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[19] OW Sakowitz et al. (2001), p.267 ff.
[20] JB Caplan et al. (2001) p. 380

activity on an EEG is shielded by the hippocampal pyramidal layers (the results used in this study have been obtained by intracranial studies in epileptic patients).[21]

The involvement of rhythms in memory formation is best known for the transition from long-term to permanent memory during sleeping. This mechanism might also help us to understand what happens on the transition from short to long-term memory, which is the subject of this paper. It is hypothesised that the temporal sequence of spikes in bursts (during sleep when the burst-suppression pattern occurs in the EEG) is determined by the history of the network.[22] The burst initiation and which of the neurons are involved in the burst is then determined by the synaptic weights in the network (which are changed by experience). 'The bursts are initiated by the neurons with the strongest synaptic connectivity and spread to other neurons with less synaptic strength.'[23] Thus with each burst, the pattern of connectivity pertaining to a recent memory is replayed, thereby strengthening the connections, causing the memory to be stored into the neocortex (by means of long-term potentiation (LTP)). This form of memory storage I call storage in neural nets.

Before this transfer can occur, it is however necessary that short-term memories are stored in long-term memory. This happens during waking, and the hippocampus is necessary for that. The role of the hippocampus is initiating or co-ordinating this process (the hippocampus is essential for memory formation as has been shown by lesion studies[24]). Fell showed that synchronisation is necessary for this process to occur. In the case of synchronised oscillation, we need a network of inhibitory and excitatory neurons because they can restrain each other in order to work together. The inhibitory (inter)neurons pace the networks into the required oscillations (for example gamma oscillations), whereas the excitatory neurons (e.g. pyramidal neurons) bring the information that has to be put into the system into a coherent whole. When the drive of the excitatory neurons is too high, they will be inhibited by the inhibitory neurons, and in that way their frequency will be slowed, up to the required firing frequency. (Whittington et al. (2002)).

During successful memory formation the same oscillations appear as during memory consolidation. It could be possible that the pattern of neuronal activation that represents the memory can only be transmitted to the hippocampus by synchronising oscillations, because the hippocampus needs to be connected in a transient assembly to the memory (or pattern of neuronal activation), which then has the same idea of replaying as occurs during the burst-suppression rhythm in sleeping. This would mean that gamma oscillations are necessarily involved in memory formation, as indeed Fell found. It also means that we need a network of neurons with a particular structure (e.g. networks of excitatory and inhibitory connections) as described above. In the model that I will be using in later chapters, I will also show that these requirements for successful memory formation also follow from my model. Before moving to our model however, I will put forward some justifications for proposing a new model in the next chapter.

[21] J Fell et al. (2001), p.1262
[22] G Buszaki & JJ Chrobak (1995), p.6
[23] ibid., p.6
[24] Gazzaniga (1998), p. 267

Chapter 2: Reasons for a New Memory Model

2.1 What is wrong with neural networks?

Many people surmise that memories are being stored in neural networks (just as we did in the previous chapter, in section 1.5). Neural networks are networks of neurons, interacting through excitatory and inhibitory connections. To date, neural network theories are ubiquitous in the field of explaining memory formation. An example of a neural network theory is put forward by Ingber (1994), stating that 'a pattern of neuronal firing that persists for many τ-cycles is a candidate to store the 'memory' of activity that gave rise to this pattern'[25], because it causes the strengthening of the synapses as described in section 1.5. The problem with this statement is that during and after memory formation, the brain also has to perform many other activities, thereby potentially causing interference problems. Information will be lost when the neurons are involved in different processes at a time. Neurons can only be used for one kind of activity at a time, yet the memories should be omnipresent in order to be able to be integrated in the on-going process of perception and other cognitive process that together constitute consciousness (and these different processes are spread out over the brain). Moreover, to me it seems logical that neurons all over the brain are involved in memories, because then we can imagine that a memory of something is just the pattern of brain activation that belongs to the experience of the moment or object remembered. And as Chrobak et al. mention, 'We lack sufficient understanding of how neuronal ensembles in general can function transiently and distinctively from other neuronal ensembles'.[26] One solution to this problem would be to assume that various transient assemblies are formed that oscillate at different frequencies. As we will see later however, this will not explain how long-range correlations can occur.

In this paper, I will therefore look at a deeper layer in the brain (which is not necessarily anatomically discernible), a quantum level beyond the neuronal level, to store memories. This level will not attempt to replace the classical theories of memory, because these theories (with its key concepts of long term potentiation and Hebbian learning) are already well established and have much evidence in favour of them. The quantum level theory is rather a complement to explain the non-local and other interesting properties of memory that cannot be explained by classical models. Memories are thus stored on two different levels: the quantum field level, where they can communicate with far-away memories and other cognitive processes, and the more direct level of synaptic strengths. It might be the case that the quantum level contains the 'original memories', which are always accessible to cognitive processes provided there is enough energy available, they are a dynamic type of memories. The neural network-type of memories on the contrary is a more local type of memory, which is nevertheless more concrete (it is a global type of memories that one can easily imagine (containing only salient details), whereas the quantum type of memory might be more diffuse). These more precise memories can be evoked once the specific location is known through the interaction with the quantum level memories. One can compare this to a computer: the neurons provide the directory structure and summary of the files, whereas the quantum level stores the files themselves.

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[25] L. Ingber (1994), p.4657
[26] JJ Chrobak et al. (2000), p.457

How does the new level work and fit in existing ideas on memory formation? It could be the case that quantum level memories are stored once the memory is instantiated in neuronal networks during memory consolidation (as discussed in section 1.5). The formation of these quantum-level memories thus takes more time, and it connects more distant parts of the brain through its long-range correlations. In this way, we could explain the sinking in – phenomenon (i.e. memories require some time to sink in, it takes some time to really get on top of newly acquired knowledge and to be able to use it).

The first advantage of a quantum model is that quantum phenomena exhibit special characteristics, such as superposition, which classical phenomena do not possess, and which could be very feasible to express brain functioning, because it can be used to express the existence of pre- and subconscious knowledge. In this spirit, a collapse of the wave function belonging to the specific brain state at a particular moment can refer to the becoming conscious of a memory.[27] Moreover, when the brain shows quantum characteristics, issues relating to free will acquire a new dimension (because the concept of free will is problematic in a deterministic theory of mind – consider the vigorous debates in the philosophy of science as for example in R Warner & T Szubka (eds.) (1994). By using this type of memory, one has a new way of incorporating quantum effects in the brain (because it is often argued that atomic quantum effects are on too small a scale to be perceivable in brain functioning. This is for example an objection put forward to the orchestrated reduction model of microtubules put forward by Penrose and Hameroff[28], which makes use of quantum effects on atomic scales. Here we consider quantum effects that arise dynamically on totally different scales (the correlations appear on a macroscopic scale), and therefore they might be significant). In addition to that, by considering a quantum dissipative system to work, many memories can be stored in the degenerate vacua of the potential of the quantum field because those are unitarily inequivalent.

2.2 Long-range correlations

Most importantly, the quantum field theory allows long-range correlations in the brain, which seems plausible if we would want to encode memories that are complex and involve many different parts of the brain. Another reason for requiring this feature of a model is that long-range correlations and a spread-out nature of memories could explain why storing and recalling of information is not lost after destructive action on local parts of the brain by for example electric shocks or drugs.[29] Only if the damage incorporates structures that have been implicated in memory formation and retrieval (such as the hippocampus), then damage of memory will appear. This is then not because the memories themselves have been lost, but rather the mechanism through which to access or to create them.

