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Complex biological memory conceptualized as an abstract communication system -human long term memories grow in complexity during sleep and undergo selection while awake

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1.1 Summary

Biological memory in humans and other animals with a central nervous system is often extremely complex in its organization and functioning. A description of memory from the perspective of complex systems may therefore be useful to interpret and understand existing neurobiological data and to plan future research. This summary section summarizes our results, which are explained in more details in the following sections.

We define systems in terms of communications. A system does not include the communication units ('CUs') that produce and receive communications. A dense cluster of inter-referencing communications surrounded by rare set of communications constitutes a communication system. Memory systems are based on communication units that are more temporally stable than the CUs of the system which is using the memory system.

We propose that the long term memory (LTM) system is a very large potential set of neurons among which self-reproducing communication networks (ie. individual memories) may be established, propagate and grow. Long term memories consist of networks of self-reproducing communications between the neurons of the LTM. Neurons constitute the main communication units in the system, but neurons are not part of the abstract system of memory.

Since neurons tend to be lost from memory systems by entropic mechanisms, there is a necessary tendency for all potentially-sustainable memories to grow by recruitment of new neuron communication units to form larger (more complex) networks of communications. Such growth of memories may occur by mechanisms such as expansion and combination of already existing memories, leading to some of the familiar distortions of memory such as confabulation and generation of standard scenarios.

Memory systems are therefore conceptualized as systems that spontaneously grow by recruitment of neurons to participate in expanding net-

works of communications. We suggest that growth of memories occurs mainly (although not entirely) during sleep, and memories are subject to selection mainly while the organism is awake.

Selection of memory systems occurs by interaction with other brain systems. Memories systems that lead to further communications that are not contradicted by 'experience' of neural communications during waking behaviour may persist and continue to increase in complexity - these are provisionally assumed to be correct memories. Memories that create contradictions with other communications within the LTM system, or with communications from other neural systems, do not lead to further communications within the long term memory system. They are regarded as informational 'errors' and eliminated from the long term memory system by their failure to propagate. (Note that contradictions are qualified as such by the impossiblity of further use of them within the memory system, according to the rules of this system. There is no particular observer component or mechanism within the system that decides that some memory creates a contradiction.)

The adaptiveness of memories is constrained in the first place by the nature of the memory system, which has been shaped by the organism's evolutionary history; and in the second place by the selective pressure of the organism's continued experience interacting with the self-reproduction of memory scenarios.

The 'memory function' of a complex biological memory system represents a small proportion of the possessing of the memory system since differentially much greater amounts of internal processing are intrinsic to the existence, maintenance and growth of biological memory. In other words, most of what the biological memory system does is not related to the 'memory function' observable from outside, but it is rather internal processing that is usually inaccessible for an external observer. Internal processing in the human long term memory system probably occurs mainly during sleep. During sleep memory systems are more-or-less cut-off from communications with the rest of the organism and its environment.

The primary function of sleep is therefore to maintain and increase the complexity of the long term memory system, which includes combination and harmonization of memories. In a paradoxical sense, the LTM system exists mainly to sleep, and its memory function is merely the 'rent' that the LTM system pays to the organism in order that the organism will allow the LTM system's continued existence. This conceptualization may help explain the indirect and imprecise association between sleep and LTM function in humans, since the memory function is a secondary and subordinate attribute of the LTM system.

What follows is not intended as a contribution to the neurobiology of memory. Rather this account is an abstract reconceptualization of the nature of memory - a framework intended to lead to an improved interpretation and understanding of the neurobiology of memory and to guide future scientific investigations. The novelty of this description arises from its reversal of the usual description of memory as being formed while awake and consolidated while asleep. By contrast, we propose that memories are systems of communications which grow during sleep and are selected by interaction with other brain communications when awake. In contrast to traditional 'instructionist' ideas of learning and memory - which see the environment as instructing the mind - our theory is more akin to 'selectionist' accounts of neurobiology such as those provided by Edelmann [9] and Gazzaniga [11]. Like these authors we regard memories as a consequence of the generation of diversity and selection among variants. But we also believe that only systems can undergo selection, and not communication units such as neurons; that therefore systems are primary and selection is secondary; and that long term memories are abstract systems of communications between neurons.

First we introduce our conceptualisation of communication systems. This is followed by the interpretation of LTM in this context. Finally we discuss the role of sleep in the LTM.

