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Self-Organization in the Dreaming Brain

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This paper approaches dreaming consciousness through an examination of the self-organizing properties of the sleeping brain. This view offers a step toward reconciliation between brain-based and content-based attempts to understand the nature of dreaming. Here it is argued that the brain can be understood as a complex self-organizing system that in dreaming responds to subtle influences such as residual feelings and memories. The hyper-responsiveness of the brain during dreaming is viewed in terms of the tendency of complex chaotic-like systems to respond to small variations in initial conditions (the *butterfly effect*) and to the amplification of subtle emotional and cognitive signals through the mechanism of *stochastic resonance*, all in combination with psychophysiological changes in the brain during both slow wave sleep and REM sleep dreaming. Such changes include the active inhibition of exteroceptive stimulation and, especially in REM sleep, alterations in the brain's dominant neuromodulatory systems, bombardment of the visual cortex with bursts of PGO activity, increases in limbic system activity, and a reduction of activity in the prefrontal regions.

Sleep affords the opportunity, within certain limits, for the brain to act of itself, and dreams are the result.
— Edward Clarke, *A Study of False Sight*, 1878

There have been a variety of recent theoretical approaches to the process of dreaming. These have emphasized the cognitive aspects of dreaming (e.g., Bosinelli, 1995; Foulkes, 1985, 1999; Moffitt, 1995), the underlying psychophysiological processes (e.g., Hobson and McCarley, 1977; Hobson, Pace-Schott, and Stickgold, 2000), the neurological substrate (Jouvet, 1999) combined with psychoanalytical considerations (Solms, 1997, 1999; Ullman,

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1999), as well as connectionist (Globus, 1989; Hartmann, 1999) and neural network models (e.g., Antrobus, 1990, 1991; Crick and Mitchison, 1986; Fookson and Antrobus, 1992) for understanding the dreaming brain. The present paper combines the psychophysiological approach with the connectionist and neural network models, leading to considerations about the cognitive structure of dreams. It views the dreaming brain in terms of dynamical neurological processes that are most accurately described as chaotic (e.g., Arden, 1996; Screenivason, Pradhan, and Rapp, 1999).

Dreaming in REM Sleep

Much research on the dreaming brain pertains specifically to REM sleep. There are two reasons for this. The first is the misconception that dreams occur *only* in this state. The second is that since awakenings from REM sleep are more likely to be associated with dream recall — as much as ten times more likely according to Foulkes (1962) — REM itself has become a widely accepted signal that dreaming is taking place. Thus, in laboratory and clinical settings there is often an ipso facto association between REM sleep and dreaming.

The reason why dreams occur more frequently during REM sleep is not well understood, but it is evident that during the REM state the brain is especially disposed to dreaming. For one thing, however, the brain actively inhibits exteroceptive sensory input during REM sleep, and also blocks motor output from the higher centers of the brain (Mountcastle, 1974). Only those motor commands that are sent to the extremities, that is, to the fingers and toes, ordinarily get through, as do those sent to the eyes. The latter results in the *rapid eye movements* for which REM sleep was named. There is no question that REMs occasionally follow dream gazes (Herman, 1992), though it is doubtful that they usually do (but see Antrobus, 1990). In fact, their presence is highly correlated with bursts (or “waves”) of large and seemingly randomly timed “spikes” of neuronal activity which originate in the pons of the lower brainstem and travel upward to the lateral geniculate bodies, from where they proceed on to the primary visual cortex. These *pontine-geniculate-occipital* (PGO) waves play an important role in the widely respected *activation-synthesis hypothesis*, originally proposed by Allan Hobson and his research group in 1977 (e.g., Hobson and McCarley, 1977). It stated that the arrival of this irregular PGO activity at the occipital lobe serves as a powerful unstructured stimulus in which the sleeping brain seeks meaning, finding it in the creation of the images that we experience as dreams. Since its original publication Hobson's theory has undergone a series of revisions (Hobson, Pace-Schott, Stickgold, and Kahn, 1998; Kahn, Pace-Schott, and Hobson, 1997). The theory has retained its original form while honing its physiological accuracy

and expanding its reach toward a general theory of conscious states and the brain. The present form of the theory is abbreviated as AIM, referring to the *activation* level of the brain in wakefulness, REM and NREM sleep, the source of the *information* that the brain processes (external or internal), and the chemical *modulation* (aminergic or cholinergic) of the brain (Hobson, Pace-Schott, and Stickgold, 2000).