Long-range correlations are problematic in a neuronal-level approach to brain modelling.[30] Steriade mentioned that it would be very unlikely that there were connections between brain parts far apart, since volume conduction takes too much time and thereby it would create phase-lags in the signals (M. Steriade et al. (1996)). Indeed,

[27] NJ Woolf & SR Hameroff (2001), p.473
[28] described for example in “The Emperor’s New Mind”, R. Penrose (1991) New York: Penguin
[29] G Vitiello (1995)b, p.2
[30] in Ingber’s model the long-range interactions are clearly absent

the long-range correlations are considered to be an important problem in contemporary theories.[31] One solution has been put forward, namely doublet firings. Traub et al.(1996) found by using simulations that long-range correlations could be produced by letting interneurons fire on doublets with a lag of about 5.25 ms. between the two firings. When this lag matches the conduction delay between the two distant areas, it exactly compensates for this conduction delay and thereby oscillations are synchronised. I think that this model still doesn't explain long-range correlations sufficiently, for 10 ms. conduction delays (which are the maximum time-lags found) imply at most 0.5 cm distance between the brain areas, which is not long enough to connect distant brain areas.[32] Even in the orchestrated reduction model (NJ Woolf & SR Hameroff (2001)), the coherence does not reach a very long distance. The coherence arises from the coupling of the cytoplasma of different neurons through gap junctions mediated by (MAP) proteins. In order to reach the other end of the brain, this already fragile coherence would need strong protection (e.g. ion shields in the cell membranes). On the other hand, it has to be admitted that an advantage of this theory is that it can be tested, some predictions have already been verified such as the decoherence times of microtubules. But, the model they propose is only valid for visual consciousness, and not so clearly related to memory. In addition to that, it does not explain other oscillations than those of 40 Hz.

Finally, long-range correlations allow consciousness to be involved in memory processes and the other way around. The essence of consciousness namely is its integrative function of processes in different brain parts. Memories cannot be localised when one assumes that they are just the particular pattern of brain activation (e.g. if you hear something, the memory will relate to auditory areas in the brain, but also connect it to memories in other parts of the brain).

2.3 A dynamical picture

Memory formation does not solely depend on events on a quantum scale, but are also dependent on interactions at macroscopic scales, that is, by other cognitive processes that are mediated by neurons. In addition to that, memory formation can be viewed as a dynamic process. In the picture of Hebbian learning, memory formation is caused by the strengthening of synapses. In this paper, we look at how oscillatory processes influence not only memory storage at a neuronal level, but also at a sub-neuronal level, because this way of memory storage can explain extra features of memory. A more dynamical picture for memory storage is required, because 'the total set of retrievable memories changes continually with time'.[33] The relative timing of neuron firing affects the strength of synapses in the classical picture, and hence the memories that are present. Therefore the timing of oscillations plays a very important role, and in this paper I will claim that these oscillations are intricately connected to the quantum level in which memories are stored, so that their timing is affected by the quantum level. This then also might explain how it occurs that it is easier to remember something when you can link it to earlier memories. Once this has happened, these memories might then interact with memories stored far away. This would also explain why memories require time to sink in.

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[31] SR Campbell, D Wang (1996), p.1
[32] calculation using data of Traub et al.(1996), p.621
[33] ER Kandel (2000), p.1245

It has been shown that successful memory formation is accompanied by 40 Hz oscillations (J Fell et al. (2001)). Moreover, these gamma oscillations, as they are also called, have been implicated in consciousness and many other cognitive processes (as discussed in section 1.3, which makes them very relevant to consider in our model). How do 40 Hz oscillations on the electrochemical level affect the quantum fields? How do the quantum fields affect the 40 Hz oscillations? These are the main questions to be answered in this attempt to connect a quantum field theory of memory with a neuropsychological one.

Chapter 3: A Quantum Field Theory of Memory

3.1 Vitiello's quantum brain dynamics model

The model I will base my calculations upon was first put forward by Ricciardi and Umezawa in 1967. It was later adopted by Guiseppe Vitiello, whose articles I mostly used. Vitiello's model of memory is based on the formalism of Quantum Field Theory (QFT). The mathematics used is that of QFT of many body systems, which is a dissipative quantum field theory. Memory in this model is 'a printed pattern of order supported by long range correlations'.[34] The most revolutionary feature of this model is the existence of a field, which is quantised into field quanta. Vitiello proposes this field arises from molecular oscillations in the brain. In the brain many molecules, such as water and bio-molecules show dipole vibrations. These vibrations cause waves, which are quantised (like all waves), and therefore Vitiello calls them dipole wave quanta, dwq. It are those dwq that cause long-range correlations. However, there are also objections against this source of the field, given the fact that these water molecules and bio-molecules are ubiquitous. I will therefore not specify the source of the field, just consider that it exists, and leave this question open for further research)

If you look at the model mathematically, you see a potential with more than one ground state, so that a spontaneous breakdown of symmetry can occur when the particle settles in one of the ground states. So-called Nambu-Goldstone bosons are then formed (as consequence of the Goldstone theorem), which are in fact the dipole-oscillations. When these Nambu-Goldstone bosons settle in one of the possible ground states, memories are formed. Normally, these bosons would have a zero mass, and consequently infinitely long-range correlations. In our case, these correlations do not have an infinite range (because the brain is a system that has boundaries), which results in finite-size correlated domains. Because the dwq have mass, it will cost them time to propagate. In addition to that, it also explains why memories decay: the mass of the bosons causes an excitation threshold, and it is only by excitation that memories are refreshed. Dissipation is thus an essential feature of the model. We will come back to this in section 3.4.

Another interesting advantage of this model is its ability to explain association and confusion of memories. The system has finite boundaries, which causes the different vacua (separated from each other via spontaneous symmetry breaking), to be not entirely unitarily inequivalent. If they were unitarily inequivalent, it would be impossible to move from one vacuum to the next, and many memories could be stored 'on top of each other', in a unitarily inequivalent vacuum. However, the existence of bubbles implies some possibility of a phase transition between the vacua, which consequently implies that memories can be confused, but also that one memory can associate with another. The probability of phase transitions can be computed as well as the size of the bubbles, as has already been done in a similar (but slightly different model) for limiting cases in Buhai (2001).

3.2 Quantum brain dynamics versus orchestrated reduction model

It should be noted that neither neurons nor microtubules are the fundamental units of the brain in this theory, but the field quanta are. This is a striking difference with many

[34] G Vitiello (2000), p.2

of the other theories of brain functioning. By using a QFT description, as opposed to a quantum mechanical description as in the orchestrated reduction model, and by using spontaneous symmetry breaking, we can have infinitely long correlations due to the existence of inequivalent vacua. Because they are all ground states, these states of the system are stable. This is not the case in the orchestrated reduction model. Another problem with the orchestrated reduction model is that consciousness is too quickly linked to the occurrence of gamma oscillations: As discussed in chapter 1, gamma oscillations also occur in relation to other cognitive processes. Moreover, the type of cognitive process appears to be related to the specific form of oscillation that occurs. Thus, not exclusively consciousness can be linked to gamma oscillations, and gamma oscillations cannot be exclusively linked to consciousness.