1.2 Communications and abstract communication systems

There are numerous version of systems theory, and conceptualizations of complexity. To distinguish the version deployed here we use the term 'abstract communication systems', The main source of the theory is the work of Luhmann [18] as modified by our earlier works [2] [3] [6] [7].

We take it as axiomatic that the world consists of systems and their environment. From the perspective of a specific system there is only itself (the system) and the environment - and all knowledge is knowledge within systems. The environment beyond the system is only inferred indirectly, as a system's 'explanation' of why the system is not perfectly predictive. The system only knows that it does not function perfectly, ie. that it does not know everything about itself, and therefore infers that there is a world outside itself. A system can model what happens in this environment, it can be aware that its models of the environment have not (yet) been contradicted by experience, but the system does not know anything directly concerning the environment (ie all its knwoledge about its environment is derived from the problems of its predictions about itself, without being directly derived from the environment). For example, this implies that a 'memory system' is primarily a system defined by a specific processing 'logic' and only secondarily functions to provide memories. The 'memories' within a memory system should therefore be conceptualized as elements of the memory system's model of its environment. (This perspective of memory as a conjectural 'model' of its environment is in line with the concept of autopoesis described by Maturana and Varela [21].)

The critical conceptual breakthrough deriving from Luhmann is that systems are defined in terms of communications, and therefore that systems exclude the communication units ('CUs') which produce and receive communications (see a representation of an abstract communiction system in Figure 1). Biological systems such as memory therefore do not include the physical brain communication units (such as nerve cells), and social systems such as the economy, politics and the law do not include the human beings who work in them. Nerve cells and human beings are, in this context, communication units - but are not themselves communications, hence cannot be part of the systems under consideration. Other CUs may be non-living such as books and computer disks.

Communications are sequences of symbols communicated between communication units. Abstract communication systems are made by such communications between communication units. (To count as a communication, a signal must be generated, transmitted and received.) The communication units are not part of the system, since they are not themselves communications but instead transmit and receive communications. CUs may be inert - books, computer disks and DNA molecules do not 'generate' and 'receive' communications exactly, but are structurally altered by communications in ways that enable these alterations to affect subsequent communications, and this is a more precise definition of CU.

Communications 'reference' other communications, in the sense that the sequence of symbols contained in a communication is dependent on the contents of other earlier or simultaneous communications and thereby refer to them. A dense cluster of inter-referencing communications surrounded by rare set of communications constitutes a communication system [2] (dens cluster of communications means a set of communications that are frequently referenced by other communications within the cluster, and which also reference other communications within the cluster, rare set of communications means that these communications are rarely referenced by communications within the dense cluster and they rarely reference communications from the dense cluster - see Figure 1 for a graphical representation). In quantifiable terms it may be said that a system is a 'significantly' dense concentration of inter-referenced communications which persists over a 'significant' timescale - in which the cut-off levels of significance define the probability that there is indeed a system [6].

A communication system is defined by the regularities that specify how referenced communications determine the content of a referencing communication. In other words, each system has a specific 'logic' by which communications are evaluated, and systems have a characteristic mode of processing. All communications that follow the set of rules defining the system are included as part of the system. Other communications that do not follow the rules of the system are part of the system's environment.

A system needs to be self-reproducing in order to maintain its characterizing density of communications over time, and this self-reproduction generates surplus communications and the tendency for expansion of the system by inclusion of communications produced by more communication units contributing to the system or expansion of communications from the units al-

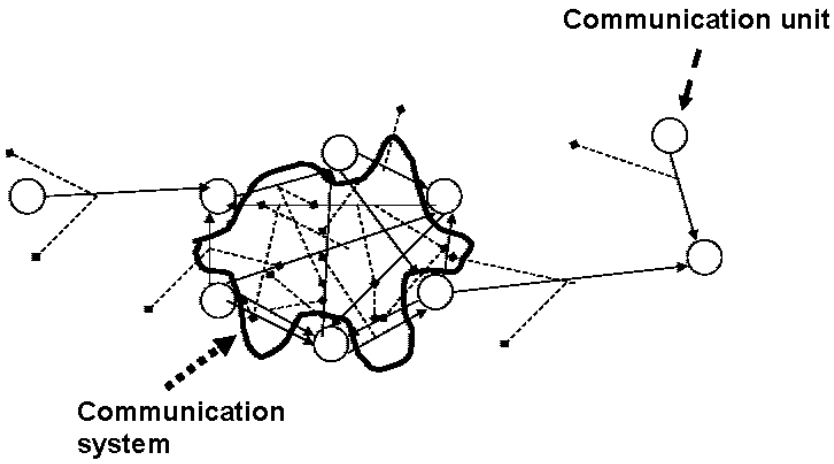

Fig. 1.1. A representation of a communication system. Arrows represent communications, segmented lines represent referencing relations.

ready contributing - this tendency for growth of systems generates the basis of competition between systems. The self-reproduction also randomly generates variations by entropic mechanisms, which will eventually (because of the competition created by system expansion) be subject to selection pressures.