Hobson's theory has in its favor that the timing of PGO waves is irregular, and globally (though not precisely) correlated with REM activity. It also helps put into perspective the fact that animals compensate for lost PGO activity to a greater degree than they do for lost REM time (Dement, Ferguson, Cohn, and Barchas, 1969). And at least one "primitive" mammal, the *echidna* (spiny anteater), exhibits periods of PGO activity in the brainstem during sleep while showing no REM whatsoever (Finkbeiner, 1998).

The theory is not, however, without difficulties. From a physiological point of view, it elevates diffuse cortical stimulation from the brainstem to the status of optical sensory input (Vogel, 1978). This inconsistency is especially problematic if Foulkes' (1999) contention turns out to be true that infants — who exhibit a great deal of REM sleep, in fact hardly dream at all (but see Hobson, Pace-Schott, and Stickgold, 2000, for a considered counter-argument). From the psychological point of view Hobson's approach puts dream activity under the control of seemingly random PGO bombardment arising from the oldest and lowest levels of the brain.

Hobson, however, has not pursued a relentless reductionism. In 1993 he and his colleague David Kahn published an exploration of the idea that dream experiences are in part a product of self-organizing tendencies in the brain during REM sleep (Kahn and Hobson, 1993). This paper moved beyond the notion of dreams as random brain events, but did not yet articulate the actual formative processes that might underlie dreaming. Recently the present authors have worked with Kahn to develop a more detailed understanding of the brain's dream process, one that spans the traditional chasm between the neurobiology of dreaming and the study of the content of dreams (Kahn, Combs, and Krippner, 1998).

The Self-Organized Brain in REM Dreaming

The basic idea in Kahn, Combs, and Krippner's papers is that the dreaming brain "relaxes" into natural patterns of self-organized activity, which often reflect the residual moods, stresses, and concerns of waking life. To understand this, recall that during dreaming the brain is immersed in something like a sensory isolation tank and cut off from the influences of external sensory input. In this situation patterns of brain activity can relax into forms that are dependent primarily upon internal conditions (e.g., Antrobus,

1990). Consider, for instance, what happens when sand is dropped onto a vibrating surface like a drumhead or orchestral symbol. It dances about forming complex patterns characteristic of the physical dynamics of the vibrating surface beneath. Such patterns have been used to study the resonance properties of instruments such as violins. In chaos theory, the pattern created by the vibrating sand is termed an *attractor*, because it is the configuration toward which the system of the sand on the vibrating surface is naturally drawn. Attractors can also be seen in fluid systems, such as the complex patterns of ripples that appear in water flowing over and around stones in a stream. One can disrupt such a pattern by dipping a hand into the water and disrupting the current, but unless the rocks themselves are moved the pattern will quickly reestablish itself. The idea here is that the complex electrochemical activity of the brain during dream sleep likewise finds its own inherent configurations. This notion is similar to Globus' (1989) application to dreaming of the *harmony principle* exhibited by connectionist networks.

In our view, the patterns of activity that unfold over time in the dreaming brain are experienced as narratives, which play themselves out in dreams (Combs and Krippner, 1998). We suggest that while the conditions under which these patterns unfold are different than in the waking state, the fundamental principles that underlie their creation are the same. A beginning has been made in working these out for cognitive systems (Hardy, 1998; Kampis, 1991; Port and van Gelder, 1995; Tschacher and Dauwalder, 1999), for algorithmic systems (Goertzel, 1994, 2000), and in terms of the phenomenology of the mind (Combs, 1996; Combs and Krippner, 1998). The basic idea in each case concerns complex chaotic systems that contain multiple processes which interact with each other to create new processes. These in turn interact, and so on. Out of this complex soup of interactions emerge more or less stable configurations of processes that evolve in time. There is considerable evidence to suggest that many brain processes might be understood in terms of such dynamics (Basar, 1990; Freeman and Barrie, 1994; Halaz, 1995; Jeong, Joung, and Kim, 1988; Pribram, 1995; Robertson and Combs, 1995; Screenivason, Pradhan, and Rapp, 1999). Of course, the evolving patterns of neuronal activity in the brain and the emerging contents of the dream need only have a formal relationship with each other. To go beyond this would bring us face to face with Chalmer's (1995) "hard problem," the difficulty in explaining the neurochemical basis for the qualia of consciousness. More to the point, we note that Haskell (1986) has convincingly argued that the appearance of seemingly random activity in the brain, as exemplified by PGO waves, does not preclude the operation of a systematic and fully functioning cognitive system. In the present paper we propose that the experiential elements of dreams, such as thoughts, perceptions, emotions, and memories, ride on underlying brain processes, which interact to elicit new