3.3 A field influences a neuron

One of the legitimate questions that comes up when considering a field theory of memory is whether it changes something in the brain: are the quantum-scale effects actually perceivable in the brain? This section will discuss how neurons could be influenced by an underlying field theory in a biological sense (anatomical sense). The firing of neurons depends on a number of influences, and a very intricate system of ionic currents. In specific regions in the neuron, the currents are collected and integrated. When this integrated potential reaches a certain threshold, the neuron will fire and an action potential is generated.[35]

The quantum field, which I use in my model, is quadratically coupled to the neurons and can influence their firing by producing currents. These currents will be an extra influence on the neurons, on top of the macroscopic currents coming from other neurons. The question is whether this influence is strong enough. One can decide on that after calculating some energies. In quantum physics, energies are obtained from calculating a Hamiltonian, which could give the energy related to this process of condensation in biological media, on which the quantum field model is based. Because of the highly ordered form of the condensate, the energy can be channeled into a single mode. Condensation in biological media is often hard to investigate[36], especially because laser scattering experiments are not feasible in the brain. The means we possess is the EEG, and extensive modelling studies could possibly reveal scattered EM waves (by the long-range correlations), but this will be discussed in more detail in chapter 5.

3.4 The importance of dissipation

The quantum field theory that is used here is not a ‘normal’ quantum field theory, but one with dissipation. There are several reasons for this. First of all, dissipation causes a doubling of the degrees of freedom of the system, because we consider the system to be broken up in a ‘bath’ part and the ‘working’ part, analogously to a classical harmonic oscillator with dissipation (which can be considered to be causally coupled to another harmonic oscillator in order to take up the energy of the first one).[37] So far there has not been any consensus by the scientific community on the ontological status of these ‘ghost fields’ or ‘mirror variables’. Some people feel it is just a mathematical tool, arising from

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[35] MS Gazzaniga (1998), p.28
[36] H Frohlich (1968), p.648
[37] G Vitiello (1995)a, p.3

a separation of a dissipative system from the environment. In the case of the harmonic oscillator example, this means looking at only one of the system of coupled oscillators, which then shows dissipation, even though the system as a whole does not. This idea is advocated for example by Calzetta and Hu (1988), who claim it ‘is discernible in principle by an analysis of the experimental apparatus being used to monitor the whole arrangement’.[38] Warren (1999) even believes that they are unphysical degrees of freedom, which are cancelled by similar degrees of freedom with opposite statistics.[39] Vitiello on the other hand believes that ‘ghost fields’ are real, existing things and in his model they represent the influence of the outside world on memory (they are the ‘bath’ in which the normal oscillator exists). The puzzling thing about these ghost fields, is that they seem to obey extra symmetries, that the Lagrangians in terms of normal dissipation variables not seem to obey.[40] Hence the meaning of the ‘double’ is a question that still remains to be solved by the scientific community.

Moreover, the dissipation also incorporates an arrow of time in the model: a thermodynamic arrow of time. By considering this type of model one represents the fact that memories are formed at a certain point in time, subsequently decay, but can be revived by repeated stimulation (which is in more physical terms the excitation of the field quanta). Thus, if a certain pattern of brain activation repeats itself, then the dwq concerned are excited. The evolution of a memory state is controlled by variations in entropy, because these entropy variations can cause a memory to be excited. The entropy variation in this case will most probably be the patterns of activation of neurons during successful memory encoding.

In line with Vitiello, one can introduce an extra field to model dissipation, obeying exactly the same equations of motion as the other field, but with its time reversed. This is in literature often referred to as a ‘closed time-path formalism’. The extra field is then referred to as mirror variable or ghost variable. When looking at the system as a whole, there will then not be any dissipation. However, when considering one of the two fields separately, a dissipation term occurs. The form of this dissipation term is still subject of discussion, because the exact ontological status of the field is not even clear, and how the field interacts with the environment. It could be conceivable that only on certain spots in the brain there will be a coupling to the environment, for example there where perception occurs. That would result in a complicated expression for the dissipation term, of the form $a(x,y)\partial_t \phi(x,y,t)$. For we are only discussing the foundation of this model, we will leave this term out at present.

3.5 The model – equations

I will consider a self-interacting quantum field theory of the simplest kind. This field theory will then be coupled to a lattice of neurons, which I place in a regular array in order to simplify calculations. Because the neocortex, in which the neurons relevant for memory reside, is a relatively flat sheet (with a thickness of 2-4 mm.), we will use two-dimensional coordinates. The cerebral cortex is organised in cell layers [..]. The most typical form of neocortex contains six layers’.[41] The more inner layers of neurons (close

[38] E Calzetta & BL Hu (1988), p.2885
[39] G Warren (1999), p.266
[40] H Kleinert (2000), p.12-13
[41] ER Kandel (2000), p.327

to the white matter), are mainly feedback neurons, whereas the more outer layers of neurons are mainly feed-forward neurons. In our model, we can consider the different layers of neurons similarly to different fluid layers in fluid dynamics, and give them all different spontaneous symmetry breaking properties. For now, let us first look at only one of these layers. We can consider two Lagrangians: one for the neurons and one for the fields that underlie these neurons. The fields do not have a direct interpretation, but the charges are electric charges of the neurons. After all, neurons are objects that communicate through currents, and which send electric currents through the brain.

$$L_{neuron} = \mathrm{q_i}'(t)^2 + \varpi^2 q_i(t)^2 + \gamma\ \mathrm{q_i}(t) q_{i+1}(t) + q_i(t)^2 \phi(x,y,t)$$

$$L_{field} = \tfrac{1}{2}\partial_\nu \phi(x,y,t) \partial^\nu \phi(x,y,t) - m^2 \phi(x,y,t)^2 - m^2 \left(\left|\phi(x,y,t)\right| - \phi_0\right)^2$$

Note the quadratic coupling between the neuron and the field. This coupling was chosen because it results in a term proportional to the neuron in the neuron's equation of motion. When the neuron is more active, it is also more receptive to changes in the underlying quantum field. Moreover, a term of this form is known to generate so-called 'small oscillations', which means that we will be able to use perturbation theory in our calculations. The last term in the field Lagrangian is the term including φ0, which causes spontaneous symmetry breaking by creating two vacua with mirror symmetry around the origin. This is very important for the generation of storage capacity in the brain because it creates a number of unitarily inequivalent memory states. It is namely impossible to jump from one vacuum to the next while retaining unitarity. The reason why we use oscillators at all is that we consider dipole vibrations to be the sources of the field. Instead of harmonic oscillators, we take double oscillators, which also allow for symmetry breaking as described above.
The equations of motion that follow from these Lagrangians are the following:

$$\begin{aligned} &\partial_\nu \partial^\nu \phi + m^2\phi - m^2\phi_0 sign(\phi) + \mathrm{m}^2\phi_0{}^2 = \sum_i q_i{}^2(t)\delta(x - x_i) \\ &q_i''(t) + \omega^2 q_i(t) + \sum_j \gamma\ q_j(t) = \phi\ q_i(t) \end{aligned} \qquad (3.1)$$

Where the q_i represents the i-th neuron and where i and j are two different indices, φ0 represents the ground state of a neuron, γ the coupling constant between two neurons, and ω the frequency with which the neurons oscillate. The coupling constant is most likely not going to be the same in reciprocal connections between two neurons, moreover, very often the coupling constant is only going to be non-zero in one direction. The coupling constant need not be constant over time, because it can be a function of the neurotransmitters present, as well as drugs or hormones and other substances that influence the strength of connections between neurons (but in order to simplify calculations, we assume it to be constant). If the neurons oscillate in synchrony, for example with γ-oscillations, then this ω will be the same for all neurons. If there is no synchrony on the other hand, ω will have a position dependence (and possibly time-dependence as well). Also this oscillation frequency will be taken constant for simplicity.