For example, the system of computer science contains all communications which reference earlier scientific communications from the domain of computer science and which follow the rules of these scientific communications (e.g., allowing the possibility of falsification, using logical reasoning, discussing admissible topics using admissible arguments etc.). A large part of these computer science communications are derived from scientific papers, which explicitly reference other scientific papers, and use the conclusions of earlier papers as premises of the logical reasoning presented in the paper. According to systems theory, the human computer scientists are not part of the system of computer science, nor are the physical objects that are scientific papers. Only the dynamic scientific communications about computer science topics are part of this system. In order that computer science continue as a dense communication cluster over time, it needs to continually generate a surplus of communications, so the system has a tendency to expand. Since communication units have a finite capacity, the expansion (sooner or later) leads to competition and selection among variant systems of communications.

1.3 Growth of systems

From each system's perspective "the world" is constituted by binary division between itself (the system) and its own environment (not-the-system) - and there are as many such 'worlds' as there are systems. The same communication will have different meanings (ie. be a different communication) in different systems, or be included in one system but not another. The set of regularities of referencing constitutes an abstract grammar, which defines an abstract language, characteristic of the system. For example, the sciences of economics and medicine have different specialist languages, and scientific communications belong to one of these sciences according to whether they follow the rules of the specific language. (Note that a scientific communication may not be for example exclusively about economics, but it will be part of the science of economics in terms of its economics-relevant aspects. In other words, when a later economics paper reference this communication, the reference will relate to the economics aspects of the communication, and not to other aspects that are irrelavant int he context of the science of economics.)

Communication systems reproduce themselves by recruiting new communications, which follow the referencing rules of the system. This often occurs by the recruitment of new communications units to contribute to the system. For example, in the system of computer science (or any other science) many of the communications units are the scientists (human beings), and one of the ways the system grows is by increasing the numbers of computer scientists, or by increasing the proportion of time the scientists spend on communication of computer science information [14]. Also, the system grows by increasing the frequency of communications between the scientists, and this may involve the inclusion of other types of communication units such as scientific journals.

How successful is the recruitment of new communications, depends on earlier communications generated by the system and on the match between the system and its environment. We can view the system as a self-describing system made of communications, which at the same time describes its environment in a complementary sense. More complex and potentially more-adaptive descriptions of the systems environment may lead to greater success in recruiting new communications and more rapid reproduction and expansion of the system. Memories constitute (possibly compressed) descriptions of sets of earlier system communications and in a complementary sense descriptions of aspects of the system's environment. Memories potentially may increase the adaptedness of a system by increasing its complexity, and therefore the potential closeness of 'match' between the system's model of the environment and the (infinitely complex) environment itself.

The system communications are about the system itself. System communications reference other system communications in order to prove that these communications are part of the system (i.e., that they are correct according to the rules of the system). If the communications lead to continuation of further communications, the process of proving that they are correct continues. If the system is able to continue to exist, i.e. to generate/recruit new communications according to the rules of the system, then this continuation implies that the proving process of the correctness of earlier communications continues.

In general it is not possible to prove the correctness of system communications; it is possible to prove only the incorrectness of them, when there is not further continuation of communications rooted from the original communication. We term this the 'Popper Principle', i.e., that only the falsity of system communication can be proven by stopping the generation of communications rooted from the communication in question [2].

1.4 Selection of systems

Systems must grow if they are to be sustained, since there is a tendency for systems to decline due to entropic loss of communications units. For example, the system of computer science would become extinct from loss of communication units as individual scientists aged and died unless new CUs were recruited (eg. more scientists, more publications, more professional journals etc.). Therefore all viable systems have the capacity of self-reproduction - the complexity of their communications will tend to grow. Specific memories tend to disappear, for example in the case of human memories this is due to random entropic damage to neurons [16], hence memory systems must grow to ensure their own survival.