experiential elements, and so on. During dreaming this process is both constrained and facilitated by the particular conditions of the dreaming brain.

Now, returning to the role played by PGO activity in the REM dreaming brain, we suggest that this activity sets the cortical system into motion and keeps it there. PGO discharges carry with them waves of powerful cholinergic stimulation to the cortex, keeping the brain on the move, and shaking it down again and again toward relaxed configurations. In line with this way of thinking, Mamelak and Hobson (1989) have suggested that PGO stimulation is tied to the high rate of narrative or plot shifts experienced during REM dreaming. Such shifts are significantly more frequent in REM dreaming than during dreaming reported from slow wave sleep (Cavallero, Cicogna, Natalie, Occhionero, and Zito, 1992; Foulkes, 1962), and may be essential to the "bizarreness" of REM dreams (Porte and Hobson, 1986).

One of the major contributions of Hobson and his group was the discovery that during REM sleep the brain shifts away from the widespread inhibition that characterizes waking activity because of the dominance of aminergic neurochemicals (serotonin and norepinephrine). With the onset of sleep the brain comes under the influence of the cholinergic neurochemical acetylcholine, which predisposes it to easy activation (Hobson, 1988, 1994). In other words, activity in the REM dreaming brain is less viscous and more mercurial than in the waking brain, allowing us to move easily into residual patterns left by moods and concerns of waking life. Such fluidity would also enlarge the attractors through which brain activity flows, effectively allowing easier connections to be made between feelings, memories, and the products of the imagination, all of which is to say that dream experience is open to greater novelty than is waking experience. An idea similar to this is suggested by Hartmann (1999), who notes that during dreaming the neural networks that comprise the working circuitry of the brain seem less constrained by daytime reality and more open to novel connections. The extent of agreement between Hartmann's approach and our own is witnessed by the fact that the formal analysis of activity patterns in complex neural networks such as those found in the brain are often carried out in terms of attractors.

Studies of Brain Activity During REM Sleep

Modern brain imaging studies are beginning to provide valuable insights into the nature of the REM sleeping brain. It turns out that one important aspect of REM sleep is a significant reduction in the activation of the prefrontal cortex (Braun, Balkin, Wesensten, Gwady, Carson, Varga, Baldwin, Belenky, and Herscovitch, 1998; Maquet, Peters, Aerts, Delfiore, Degueldre, Luxen, and Franck, 1996). This region of the brain is important for a number of higher mental abilities on which we rely during wakefulness. These

include working memory, which is the ability to keep important facts in mind while carrying out a task. With a reduced working memory during dreaming it is not surprising that we find the abrupt transitions in plot and location less surprising during dreaming than we would in waking life. The idea of a state-specific amnesia for working memory during REM sleep is further supported by Hobson and his colleagues, who note that such amnesia is facilitated by a reduction of aminergic modulation in the brain by 50% in NREM sleep and nearly 100% in REM sleep (Hobson, 1988; Hobson and Steriade, 1986).

The prefrontal cortex also plays an important role in making plans for the future. People with damage to this area often seem listless and without direction, in part because they do not think about what lies ahead. In dreaming we likewise think little about the future, simply going along with the dream narrative without question (Hall and Van de Castle, 1966; Tonay, 1991). In this vein, there seems a significant attenuation of attention during dreaming (Hartmann, 1966), as well as a loss of self-reflection (Blagrove, 1996). In waking life the prefrontal lobe may also play an important role in maintaining a sense of self-identity, and particularly an ability for self-reflection. With these abilities "off-line" during dreaming (Blagrove, 1996), the dreamer has little ability to reflect on the situation, or even notice the strangeness of events experienced.