Because these equations are coupled, they are quite hard to solve. This is the reason to first look at a simplified case, which is static and has only 1 dimension and two neurons involved in the coupling (in reality each neuron couples to about 2000-3000 other neurons). One then obtains (after Fourier-transforming back and forth):

$$q(t) = \frac{\sqrt{\pi}}{2\delta} e^{\frac{1}{4}(-2(\phi 1+\phi 2)-t^2 \pm 2\sqrt{(\phi 1-\phi 2)^2+4\gamma\delta}+4\omega^2)} (\phi 1 - \phi 2 \pm 2e^{\sqrt{(\phi 1-\phi 2)^2+4\gamma\delta}}\delta + \sqrt{(\phi 1-\phi 2)^2 + 4\gamma\delta})$$

Here we denote the coupling constants by γ and δ, and where φ1 and φ2 refer to φ(x1) and φ(x2). This expression shows indeed dissipation: over time the value of q will go to 0 quadratically (since there is a quadratic term in time). It is interesting to note that this expression shows oscillations once γ and δ have opposite signs and the fields φ1 and φ2 are quire similar. In other words: inhibiting neurons connected with exciting neurons can cause oscillations, if they are similar fields (i.e. with a similar spatial distribution). In section 1.4 we discussed that networks of excitatory and inhibitory neurons are required for (gamma) oscillations to occur. The most important prerequisite for gamma oscillations were re-entrant loops, provided by reciprocal connections. This occurs in our expression where both γ and δ have to be non-zero. It is also confirmed by Whittington et al. (2002) who state that 'the magnitude of the synaptic inhibition between interneurons governs the frequency of the ING [interneuron network gamma oscillations]'. However, they *also* find this in inhibitory networks of reciprocal inhibitory connections. In our calculation, we only find mixed networks (i.e. a combination of inhibitory and excitatory neurons), because in the hippocampus and rhinal cortex mainly those are found. The reason for this is that in mixed networks, the synchronised oscillation only occurs after a driving force of tetanic stimulations, which occurs naturally in these two areas (Whittington et al. (2002)). In the neocortex therefore it is likely that in the generation of gamma oscillations, both excitatory and inhibitory neurons are involved, as we have found here (since our model is used for the neocortex), especially in specific localised regions within the neocortex. This last observation is interesting, for it could point at another connection with Vitiello's model, which says that memories are more persistent in more localised domains.[42]

The problem with this expression however is that as soon as the oscillations start to occur, the whole expression will have an imaginary part added to it. It is unclear how we should interpret this. Maybe we can assume these are just a translation in the imaginary plane which can be gauged away, since electrical and energy fields are relative to a chosen zero (they do not have absolute zero values). The value of q(t) can also be negative when oscillations occur, but that is no problem because the charge of neurons can be chosen relative to an arbitrary 0 value.

3.6 Why would there be 40 Hz oscillations involved? (and not any other frequency?)

One of the first questions that arises when considering the above model for memory formation and retrieval concerns the role of gamma oscillations. Why would in specific oscillations of this frequency be implicated in memory? Why not other frequencies? We already saw that oscillations arose from particular combinations of inhibitory and excitatory connections between neurons (that is, connections with opposite signs). The specific values of the field and the coupling constants in these connections together determine the normal mode or frequency of the oscillations. Since in different types of cognitive processes, different types of neurons are involved, which can correspond to the different layers in the cortex. In the neocortex, different layers of neurons project to different parts of the brain and are therefore often involved in different

[42] Vitiello (2000), p.14

types of processes: motor processes, memory, perception etc. In each of these layers there are different types of neurons with different coupling constants. It has already been argued that 'synchronisation at different frequencies of large-scale brain electric activity might be used for integration of cell assemblies being involved in tasks differing in complexity.'[43] For example, less complex processes, such as perception might be encoded in high-frequency oscillations, whereas more complex tasks, such as memory, might have components in theta band activity etc (as we already discussed earlier). Multimodal integration on the other hand is achieved by gamma oscillations, as has been found by various researchers discussed in Chapter 1. In addition to that, it has been found that different oscillatory patterns occur indeed in different layers of the cortex.[44] The normal modes (ω_0 in our model) determine the cognitive function in which the neurons are involved.

However, the value of the field is also present in the above equation. Oscillations will most easily occur if the value of the two fields are almost identical, because then the positive term in the square root will be small. A possible explanation for this could be that maybe for semantically related memories the field will be similar (in its spatial distribution). In order to test this hypothesis, first the ontological status of the field still has to be clarified: what does it exactly mean and how does it arise? Is it indeed the result of dipole oscillations as has been surmised? Assuming this as a source would make it easier to arrive at quantitative results because then the potential in the field equation is known. Does its distribution relate to the content of the memory it represents (that is, is it a kind of map which represents from which brain areas, such as the auditory area different components of the memory derive)? These questions still remain to be answered.

[43] A Keil et al. (2001), p.405
[44] JJ Chrobak et al. (2000), abstract

Chapter 4: Calculating the Field

4.1 The field without spontaneous symmetry breaking

In order to calculate the field in the model we adopted, we will use Green's functions. We will start with the simplified case where m and φ0 are both 0. We define the Green's function as:

$$\phi_i(x,y,t) = \int dx'\,dy'\,dt'\; G(x\text{-}x',y\text{-}y',t\text{-}t')\; q_i^{\,2}(t')\,\ddot{a}(x')\ddot{a}(y') = \int dx'\,dy'\,dt' G(x\text{-}x',y\text{-}y',t\text{-}t')\,\mathrm{f}(x',y',t')$$

This equation then gives, upon substitution in the equation of motion,

$(\frac{1}{c^2}\partial_t^{\,2} - \nabla^2)G(x,y,t) = \delta(x)\delta(y)\delta(t)$, where I use the relative coordinates x → x –x', y → y-y', t→ t-t'. The constant c denotes the speed of the dipole waves through the brain. So far, I have not been able to find values for this, most probably because dipole waves are not considered often in connection to brain functioning. Fourier transforming gives the following expression for G:

$\tilde{G}(k,l,w) = \dfrac{1}{k^2 + l^2 - \frac{w^2}{c^2}}$, which should be transformed back. That is done by the following integral:

$$\frac{1}{(2\pi)^3}\int dk\; dl\; dw \frac{1}{\mathrm{k}^2 + l^2 - \frac{w^2}{c^2}} e^{i(wt-kx-ly)} \quad (4.1)$$

We can choose the sign of the factors in the exponent arbitrarily as long as we also multiply the integration variables with it. Integration can be done using Cauchy's Integral Formula with the Residue Theorem. Note that we have two simple poles here. We choose the contour that encloses both poles when integrated for positive time, and note that the poles are simple poles.

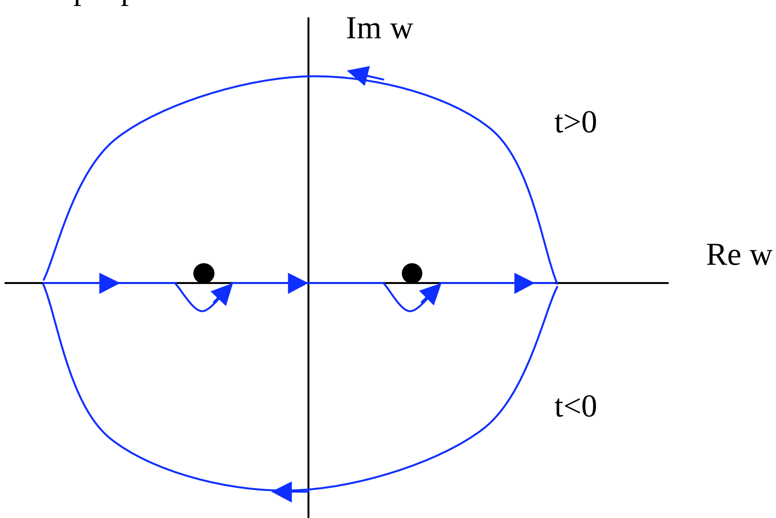


Figure 1: integration over w in the complex plane

That leads to the following result of the w-integration.