But since there are many systems all with the tendency for growth, this expansion eventually will lead to competition between systems. Systems compete for finite communications, and this may be manifested as competition relating to communication units. Communication units tend to generate communications for several systems; but communications in one system may compete with those in other systems. For example human computer scientists never expend their whole time and energy purely on computer science communications - they will also participate in many other social systems such as politics, the legal system, the mass media and the family [23]. There will be competition between social systems for participation in the system communications. The 'work versus family' dilemma is just one aspect of this kind of system competition.

Competition between systems leads to selection. There are many types of selection - such as natural selection and market economics - but all share essential formal properties [15]. One important consideration is that only systems are selected - since only systems have the property of self reproduction and growth [6]. For example, if a mountain is eroded such that soluble limestone is dissolved but resistant granite is left standing then this is not an example of selection since the granite is not capable of growth. Likewise, selection does not act upon DNA since DNA is - of itself - not capable of self-reproduction. Rather, the relevant unit of biological selection is actually the genetic system which includes DNA and all the other communication elements necessary for its reproduction - the system consisting of interactions between DNA, RNA, protein and other molecular types [1].

Selection of memories occurs by interaction with other memories within the long term memory system, and also with other brain systems. Individual LTM neurons will typically participate in 'coding' more than one memory, and some LTM neurons will also participate in other neural systems. For example, a cortical neuron may participate in several memories (ie. networks of communication) relating to an individual person, and also in the awake processing relating to visual perception [16]. Some of the networks of communication will be compatible and may be combined and grow to generate more complex systems of communications by including more neurons into the network. Other memories will conflict such that they cannot be combined and cannot grow in complexity - these systems are more likely to become extinct.

It is plausible that memory networks will tend to combine and grow in complexity mostly during sleep, when internal processing of the LTM can proceed without interaction with perceptual information. During waking, sensory perceptual and motor communications exert a selection pressure on the long term memory system via competition for communications at the level of neurons. This is especially the case for human vision, which generates an extremely heavy computational load and involves a high proportion of cortical neurons including those used in long term memory systems [16]. The assumption is that memories which are incompatible with ongoing visual communications during waking hours will not be reinforced, and may be suppressed; for example, if visual memories conflict with current visual information then the memory will not be able to expand by recruitment of more communication units.

Memories are subject to continual selection and reshaping by the organism's ongoing waking experience, so that memories will tend to evolve over time. Most memories will become extinct, and those which are not contradicted by experience will continue to increase in complexity (mainly during sleep) until such a point that they do lead to contradiction after which the erroneous memories will be pruned-back. This process can be seen as one in which informational errors are generated, identified and eliminated.

1.5 Information errors in communication systems

Information errors are problems that are encountered by systems which are due to the limitations of the system, even when the system is working properly [2]. Since the environment is infinitely complex, any system's modelling of the environment will be highly simplified, and contingencies may arise in which the system behaves (relatively) maladaptively. All systems necessarily have highly simplified models of the environment and the environment is more complex than the system. Therefore 'incorrect' descriptions of the system's environment are inevitable and all systems are prone to information errors.

Information errors of communication systems are therefore cases of system maladaptiveness where communications happen according to the rules of the system, but they cannot lead to continuation because of environmental constraints. From the internal perspective of the system, communication units that are expected to produce continuations of communication do not in fact do this. For instance, a 'perfectly functioning' factory may be producing fully functional drinking glasses according to proper procedure is nonetheless running at a loss and is in danger of bankruptcy. The implication is that when a system is working according to its rules and is nonetheless contracting, then there is something wrong with the system's description of its environment such that relevant aspects are not being modelled. In this case perhaps the drinking glasses are not being delivered to shops (but deliveries are not being monitored by the system) or nobody is buying the drinking glasses (but this is not known because sales are not being monitored).

System information errors are therefore signs of a mismatch between the system's description of the environment, and the actual environment. Mismatch errors imply that some of the rules defining the system are damagingly wrong (i.e., they do not fit the environment well enough to permit the continuation of the system).

We suggest that memories are selected largely in terms of whether or not they generate information errors. By the Popper Principle, memories which are leading to continued expansion of the LTM continuations are regarded as provisionally 'true', 'correct' or 'accurate' - for as long as the system continues to expand. Memories that do not lead to continued communications are regarded as 'false', 'incorrect' or 'inaccurate', and are - in effect - purged from the system. This purging of memory may occur passively simply by failure to propagate. But in addition it is likely that in a complex system such as LTM there are mechanisms for 'checking' communications, and for tracing information errors back to their originating root 'false assumption' and eliminating the branching consequences of that assumption [2].