Recently recorded images of the sleeping brain during REM show that in contrast to the prefrontal cortex, portions of the limbic system are highly active during REM sleep (Braun et al., 1998; Maquet et al., 1996). These structures are associated with emotion, which makes perfect sense given the fact that dreams are high in emotional content. The limbic system is far from well understood, however, and research continues to disclose new aspects of its operations. Carl Anderson (1998; Anderson and Mandell, 1996), for instance, is currently exploring the idea that the right and left amygdaloid complexes of the limbic system are key structures for cataloging emotional memories, and that PGO activity shared between them in REM sleep helps balance the activation of such memories to keep the brain from getting stuck in particular attractor patterns such as depression or anxiety.

For interest's sake we also mention that images of the sleeping brain during REM show increased activity in the anterior cingulate cortex and the right parietal lobe, both associated with the regulation of attention (Braun et al., 1998). Contrary to what would be expected from the original activation-synthesis hypothesis, there actually seems to be a lowered level of activity in the primary visual cortex of the occipital lobe compared to that seen during waking visual activity, but relatively robust activation of the adjacent (parastriate) regions. According to some researchers (Crick and Koch, 1995; Koch, 1998; Revonsuo, 1998) the latter are involved in the processing of

visual images and are essential to the conscious experience of vision. Recently, Hobson has expanded his theory to include the importance of activity in the parastriate area in dream imagery (Hobson, Pace-Schott, and Stickgold, 2000).

REM and SWS Dreaming

At this point some accounting must be made of the fact that dream reports are often obtained following awakenings from NREM, or slow wave sleep (SWS). Though the likelihood of obtaining dream reports is lower for SWS than for REM sleep, in fact such reports are associated with all stages of SWS (Foulkes, 1962). On the average they indicate less vividness and clarity of imagery (Antrobus, Hartwig, Rosa, Reisel, and Fein, 1987; Arkin, Antrobus, and Ellman, 1978) and fewer plot shifts (Cavallero et al., 1992; Foulkes, 1962) than REM associated reports, but the differences are usually small and not always reliable. Tracy and Tracy (1974), for example, reported dreams of high vividness from both light (stage 2) and deep (stage 4) SWS, casting doubt on the commonly held assumption that REM dreams are vivid because cortical activation is high during REM sleep. Interestingly, however, Hobson and his colleagues (Hobson, Pace-Schott, and Stickgold, 2000) as well as Nielsen (1999) have recently undertaken extensive re-analyses of REM and NREM dream studies reported throughout the literature, leading them to reaffirm the importance of differences in dream content between these two types of sleep. A thorough review of Hobson et al.'s analyses is beyond the scope of this article, but paramount among their considerations are concerns regarding memory deficiencies associated especially with REM sleep, and the statistical methods typically used to analyze dream reports. The authors, for example, note that longer reports, with more words, often indicate greater bizarreness, though this fact is often obscured in their statistical treatment.

At the time of this writing, the issue of differences between REM and NREM dreaming is not settled. It would appear to the present writers, however, that differences do exist and that they are important. This means that, on average, the characteristics of NREM dreams are somewhere between those of REM dreams and ordinary waking consciousness. Such a view still leaves unanswered the question why NREM dreams occur in the first place. The simplest answer would seem to be that NREM sleep is sufficiently similar to REM sleep to support dreaming, albeit dreaming that is more like waking mentation than is REM dreaming. This idea is consistent with the observation that a significant predictor of vividness is simply the level of energy metabolism in the cortex (Antrobus, 1991; Pivik, 1991). Beyond this, it seems likely that the process of dream production is not centered in the brainstem, but in the forebrain. Solms (1999) has recently made such a sug-

gestion, arguing that dreaming and REM sleep are distinct in terms of the brain processes that underlie them. He supports this contention with clinical studies that show no loss of dreaming following deep brainstem lesions (but see Hobson, Pace-Schott, and Stickgold, 2000), while dreaming is lost after certain cortical lesions even when brainstem initiated REM sleep is not disturbed (Solms, 1997). In a similar vein, Foulkes (1999) argues that dreaming is characterized by high level cognitive processes and self-awareness. He maintains that this explains why dreams are rarely reported by infants or young children, though Hobson believes this to be an artifact of REM state amnesia (Hobson, Pace-Schott, and Stickgold, 2000).