$$\frac{2i}{(2\pi)^2}\int_{-\infty}^{\infty} dkdl \left[\frac{-\mathrm{e}^{\mathrm{i}(\text{-}\mathrm{c}\sqrt{\mathrm{k}^2+l^2}-kx-ly)}c^2}{2\sqrt{k^2+l^2}} + \frac{\mathrm{e}^{\mathrm{i}(\mathrm{c}\sqrt{\mathrm{k}^2+l^2}-kx-ly)}c^2}{2\sqrt{k^2+l^2}}\right]\theta(t) \quad (4.2)$$

where θ(t) denotes the step-function, used to perform the integration only for positive t (i.e. t > t' in our ordinary coordinates). In order to perform this integral, we have to change to polar coordinates, whereby integral (4.2) becomes:

$$\frac{2i}{(2\pi)^2}\int_0^\infty \theta(t)\kappa d\kappa \int_0^{2\pi} d\vartheta \tfrac{c^2}{2}\left[-e^{i(-c\kappa t-\kappa r\cos\vartheta)} + e^{i(c\kappa t-\kappa r\cos\vartheta)}\right] \quad (4.3)$$

Integral (4.3) does in principle not give a converging result, but we use the fact that a complex exponential can be written in terms of sines and cosines. Since cosines are even functions, we can also integrate of all space (from –∞ to ∞) take the ½ times the value of that integral. We also say that the imaginary part of the integral is some imaginary function, which I ignore for now (later I will present a justification for that). The integral then turns into the following form:

$$\frac{i}{(2\pi)^2}\theta(t)\int_0^{2\pi} d\vartheta \tfrac{c^2}{2}\left[-\delta(r\cos\vartheta+ct)+if-\delta(r\cos\vartheta-ct)+ig\right] \quad (4.4)$$

Where we used the definition of the delta-function in terms of the complex exponential. A change of variables u = c r cos(θ) makes the integral much more simple:

$$\frac{i}{(2\pi)^2}\theta(t)\tfrac{-c}{2}\int_{-r}^{r}\frac{du}{|r\sin(\vartheta)|}(\delta(u+t)+\delta(u-t)) \quad (4.5)$$

The absolute value bars are necessary to avoid jumping of the derivative du/dθ. Integral (4.5) only has solutions for r > t (because of the delta functions).

$$\frac{-i}{(2\pi)^2}\theta(t)c\sum_n \frac{1}{|r\sin(\vartheta)|} \qquad \vartheta_n = \vartheta_0, \vartheta_0+2\pi, \vartheta_0+4\pi....$$

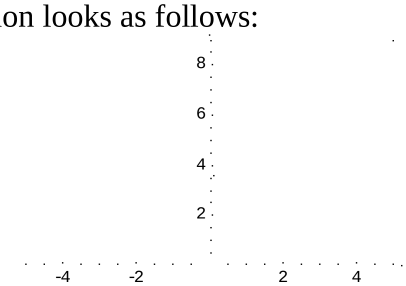
However, since u = c r cos(θ), we can have only one value for θ: cos(θ) = t/c r, and our equation becomes:

$$\frac{-i}{(2\pi)^2}\theta(t)\theta(r-t)c\frac{1}{\sqrt{r^2-\frac{t^2}{c^2}}} = G(r,t) = \frac{-1}{(2\pi)^2}\theta(t)\theta(r-t)c\frac{1}{\sqrt{\frac{t^2}{c^2}-r^2}} \quad (4.6)$$

Here we note that this Green's function is the same one as we would obtain from calculating the Green's function for the standard case ΔG = δ(x,y,z), except that we have made the following replacement: $\partial_z \to \partial_t / ic$, resulting in the Green's function we arrived at above.

4.2 The field with spontaneous symmetry breaking

As discussed above, we can use an analogy with textbook problems of Green's functions to calculate the case with spontaneous symmetry breaking, replacing the z-derivative with a time derivative. We will not use a φ^4-theory here, but rather a double oscillatory field theory, which also displays spontaneous symmetry breaking. The graph of this potential in 1 dimension looks as follows:



The latter model is analytically solvable in principle, unlike the former, where one always has to resort to perturbation theory. We have already incorporated this model into our Lagrangians (3.1). We will look for solutions of the form φ(x,y,t) = ±φ0 + η(x,y,t), because then we get an equation for η without the constant $m^2\varphi 0^2$. This solution is only valid for relatively small amplitude oscillations in the double oscillator potential, that is, only for oscillations which remain in the wells and do not jump to the other well. The equation for the Green's function becomes:

$$\left(-\partial_x{}^2 - \partial_y{}^2 + \partial_t{}^2/c^2 + m^2\right)G(x,y,t) = \delta(x,y,t) \qquad (4.7)$$

What has already been done very often in the physics literature is to solve a problem of the kind $\left(\nabla^2 + k^2\right)G(k,r,r') = \delta(r-r')$, and we can again model our problem on that by replacing the derivative with respect to x and y by i x and i y, replacing k with m, and ∂_z with ∂_t/c. The solution then becomes, modelled after Joachain & Bransden (2000), p.609 (with $r = \sqrt{x^2+y^2+z^2} \rightarrow \sqrt{-x^2-y^2+t^2/c^2} = i\sqrt{x^2+y^2-t^2/c^2}$):

$$G_{SSB}(x,y,t) = \frac{c}{(2\pi)^2}\theta(t)\theta(r-t)\frac{\exp(-m\sqrt{x^2+y^2-t^2/c^2})}{\sqrt{x^2+y^2-t^2/c^2}} \qquad (4.8)$$

We can use this expression for the Green's function to calculate our field.

$$\phi_{SSB}(x,y,t) = \sum_i \int_{-\infty}^{\infty} dt' \frac{c}{(2\pi)^2}\theta(\tilde{t})\theta(\sqrt{\tilde{x}_i{}^2+\tilde{y}_i{}^2}-\tilde{t})\frac{\exp(-m\sqrt{\tilde{x}_i{}^2+\tilde{y}_i{}^2-\tilde{t}^2/c^2})}{\sqrt{\tilde{x}_i{}^2+\tilde{y}_i{}^2-\tilde{t}^2/c^2}}q_i(t')$$

(4.9)

In the above equation the variables with a twiddle denote x-x', y-y' and t-t'. The theta functions in the equation above mean that we will only integrate over the history of the field, something that makes sense considering that we are modelling the brain. The field should not depend on future states of the neurons. The other constraint introduced by step functions is that r > t, which means that only events which exist inside the light cone (or something analogous when the speed c of the waves caused by the field is not the speed of light) of the field or the neuron are to be considered for calculation. By the same token as before, this seems to be a reasonable constraint. However, the equation above is only the 0-th order in the perturbation expansion of the field. We can write these expansions in compact notation where ◦ denotes a convolution:

$\Psi_0 = G \circ j$ where $j = q_i{}^2(t)\delta(x)\delta(y)$

$\Psi_1 = G \circ m^2\varphi_0{}^2\mathrm{sign}(\psi_0)$

$\Psi_2 = G \circ m^2\varphi_0{}^2\mathrm{sign}(\psi_1)$

And so on. The problem with calculating this perturbation is that it is extremely difficult to do because we do not have a very easy expression for ψ_0, which makes it hard to say something about the sign of this function. We will therefore first stay with the 0-th order term. In this term also the equation for the neuron q appears. This function is a solution of

$$\partial_t{}^2 q_n + \omega_0{}^2 q_n - \sum_j \kappa\left[\int_0^{\infty} dt'\,\mathrm{G}(\mathrm{x}-\mathrm{x}_j, y-y_j, t-t')q_j{}^2(t')\right]\mathrm{q_n}(t) + \sum_i \gamma_i q_i(t) = 0 \quad (4.10)$$