The primary mechanism for checking memories is internal checking for consistency within the LTM. Emerging memories will grow more rapidly if they are compatible with already existing memories, because such memories can join-up to form what are sometimes termed memory 'schemata'. Presumably, at the level of communication units, the neuron network constituting one memory can increase their communications with the neurons of another memory network to expand the number of communication units in the system hence the complexity of communications in the system. By contrast, memories that are incompatible cannot join-up with existing memories, presumably because they differ in their 'semantics', and so will constitute smaller and less complex systems which are more likely to become extinct as a natural consequence of entropic events.

By such mechanisms, memories in LTM tend over time to become combined and semantically harmonized in complex, expanding, non-contradictory networks.

1.6 Memory subsystems are based on communication units with longer-lasting communications

As described above, systems that reproduce and expand faster than other systems may drive to extinction the slower reproducing and expanding systems. The evolution of memory subsystems may play a significant role in this process - indeed some kind of memory function is probably necessary for systems to expand beyond a certain degree of complexity.

The limits of system expansion are determined by the probabilistic nature of referencing rules. A communication may reference several earlier communications indirectly through other referenced communications constituting referencing sequences of communications. The indeterminacies of referencing rules determine how long such referencing sequences of communications can be before the later communications become a random continuation.

Longer referencing sequences of communications (i.e., more detailed descriptions) allow better, more complex descriptions of the systems and its environment. In principle, the more complex the system the greater its adaptive potential. However, in practice the optimal size of the system (i.e., the number of simultaneous communications being part of the system) is also determined and constrained by the indeterminacies of referencing rules. Systems that overgrow their maximal sustainable size may split to form two or more similar but distinct systems (the maximal sustainable size depends on the system). When the system splits into two systems, each of the two systems will form part of the environment for the other, and the frequency of referencing communications from the other system will be reduced.

Communication systems may develop subsystems that are systems within the system, i.e., they constitute a denser inter-referencing cluster within the dense communication cluster of the system (the subsystem emerges if within the subsystem there are significantly more frequent references to communications of the subsystem than to communications within the system, but not within the subsystem). Communications that are part of subsystems follow system rules with additional constraints that are characteristic of the subsystem. For example there are overall rules of human brain information processing, but this is also sub-divided into specialized functional systems dealing with sensory perceptions, movement etc. and these systems have distinctive further constraints on their information 'inputs' and 'outputs' and processes. More constrained referencing rules decrease indeterminacies and allow the system to generate better complementary descriptions of the environment and expand itself faster than systems without subsystems.

Another way of extending reliable descriptions of the environment (i.e., non-random sequences of referencing communications) is by retaining records of earlier communications, i.e., by having memories of earlier communications that can be referenced by later communications. Memory systems are therefore subsystems with particular formal properties to do with their relationship with the primary system to which they are a subsystem.

Memory systems depend upon the existence of new communication units that can produce longer-lasting communications (or recruitment of existing communication units able to produce longer-lasting communications) that potentially produce for a certain period a certain communication (i.e. they produce the same communication repeatedly, with very small likelihood of errors in the reproduction of this communication) that can be referenced in place of some other communications (i.e., the ones which are represented by the memory). Having memory subsystems with CUs with longer-lasting communications reduce the indeterminacies in referencing by allowing direct referencing of earlier communications, instead of referencing early communications indirectly through a chain of references.

Traditional computer memory is based on CUs with longer-lasting communications (eg in magnetic changes to tapes or disks, or in binary codes etched onto CD or DVD). This is essentially a form of 'storage' rather than a true memory system, since the communication units in computer memory do not communicate significantly among themselves, so there is no 'system' of communications. The 'memory' communication units are inert except when the communication is being encoded or recalled by the primary system.

But in biological memory, the communication units with longer-lasting communications (neurons in the long term memory) communicate among themselves, and (presumably) do so to such an extent that there are more communications among and between the communication units than there are communications between the units and their environment. In other words, human LTM is a true system, defined as a dense inter-referencing cluster of communications. In evolutionary terms, our assumption is that memory systems began to evolve and differentiate from the primary system of the CNS when communication units with longer-lasting communications began to communicate among themselves with communications referenced-to (eg. caused-by) other internal communications. A memory system can be defined as forming at that point where these communications between such communication units quantitatively exceeded those between these CUs and their CNS environment.