The factors that could facilitate dreaming during SWS include a relaxation of waking constraints on cortical activity brought about during sleep by isolation from outside stimulation, the cessation of ordinary rational thought, and the sleep-associated neurochemical changes mentioned above. Such factors also include the presence of residual feelings and concerns from waking life. All this must be animated by chaotic-like perturbation (see below) that allows cortical circuits to "relax" into the inherently comfortable but ever-changing attractor patterns that underlie the dream experience. Finally, some minimum level of arousal is necessary to sustain consciousness. It would seem from Tracy and Tracy's (1974) findings, above, that this minimum level is lower than commonly thought.

We further note that during SWS higher brain functions are evidently isolated from external sensory input to a greater degree than is usually appreciated. This is evidenced, for example, by the general failure of sleep-learning studies to obtain positive results, even when using highly sensitive verbal priming techniques during light SWS (Wood, Bootzin, Kihlstrom, and Schacter, 1992). From this it would seem that the brain in SWS is sufficiently isolated from environmental stimulation to allow independent internal activities (also see Antrobus, 1990). In this connection, let us also bear in mind that chaotic-like activity is inherent in cortical processes in general, even during deep SWS (Roschke and Aldenhoff, 1991, 1992). This being the case, it would seem that the cortex is primed to flow from attractor to attractor even when not in REM sleep, though not as vigorously as when stimulated by PGO bombardment. Brain imaging studies need to be done that recognize the importance of SWS in dreaming. Preliminary data, for instance, seem to indicate a complex relationship between REM and SWS in terms of frontal lobe activation (Braun et al., 1998).

Hobson's (1988, 1994) finding of neurochemical differences in the brain between REM, SWS, and wakefulness, suggests a greater elasticity in the REM dreaming than the waking brain, with SWS falling in between, as is consistent with dream content reports. It is not surprising, however, that REM dreams evidence greater emotional intensity than do those associated

with SWS (Cavallero et al., 1992; Foulkes, 1962). As indicated above, brain imaging studies point to greater limbic system involvement in REM than in SWS sleep (Braun et al., 1998; Maquet et al., 1996), though specific comparisons of SWS *dreaming* and non-dream SWS are not available.

All and all, it would seem that essentially the same dream-facilitating factors are at play in SWS as in REM sleep. Nevertheless, the presence of PGO stimulation in the latter, along with greater limbic system involvement, as well as differences in neurochemical modulation and decreased frontal lobe activity, render the REM sleeping brain more favorable for dreaming. As suggested by Solms (1999), however, the best guess at this point is that dreaming and REM sleep are fundamentally coincidental.

Dream Content and Sensitivity to Subtle Influences

There are two important aspects of the behavior of complex systems such as the human brain during sleep that can make such systems sensitive to subtle influences. First, systems that reside in chaotic or near-chaotic states are subject to the *butterfly effect* (Kellert, 1993; Peak, 1994): very small alterations in the present state of a system can lead to surprisingly large variations in the system's future states. There seems little doubt that the human brain with its many chaotic and chaotic-like patterns of activity is subject to the butterfly effect. Second, and more importantly, under certain circumstances the introduction of noise into such a system (chaotic or not) can cause the system to respond to signals too small to ordinarily be effected by them. Termed *stochastic resonance*, this seemingly paradoxical effect has been demonstrated in electronic circuits as well as in nerve cells (Moss and Wiesenfeld, 1995). It results from the fact that the presence of noise, or vibration, keeps the system in motion and following the signal, rather than allowing it to become stuck. This is an active instance of the relaxing of a system that is exposed to vibration, as described above. For instance, objects on a vibrating tabletop are sometimes seen to "walk" about, especially if the table is not level. In fact, they are following the line of least resistance down the slope of the surface, ordinarily not available to them because of friction with the top of the table. Here, we might imagine that the arrival of PGO waves has a similar effect on the higher cortical regions of the brain during REM sleep, causing activity there to "slide" in the direction of least resistance.