We can rewrite (4.10) as the following simple equation:

$$\partial_t{}^2 q_n + (\omega_0{}^2 - d)q_n + \gamma = 0$$

We see that the oscillation frequency of the neurons is modulated by the term d, which is due to the field. The neuron accumulates the firings of all neurons it is connected to in the past and this term modulates the frequency with which the neuron fires. Here we see again that neurons are integrate-and-fire devices. The difference with conventional (integrate and fire) approaches is that here the integration is done over all time, instead of over a relatively short period. However, when the time becomes too long, the Green's function will not satisfy the constraint anymore which keeps its square root real, and hence these times will not count. Moreover, this constraint causes the fields far away to be integrated over longer time periods in the past than neurons close by. These can maybe be interpreted as long-range correlations. The coupling constant κ denotes the strength of the coupling between the field and the neurons. It is this constant which will also determine whether the influence of the field on the neurons will be significant. In face of our earlier discussion concerning the origin of the fields, and why the dipole oscillations in other parts of the body would not influence the neurons, I hypothesise that *there* the constant κ is too small to allow a significant influence of the field. The value of this constant (which is therefore not really a constant in reality, we just made it constant for simplicity) could be found by looking at brain activity during memory storage and retrieval with gamma and theta oscillations, and relate the changes in frequency of oscillations to the particular brain areas.

If at a certain point in time a neuron would fire a very short pulse (delta-function like), where the duration $\tau << l/c$ (the factor l/c denotes the time that a signal needs to travel a distance l), then this would contribute to the field just a factor equal to the neuron's charge after a time l/c. The pulse just travels through the brain via neuron-neuron connections, but it quickly dissipates due to the term $\gamma_i q_i$ in the equation for the neurons. The pulse can only be transmitted long distances through the action of the field, which causes indeed the long-range correlations. Short pulses will have strong effects on the fields of other neurons, because they are not modulated by these other neurons yet. They will depend only on the quantum field level coherence, not on neural responses. We might interpret these mechanisms as subconscious impulses, because there is no macroscopic brain activity involved and due to the massless nature of NG-bosons, these processes are very fast.

In section 2.3 we asked ourselves how gamma oscillations would affect the field and how alternatively the field could cause gamma oscillations in neurons. When the contributions of the different neurons are added in the equation for the field (4.9), neurons that are not in phase will on average most likely cancel each other out. Only neurons that are synchronised will contribute to the field, or neurons that send out single pulses with a very short duration (as discussed in the previous paragraph). We noted earlier that in order for successful memory formation to occur, indeed synchronisation was necessary. This model gives a mathematical reason for this requirement. Gamma oscillations in the neurons can with sufficient synchronisation give a contribution to the field, which can then through the long-range correlations connect this information to the rest of the brain. Also memory retrieval through oscillations cause a connection to the field, which then can connect different brain regions so that consciousness of memories becomes a very non-local action, in agreement with our previous discussion that consciousness is a non-local feature of the brain, emergent through synchronised oscillations. The theory proposed by Vitiello indeed *has* to be accompanied by the 40 Hz theory in order to give better results, the combination of these two theories arises naturally!

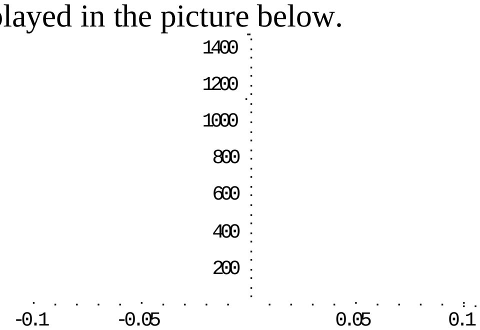
On the other hand, when the field oscillates with a certain frequency, we see that the neurons can be influenced significantly when the term d is large. When the fields are similar in different places in the brain (they are coherent), then these contributions will be large because they will not cancel each other out (in agreement with the calculation in section 3.6). The amplitudes of the fields cannot be too large, because then the model of the double oscillator does not apply anymore. It could be the case that what happens for example during epileptic seizures is that amplitudes of oscillations become too large, and the double oscillator model breaks down causing problems with consciousness. The neurons that are most active will have the strongest influence from the field, so the field can really amplify the activity of the neurons. What is also required is a strong coupling constant κ between the field and the neurons. Finally, if the signs of the connections are opposite (i.e. mixed networks), then the term $\sum c_j q_j$ cancels out, meaning that there is no dissipation. When there is less dissipation, then the oscillation will be stronger, again in agreement with our finding in section 3.6 (however, the condition here is less strict).

In short, even from these complicated expressions that cannot be solved analytically, we can still deduce a number of dynamical properties of the field in a hand-waiving manner. In addition to that, we might be able to use approximation methods, once some of the parameters are known.

4.3 Phenomenology: bubbles and solitons

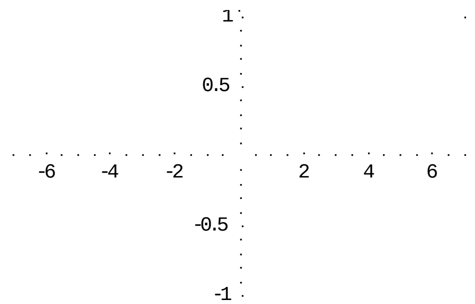
Using this model of memory, also new (in terms of modelling phenomena) appear, which might explain additional features of memory. If these correspondences prove to be useful, then that would also be a justification for using the double oscillator potential as a generator of spontaneous symmetry breaking.

The solutions found above to the equations of motion are altered forms of the Yukawa potential, as displayed in the picture below.



They show interesting behaviour: they can form bubbles and solitons. Solitons are stable solitary wave solutions to the equations of motion. These wave solutions move without changing shape or size, and therefore when they progress through the brain, they 'swap' vacua. Different solitons meeting show complicated behaviour, but asymptotically just pass through each other.[45] In the 1-dimensional case of our model, soliton solutions have been found by connecting a positive and a negative bubble to each other, as shown in the following picture.[46]

[45] properties from solitons as discussed in Ryder (1997), p.390-392
[46] personal communication and notes from Dr. Frank Witte

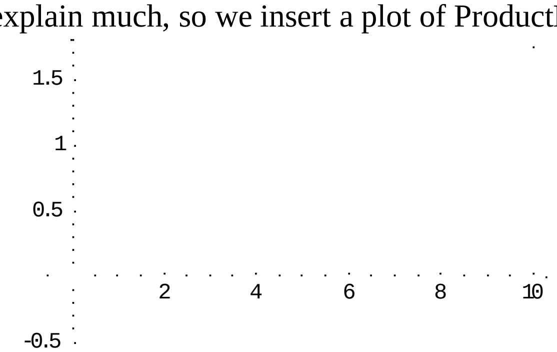


These bubbles have only components on their own side of the abscissa, because the exponential function vanishes at the other end. Bubbles are then created by the emission of a soliton-anti-soliton pair.

