A computational account of dreaming: Learning and memory consolidation

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Abstract

A number of studies have concluded that dreaming is mostly caused by random signals because "dream contents are random impulses", and argued that dream sleep is unlikely to play an important part in our intellectual capacity. On the other hand, numerous functional studies have suggested that dream sleep does play an important role in our learning and other intellectual functions. Specifically, recent studies have suggested the importance of dream sleep in memory consolidation, following the findings of neural replaying of recent waking patterns in the hippocampus. This study presents a cognitive and computational model of dream process that involves episodic learning and random activation of stored experiences. This model is simulated to perform the functions of learning and memory consolidation, which are two most popular dream functions that have been proposed. The simulations demonstrate that random signals may result in learning and memory consolidation. The characteristics of the model are discussed and found in agreement with many characteristics concluded from various empirical studies.
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1. Introduction

Dreaming refers to the subjective conscious experiences we have during sleep. The experience is vivid, intense, bizarre, and is hard to recall. Various studies have concluded that dream sleep may help us in learning (e.g., Greenberg & Pearlman, 1974; Hennevin, Hars, Maho, & Bloch, 1995; LaBerge, 1985; Smith, 1995), and may be a perceptible embodiment of a dreamer's conceptions (Hall, 1953). Findings of the correlation between REM (rapid eye movement) sleep and waking learning have suggested that dream sleep may play an important role in learning and memory consolidation (e.g., Bloch, Hennevinm, & Leconte, 1979; Fishbein, 1970; Pearlman, 1971; Winson, 1985). Similar findings have been also concluded in more

recent psychophysiological studies, although only these initiating studies are cited.

Long-term memory can be fractionated into declarative (explicit) memory and nondeclarative (implicit) memory, and declarative memory can be further divided into episodic memory and semantic memory. Episodic memory is the memory of past experiences, while semantic memory is about factual and generic knowledge (Tulving, 1972). The hippocampal complex, including the hippocampus and its surrounding areas, is considered a critical region in retaining recent episodic memory or its traces. On the other hand, the general neocortex is considered the place where semantic memory is stored. Memory consolidation is considered a neural process by which episodic memory becomes independent of the hippocampal complex and is consolidated into the neocortex (Squire & Alvarez, 1995). Findings from neural recording, which reveal the replaying of recent waking patterns of neuronal activity within the

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hippocampus during sleep, have further reinforced the view that dreaming may play an important part in memory consolidation. This reactivation of hippocampal cells has been recorded in rats (e.g., Pavlides & Winson, 1989; Wilson & McNaughton, 1994) and in humans (Staba, Wilson, Fried, & Engel, 2002); in SWS (slow wave sleep) that dominates Non-REM sleep (Pavlides & Winson, 1989; Wilson & McNaughton, 1994) and in REM sleep (Louie & Wilson, 2001; Poe, Nitz, McNaughton, & Barnes, 2000). Furthermore, synchronized activity in the hippocampus and neocortex in sleep is also reported and attributed to memory consolidation (Battaglia1, Sutherland, & McNaughton, 2004).

The significance of dreaming on learning and memory consolidation, suggested by psychophysiological studies, is also supported by the findings of hippocampal firing in sleep. In some studies (e.g., Fosse, Fosse, Hobson, & Stickgold, 2003; Pavlides & Winson, 1989; Schwartz, 2003), dream sleep has been directly associated with the hippocampal firings for the possible link between the cognitive activity of brain and the activation of stored episodic memory. This association is reasonable when we consider the fact that both vivid dreams and thought-like experiences can be recalled in >70% of REM awakenings (Hobson, 1988), and >48% of Non-REM awakenings (Nielsen, 2000), respectively.

However, studies in dream reports may lead to a different conclusion. Carefully looking into dream contents, it is often concluded that dreams are more or less random thoughts (Foulkes, 1985; Hobson & McCarley, 1977; Wolf, 1994). A recent study by Fosse et al. (2003), which is focused on the correlation between daily experiences and dream contents, again confirms the randomness nature of dreams. This study found that daily experiences are replayed in the form of segments, rather than entire episodes, during REM sleep. In other words, daily experience is replayed more in random fashion and less in sequential fashion in dreams. The randomness has led to the proposal of the activation-synthesis model (Hobson, 1988; Hobson & McCarley, 1977; Hobson, Pace-Schott, & Stickgold, 2000). The model states: dreams are caused by random signals arising from the pontine brainstem during REM sleep; the forebrain then synthesizes the dream and tries its best to make sense (i.e., dream images) out of the nonsense (i.e., random impulses) it is presented with. In short, the dream randomness has been used against some proposed intellectual functions of dreaming, and has divided dream theories into functional and functionless. Therefore, whether or not dreaming has intellectual functions depends on whether "random impulses" can lead to intellectual consequences, e.g., learning and memory consolidation.

Compared to numerous psychophysiological and neurobiological studies that are associated with dream mechanisms and functions, few computational studies have been reported on the same aspects. These reported studies are based on connectionist modelings. In the most cited study by Crick and Mitchison (1983), it is concluded that

dreaming is the "reverse-learning" process to remove so-called spurious memories (i.e., useless and old memories) in order to avoid overload of the brain. A similar simulation, however, indicates that the useless and old memory is actually increased after the "reverse-learning" of the simulated dreaming process, and suggests that we dream to roughen up our "memory space" (Christos, 2003). In either case, it is said (Botman & Crovitz, 1989; Domhoff, 1996) that the conclusions are generally disassociated with what has been found about dreaming, and are typically interpreted to contradict the psychoanalytic account of dreams.

In this study, a cognitive and computational model of dreaming is presented. This model is developed from a previous construct (Zhang, 2005) of a learning system. In this present study, dreams of the computational system are performed. The outcomes of dreaming are examined in terms of "naming" and "picture drawing," which are typical tasks in the tests for semantic memory. The characteristics of the model are discussed and found in agreement with many empirical findings from dream studies.

2. The construct of an artificial intelligence dreamer

2.1. A brief revisit of the learning system

Knowledge can be learned from experience. How learning occurs and how new knowledge is associated with prior knowledge, are questions yet to be answered. A previous study (Zhang, 2005) presents a cognitive learning system, namely AI counter, which can learn to count. That system is constructed based on two rules: (1) a concept (represented by a common feature) is learned when the common feature is abstracted and generalized; and (2) new learning has to rely on prior learning if the newer knowledge is an extension of the prior knowledge. The learning system was built with a multi-level structure of information processing, which is in fact the system shown in Fig. 1, except for the "hippocampal memory".

In the system, the base level of cognition is called "single memory" that stores and reacts to one piece of an entire external input. A single memory has three inputs (excitation input $Iexc$, signal input $Isig$, and interlock input $Iint$) and four outputs (excitation output $Oexc$, signal output $Osig$, coordination output $Ocor$, and interlock output $Oint$). The function states of a single memory on how these signals interact are summarized in Table 1. These states reflect two functions of a single memory. One function is to store an $Io/Iexco$ pair in two steps. In step 1, when $Isig$ = "Io" and $Iint$ = "yes", a single memory fires an $Ocor$ (="yes"), which is then transported to the "bundle of inter-subsystem signals" (see Fig. 1). Only when the "bundle" receives a coordination signal from both the symbol and representation subsystems, it generates a unique excitation signal ($Iexco$) and sends it back to all single memories in both subsystems. In step 2, the single memory that fired $Ocor$ stores both "Io" and "$Iexco$" together after receiving the unique "$Iexco$". The other function is to fire the stored