1.7 The nature of long term memory in humans

The main requirement for LTM is among complex animals living in complex and changing environments - in which each day generates different challenges and in which animals benefit from memories of their previous experiences [16]. In such animals (including humans) LTM often has vast capacity, and therefore necessarily vast complexity. (See also the discussion in this book in the cahpter by Perlovsky [22]

Human LTM comprises a very large potential system of communications in which neurons are the main communication units. Individual memories are assumed to be communication subsystems comprising smaller numbers of neurons which are densely intercommunicating. These individual memories can be conceptualized as 'modelling' specific environmental aspects in order to enhance the adaptiveness of the LTM system in its context within the larger communication system of the brain.

Long term memory is the memory system that is used directly to 'refer to' previous states of the organism days, years or even decades ago (in systems theory, 'referring to' previous organism states carries the implication that previous states may affect present organism states by direct communication, rather than having been the remote and indirect cause of present states). LTM - like all memory systems - therefore requires communication units that are relatively more stable over these time periods than the CUs of a system which is using LTM for its memory function, retaining information relatively unchanged. Since neurons, and their synaptic connectivity, are dynamic structures over this timescale - this implies a need for mechanism for the maintenance of information [16]. A such mechanism may be represented by repetitive replay of interaction patterns between neurons participating int he LTM [17][27].

But complex memory requires not only more-stable CUs, but also dense communications between these more-stable CUs. This implies that internal processing within LTM is relatively more complex than the exchange of information between LTM and its environment (as measured by an external observer). This primacy of internal communications reverses the usual conceptualization of memory systems. Long term memory in humans is usually conceptualized as being formed while the organism is awake, and consolidated and edited during sleep. The adaptiveness of memories (ie their tendency to enhance reproductive success) is assumed to arise from their being a sufficiently-accurate representation of the environment - as if the environment 'imposed' the memories on the structure of the brain. In other words, the environment 'instructs' the brain, and memory is a 'representation' of the environment [11].

By contrast, we propose that complex memories are autonomously formed by the long term memory system mainly (although not entirely) during sleep and these memories are selected by interaction with the environment (mainly) while the organism is awake. In a nutshell, the LTM system generates a superfluity of 'conjectural' memory variants during sleep, and the interaction of the LTM system with the rest of the brain culls most of these memory variants, to leave those memories that are most adaptive in terms of enabling the LTM system to survive and thrive in the context of the brain system which is its environment. During sleep the LTM system provides multiple 'guesses' concerning the environment, and only those guesses will survive and grow which are compatible with perceptual data generated by behaviour when awake. (Note that what is 'most adaptive' is determined by the context in the sense of enabling the LTM to survive, and there is no particular inside observer component of the brain or specific context-independent criterion that is applied by the brain to decide which are the most adaptive memories.)

This selection process operates because some memories continue to lead to further communications so that these memories expand in complexity, while memories that do not lead to further communications do not expand, and will tend to be eliminated from the LTM system because they contain ’information errors’.

1.8 The importance of sleep to the LTM system

To recapitulate, since human LTM is a highly complex system it follows that there must be a differentially much larger amount of internal communication between the neuron CUs in the LTM system, than between neurons in the LTM system and the rest of the brain.

The requirement for LTM to engage in substantial internal communications would presumably manifest itself to an external observer as memory activity ’autonomous’ from the rest of the organism, and with little or no communication between the LTM and its environment. In other words, the memory system would need to be relatively ’cut-off’ from environmental stimulation (especially visual stimulation) and likewise disengaged from initiating ’action’ - not engaged in purposive movement, and most likely with the organism either temporarily inert or merely performing repetitive and stereotyped motor behaviour. This set of conditions is a closely approximated by the state of sleep [13].

Sleep may therefore be considered to be the time during which memory systems are most engaged in their primary activity of internal processing [26][5]. There is a great deal of evidence to suggest that sleep is important for memory functions [13] - but the perspective of abstract communication systems goes considerably further than this. From the perspective of the LTM system, sleep processing is its main activity, which allows its maintenance, self-reproduction and increase in complexity - and the ’memory function’ is ’merely’ a subordinate activity which has evolved to enable the LTM system to emerge, survive and thrive in the context of the rest of the brain. In a metaphorical sense, the memory function is the ’rent’ paid by the LTM system to the organism.