Bubbles are solutions that travel between vacua. They can be found by matching the solutions of vacua of different signature, where we use as our solutions the simplified versions (assuming that the integration does not influence the x and y dependence, which is relevant for the occurrence of bubbles and solitons).

$$\Lambda_{bound}(x,y,t) = q^2(t)\frac{\exp(-m\sqrt{x^2+y^2-t^2})}{\sqrt{x^2+y^2-t^2}}, \Lambda_{\text{unbound}}(x,y,t) = q^2(t)\frac{\exp(m\sqrt{x^2+y^2-t^2})}{\sqrt{x^2+y^2-t^2}}$$

We can do that because our solutions are linear superpositions of these functions for different charges q, and we ignore the integration (that is, summation over the past) for now. We also chose units such that c became 1. Inside the bubble, the solution will be a linear combination of Λ_{bound} and Λ_{unbound}, with two sets of coefficients c1 and c2 (for each coordinate there will be two coefficients because there are matching conditions on the value of the field itself and on its derivative). Computation of these matching coefficients leads to interesting properties of the bubbles. In order to simplify matters, we write $c = \sqrt{x^2+y^2-t^2}$ and consequently we arrive at two matching coefficients, which upon substitution into the equation of motion again give a condition that these solutions must satisfy. This condition is (still in terms of c, using the proper coefficients would be a very involved computation, beyond the scope of this paper, if possible at all): $c \to \frac{1}{m}\mathrm{Pr}\,oductLog[\frac{mq^2}{\phi 0}]$ where ProductLog[x] gives the principal solution for u in x = u e^u. That still does not explain much, so we insert a plot of ProductLog[x].



From the above we see that ProductLog goes off to -∞ for negative values very fast. We can therefore impose the (a little bit too strong) restriction upon m $q^2/\varphi 0$, namely that it should be positive. This restriction then leads to the following expression for the bubble radius (using the definition for c and rearranging):

$$r = \sqrt{\tfrac{1}{m^2}\,\mathrm{ProductLog}^2\left(\tfrac{mq^2(t)}{\phi_0}\right) + t^2} \quad (4.11)$$

It is important to note here that r is *not* a function of time, because in its derivation, we used the expression for the field at only one particular point in time. Bubbles are in fact possibilities to travel from one vacuum to another. If bubbles are large, then this probability is large. Travelling to another vacuum really means that memories are changed, because memory storage is defined by the vacuum state they are in. When the neurons have large charges, then the bubbles are becoming large; i.e. if there is much brain activity in the relevant neurons (that is, neurons connected to the neurons we are looking at), then memories can be confused or associated with other memories.

In the case of 2+1 dimensions, which we have here, however the situation changes. Because of the complexity of the matching conditions, the connection between solitons and bubbles cannot be so easily made anymore. It is still likely however that solitons *do* occur. Solitons are objects that change the memories extensively than simple bubbles, which can only travel between vacua. Solitons retain their shape, and therefore influence the brain when they travel through it. They arise from topological reasons[47], when different solutions to a particular equation cannot be continuously deformed into one another. They are therefore a consequence from the particular memory model we adopt in this paper, and depend on the structure of the equations and the domain.

The influence of the quantum dynamical on the neuronal level is likely to be mediated mainly by these solitons because of their stable form and configuration. It is possible that these solitons correspond to strong emotional experiences, because those can completely change the way a person perceives the world, in a way, it can change his view on his memories and thereby the memories themselves. This could be tested by investigating first the influence of objects like solitons on EEGs, and secondly by testing whether these occur in people in highly emotional states.

4.4 Possible refinements of the model

In reality, the coupling between the different neurons cannot be considered either linear or quadratic, since neurons are excitable systems. In fact the connection between two neurons is a sigmoid function of the form:

$$g_i = \frac{1}{2}\left[1 + \tanh\left(\sum_j w_{ij} q_j + \theta_i\right)\right]$$

Here q_j is again the charge of a neighbouring neuron, and j is their index. The sum goes over all connected neurons, and w represents the synaptic strength. The symbol θ denotes the threshold for excitation of the neuron we are looking at. This term should then replace the linear coupling term $\gamma\, q_j$ in the equations of our model. It is a much better approximation because it shows clearly the slow connections between the neurons in the brain (as opposed to the field, which transmits information almost instantaneously), something which was so far not really apparent in the model we used. The difficulty with this term is however that the equations become non-linear, which is the reason why I did not take it up in my model so far. Moreover, the base frequency with which the neurons oscillate (w_0) has been kept constant in my model, but it would be more realistic to make that frequency time-dependent, because the neurons can have different base frequencies

[47] Ryder (1996), p.399

at which they oscillate, depending on the circumstances (e.g. neurotransmitters present and connections with other neurons).

In addition to that, it would be interesting to consider the question from what the quantum fields, which are dynamically generated arise. Vitiello puts forward his theory about dipole oscillations, but the problem with that surmise is that the question then arises why memories can only be stored in the neocortex and not anywhere else in the brain or even in the rest of the body for that matter. After all, everywhere in the body are these dipole molecules, which can vibrate. One possible explanation that can be considered is that only in the neocortex exist the neurons that can be used by the hippocampal structures (because they are connected to the hippocampus) to store memories. However, one might also be able to come up with other sources of the field. When the source of the field is clear, then also values for the other parameters, such as m and $\varphi 0$ can be found, which then could lead to more quantitative predictions.

Chapter 5: Possibilities of Quantitative Predictions

Even although the above set of equations can tell us something about dynamical phenomena that appear in the brain, especially in relation to consciousness and memory, it is first necessary to check in how far this model is adequate. In the present paper we have given arguments of a more qualitative nature, about features that the model should have, but in order for a model to be really valid and useful, it is also necessary that it could give novel predictions (the equations we used could for example tell us something about typical timescales of memory formation and confusion, or about effects of impulses of a certain energy and frequency on memories). When we want to know more details, and in particular more quantitative results, a major transition will have to be made. What is necessary for that will be the subject of this chapter.

5.1 From neuron to EEG

The subjects of this model are mainly humans, which will make experimental verification of results in the traditional ways of physics a bit hard. For example, placing a test charge in the brain of a person is not a reasonable experiment.

In order to connect this theory of memory and oscillations with experimental results, we have to consider the relation between the neuron and what is measured in an EEG. This EEG is in fact the 'summated activity of synaptic potentials in the dendrites of cortical neurons'.[48] Much of this activity is caused by the excitatory synaptic potentials reaching the cerebral cortex from the thalamus, which is the relay station of the brain. On the EEG, we can see 'field potentials', which is synchronised activity of a large number of cells, and these are seen as spikes, which should however be clearly distinguished from the spikes or action potentials of individual neurons. The cortical neurons involved here are mainly pyramidal cells. Finally, the EEG is influenced by the orientation of the sources and the shielding by tissue and bone.

Considering all this, it seems quite hard to connect individual neurons with the 40 Hz oscillations perceived by the EEG. However, 40 Hz oscillations have also been found in ensembles of individual cells, as well as in models of groups of neurons.[49] In our model however, we will have equations for single neurons, for reasons of computational simplicity. How can these then be linked to the gamma oscillations? It is known that the behaviour of a single neuron can be approximated by the mean field approximation.[50] This implies that we can consider equations for single neurons to represent the behaviour of a whole assembly of neurons. The behaviour of these assemblies of neurons can then also be visualised on an EEG.

It might also be interesting to apply statistical mechanics methods to these neurons, such as for instance has been done by Lester Ingber (1994) and Bruce Knight (2000). The reason why we did not do that was that we first wanted to consider the effects on micro-scale, which is much simpler to analyse. It might also be interesting to try to achieve more concrete results by running a Monte-Carlo simulation with the equations found in this paper.