In the dreaming brain, isolated from daytime sensory bombardment and detached by neuromodulatory amnesia from those experiences that immediately precede sleep, chaotic dynamics like the butterfly effect and stochastic resonance cause the brain to become especially responsive to subtle influences such as faint residual memories or emotional residues. Writing of similar effects in connection networks — which indeed is a similar way to

characterize dynamical systems such as the brain — Globus (1989) describes the following example, taken from Freud (1900/1953, p.169):

Freud happens during the day to glance at a monograph on the plant Cyclamen in a bookstore window, a seeming indifferent impression . . . that so commonly gets caught up in a dream That night he dreams that he has written a monograph on a certain plant; the book lays open before him and at the moment he is turning over a folded cover plate. (p. 189)

Globus continues with this example, explaining that Cyclamen are Freud's wife's favorite flower (Freud reproaches himself for forgetting to buy her flowers), and beyond this, that he has himself once written a monograph on the coca plant, all of which places the momentary perception of the monograph on Cyclamen in a context of existing memories and feelings. The point, however, is that a fleeting perception, which leaves no deep impression, can later set off a chain of events in the dreaming brain — though evidently to do so the perception must not occur immediately prior to sleep. This example also points to the importance of feelings, even subtle feelings such as those elicited by Freud's association of the monograph with his wife's favorite flower, and his wish to bring her flowers. As noted above, the importance of emotions in dreaming, especially REM sleep dreaming, is confirmed in the observations of heightened limbic system activity.

Given a dreaming brain that is amnesiac for short-term pre-sleep events, and at the same time responsive to subtle influences such as emotions and memories, it is not surprising that dream content frequently includes fragments of old memories and once-familiar feelings from the past (e.g., Hall and Van de Castle, 1966). In such a hypersensitive system other influences might occasionally be felt as well. For example, Smith (1986) found among cardiac patients that the number of death references in men's dreams, and separation references in women's dreams, correlate with poor clinical outcomes, an effect which seemed independent of patients' attitudes about the severity of their condition. These findings suggest the presence of a subtle biological influence on dreaming. Others have reported anomalous influences on dreams (Krippner, 1991). It is not our intention to evaluate these or other claims of seemingly unusual influences in dreams. Rather, we offer the thesis that the dreaming brain is a delicately poised system, responsive to the slightest perturbation, and thus reflective of even the subtlest aspects of human experience.

Conclusion

Bringing the above ideas together, the intent of this paper is to take a credible first step toward a reconciliation of brain-based ("process") and content-

based ("interpretative" or *meaning* oriented) approaches to understanding dreaming. Our discussion is based on the premise that the dreaming brain is a complex self-organizing system. Such systems can exhibit multifaceted adaptive properties that are, broadly speaking, "cognitive" in nature (e.g., Varela, Thompson, and Rosch, 1991). These arise through the interactions of their constitutive processes (Combs, 1996; Combs and Krippner, 1998; Goertzel, 1994, 2000; Kampis, 1991; Kauffman, 1993). In the case of the dreaming brain, these processes represent emotional, sensory, mnemonic, and other aspects of brain activity. Their ongoing readout into consciousness is the narrative experience of the dream. Note, however, that we are not suggesting that a sufficient knowledge of such processes and their interactions would yield an explanation of the meaning of a particular dream in an individual's conscious experience, or in the context of his or her life — at least not in the foreseeable future. Even if the regularities that underlie the neurological events of dreaming become well understood, they may still look quite different than those that best characterize the *experiential* aspects of dreaming (e.g., Haskell, 1986), which in turn set the stage for a dream's *meaning* in the context of an individual's life. Finding the precise relationships that connect the neurological to the experiential levels of dreaming is future work for cognitive neuropsychology. Our aim here is to lay a foundation for this work by making explicit some of the important ways in which the dreaming brain engages in complex self-organizing processes which, far from random, are more than adequate in their regularity and complexity to support, at the level of consciousness, the experiential dream narratives that are the basis of interpretative approaches to dreaming.

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