Understanding the ’function of sleep’ has proved elusive [25]. While sleep very probably has to do with the consolidation and maintenance of long term memory [16][26][5], the specifics of this have proved hard to pin-down. The reason is that sleep does not really have ’a function’ in terms of the organism as a whole. The function of sleep is specifically to do with the LTM system as a system, but only secondarily to do with the memory function that the LTM system performs for the rest of the brain. Rather, sleep is the behavioural state during which most of the internal processing of the system of LTM occurs; the primary function of sleep is therefore the maintenance and increase of complexity in the LTM.

Conversely, lack of sleep would presumably result in a reduction of complexity of communication in LTM. The consequences of this might include a reduction in potential memory capacity of LTM, less combination of individual memories to form scenarios, and a greater probability of extinction of memories - but the specific consequences of sleep deprivation may be hard to predict without knowledge of the principles (or contingencies) of internal organization of the LTM. These factors might explain the difficulties that sleep and memory researchers have experienced in precisely defining the function of sleep.

1.9 Interpretation of experimental observations

Research on memory shows that brain components (e.g. hippocampus) participating heavily in memory related activity are dominated by repetitive rhythmic activity supported by synchronous activation of large sets of neurons and expressed as theta oscillations at the macro-level (eg in EEG data) [4][12]. This is in good agreement with the prediction of our interpretation of LTM, which implies the repetitive production of communication patterns between neurons that represent memories of the organism through these neural communication patterns. Such repetitive activation patterns are predicted to be more frequent during sleep, which is again confirmed by experimental data [10]. Interestingly, our interpretation, may imply that the observed large scale synchronous activation is a by-product of energetically optimal synchronisation of many different repetitive activation patterns representing various memories.

Recent experimental evidence [8] shows that fruit flies with genetically impaired ability to sleep have significantly shorter lifespan than normal fruit flies. While a genetic defect may have multiple effects, our interpretation suggests that less ability to sleep implies less ability to adapt to the environment, including the internal environment of the organism. In other words, less sleep means less ability to maintain the internal workings of the organism in a sufficiently close to the optimal state. This means that individuals with less ability to sleep are more likely to accumulate organismal functional defects, which are likely to reduce their average lifespan.

A recent study have shown that humans receiving slow wave inducement support during their deep sleep improved significantly their memories [20]. In our interpretation the support of slow wave neural activity at the right frequency (ie the frequency of theta and delta oscillations) is likely to help the maintenance of repetitive production of memory representing neural communication patterns. In this way such support may enhance the memory performance of humans as shown by these experiments [20].

Another recent work on memory and synchronised oscillations shows that cannabis reduces the likelihood of synchronised oscillations in the hippocampus in rats [24]. The additional effect of cannabis on rats is a reduction in their memory abilities [24]. According to our interpretation if the repetitive reproduction of memories is impaired it is likely that the memory performance of the brain will reduce, which is in good agreement with the above described experimental finding. Furthermore, on the basis of our interpretation, it is a likely prediction that a memory system with impaired repetitive reproduction ability, will aim to extend its sleep state, in order to compensate for inconsistencies caused be potentially erroneous reproduction of memories. Consequently, our prediction is that rats under the influence of cannabis should be likely to sleep longer than rats that do not have cannabis treatment.

During sleep the LTM system provides multiple 'guesses' concerning the environment, and only those guesses will survive and grow which are compatible with perceptual data generated by behaviour when awake.

Taking another perspective, we expect that artificially prolonged sleep is likely to generate many wrong guesses about the real world, the elimination of which should take more time than int eh case of usual sleep. This implies that the error rate in the execution of non-rutine, sufficiently complex tasks shortly after awakening, should be higher in individuals who had excessive sleep compared to those who had normal sleep. This may also explain the need for re-learning of various skills in case of persons awaking from long duration coma. On another side, according to our view prolonged sleep should not reduce the memory ability of a person .

We also predict that if the barrier between lower level sensory and motor system components and the cortex is not maintained at a sufficient level during sleep, that should result in memory impairment and possibly in longer sleep periods. According to our interpretation if this barrier is not maintained than the separation of the memory from the sensory and motor systems is deficient, which implies that memory maintenance cannot proceed as normal. This should result in memory impairment, and also in a need for longer sleep periods to compensate for the insufficent functioning of the memory during sleep.

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