[48] ER Kandel et al. (2000), p.897
[49] RD Traub et al. (1996), p.621
[50] AW Knight et al. (2000), p.54

5.2 Quantum dynamical and electrochemical level

Another way of looking at this model is more abstract, relating to the dynamical properties that appear. In the model presented here, there are two levels involved: memory happens at a quantum dynamical level and electrochemical activity at a classical level. The quantum nature of the phenomena thus has a dynamical origin. The aim of this thesis was to examine how the two levels interact: how the transition from a continuous level of dwq to the discrete level of firing neurons (which create the electrochemical activity shown on the EEG) works.

The electrical activity in the cerebral cortex then represents the firing patterns in the thalamocortical system, which is the brain's relay system. For our purposes, it is most relevant part of the brain, since this is the place where memories are created, stored and retrieved. During waking, the thalamic relay neurons are in their transmission mode, which means they are near threshold. Recall that this is also the period when synchronised gamma oscillations can occur. During sleep on the other hand, we see a burst mode, due to the fact that the neurons are hyperpolarized. It is during sleep that long-term memories are being transferred to permanent storage. We will in this paper only be concerned with the normal mode, in which synchronisation occurs, so that we can make the connection with long-term memory (because we already established the necessary connection between synchronised oscillations and memory formation).

The coupling of the order parameter (of the quantum dynamical level)[51] to the electrochemical level is analogous to the coupling between acoustic waves and phonons in crystals. The dwq can be compared to the phonons, whereas electrochemical waves can be compared to acoustic waves. The acoustic waves then form a potential in which the dwq move. Moreover, one can consider the phonon-phonon interactions, because phonons are quanta of acoustic waves, and they can arise from the oscillations of atoms in a harmonic crystal.[52] In a similar fashion, dwq can also originate from the quantisation of electrochemical waves, which originate from the oscillations of dipole molecules in the brain. Taking on this similarity between our model and scattering phonons, we can say that electromagnetic waves are scattered by the dwq.[53] Electromagnetic waves are phenomena that can then be measured in EEG imaging. The problem is however that it will be very difficult to calculate the exact effects on these pictures due to the indirect nature of EEGs as discussed earlier. It is also the case that decay rates of phonons cause coupling of the different modes of the oscillations. This can be translated into our model by seeing that the decay of dwq (we are looking at a dissipative system) causes coupling between the different oscillations that are normal modes of the system, through which the distribution of these oscillations will become more isotropic. One test for the model under discussion could therefore be to check whether this can actually be seen to happen on a EEG. Do the neuronal waves show signs of scattering with a field?

In addition to that, it is possible to calculate the Hamiltonian of the system to determine the energy of the system. The Hamiltonian is related to the Lagrangian by:

$H = \frac{1}{2}\partial^{\nu}\partial^{\mu}\phi - L = \nabla^2\phi + m^2\phi^2 + m^2(|\phi| - \phi_0)^2$ where our ϕ is as defined before:

$$\phi_{SSB}(x,y,t) = \sum_i \int_{-\infty}^{\infty} dt' \frac{c}{(2\pi)^2}\theta(\tilde{t})\theta\left(\sqrt{\tilde{x}_i^{\,2} + \tilde{y}_i^{\,2}} - \tilde{t}\right)\frac{\exp\left(-m\sqrt{\tilde{x}_i^{\,2} + \tilde{y}_i^{\,2} - \tilde{t}^{\,2}/c^2}\right)}{\sqrt{\tilde{x}_i^{\,2} + \tilde{y}_i^{\,2} - \tilde{t}^{\,2}/c^2}}\, q_i(t')$$

[51] This is a macroscopic variable

[52] G Vitiello (2002-3-25) personal communication

[53] phonon scattering is discussed in Chapter 8 of Wolfe (1998)

We can apply the Hamiltonian to this wave-function, which as always in quantum physics will give us the energy (since Hϕ=Eϕ, where E is the energy). After a tedious calculation that results in:

$$H\phi = \left[\begin{array}{l} \frac{1}{\sqrt{\tilde{x}^2 + \tilde{y}^2 - \tilde{t}^2}} (-2m + 2m^2 r^2 + \frac{2m^2 r^2}{\tilde{x}^2 + \tilde{y}^2 - \tilde{t}^2} + \frac{2r^2}{\sqrt{\tilde{x}^2 + \tilde{y}^2 - \tilde{t}^2}} \\ - \frac{1}{\sqrt{\tilde{x}^2 + \tilde{y}^2 - \tilde{t}^2}} + \frac{3r^2}{(\tilde{x}^2 + \tilde{y}^2 - \tilde{t}^2)^{3/2}}) \end{array} \right] \phi + 2m^2\phi^2 - 2m^2\phi_0\phi + m^2{\phi_0}^2$$

where c has been put to 1 and the twiddles again denote x-x'etc, r^2 means here $x^2 + y^2$. This is a quadratic equation in ϕ, and its value depends largely upon the values of the parameters m and ϕ0. Time constraints did not permit (an attempt at) solution of this equation.

5.3 Meaning of the Parameters

In this paper, many of the parameters did not have an explicit value. One of the most important parameters not discussed so far is m. What is the mass of the field? Another interesting parameter is ϕ0, the parameter that causes spontaneous symmetry breaking. This represents the ground state of the field. Once the source of the field is known, for example dipole oscillations, this ground state can also be known or calculated. The ground state is the lowest energy state of that harmonic oscillator and depends on the different molecular forces involved. These processes have been solved with quantum chemistry methods. Moreover, once we know that dipole molecules are the sources of the field, also the mass becomes known, which will be the mass of the molecules. Generators of dipole waves can be different molecules: water, but also proteins or other dipole molecules. Which molecule would be the most likely candidate still has to be discussed. One possibility would be to check whether in some cases of brain damage a specific type of molecules has been damaged, and whether a correlation could be made between disease and memory.

Conclusion

Did the interaction of the two theories give interesting results? Quantitative results are still absent, because as mentioned in chapter 5, that would require more intricate knowledge of the ontological status of the fields and a deeper study of correspondence between this model and the brain.

One interesting observation that we did was the reason for having certain specific frequencies in the brain for certain cognitive processes. Because the frequency of the transient assemblies is determined by the connections between the neurons, and because often different types of neurons, in different layers of the cortex are involved in different cognitive processes, it might be the case that gamma oscillations are emitted by a certain specific type of neuron.

How did the 40 Hz oscillations affect the dwq and how did the field affect the 40 Hz oscillations? We saw that synchronised gamma oscillations can contribute significantly to the field, thereby changing it. The field is then capable of communicating along large distances in the brain (it has long-range correlations), unlike the neurons themselves, which suffer from slower connections and dissipation. This theory of memory can explain interesting things, for example why synchronisation is necessary for successful memory formation to occur, and how a large part of the brain can be influenced by memories.

A totally different kind of question that I asked myself in the introduction was whether it would be a useful approach to neuroscience to use quantum field theory. The use of quantum field theories leads to a rather complicated description of neuron behaviour, from which in the first instance no quantitative results can be obtained and which require many approximations to be made. On the other hand however they can point at interesting qualitative results, in particular the existence of dynamical phenomena. The theory described in this paper for example explains how long-range correlations between memories could possibly occur and what kind of other strange phenomena would link to it (for example solitons and bubbles). The latter phenomena can explain confusion of memories, forgetting and possibly influences of strong emotions. The explicit inclusion of these phenomena in a model of this kind is completely new.

Because this paper is only a first study, it also means that only preliminary interpretations can be given to these phenomena and they require much more discussion in the future. Particular drawbacks of this model are its mathematical complexity and the unknown values of parameters. Refinements of the model and linkage to experimental data (in particular EEG data, which is amenable to mathematical analysis) would be required in order for it to be useful for real predictions. However, even in a hand-waiving manner, the model can give new ideas or insights into brain functioning.

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