

A “SMALL-WORLD” NETWORK HYPOTHESIS FOR MEMORY AND DREAMS

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ABSTRACT Memories are associated to one another and to the environmental cues that accompanied the events that gave rise to them. Thus, a memory is more likely to be recalled (reconstructed) if it is strongly connected to a particular environment. We propose that memory associations form a “small-world” network. According to this hypothesis, one memory might lead to the recall of an apparently unrelated memory because they are actually connected by only a few steps. This small-world hypothesis might also be relevant to the peculiar features of dreaming.

When he came to Fifth Avenue, he kept his eyes on the windows of the stores he passed. . . . He enjoyed the sight of a prosperous street; not more than every fourth one of the stores was out of business, its windows dark and empty. He did not know why he suddenly thought of the oak tree. Nothing had recalled it. . . .

—Ayn Rand (1957, 12)

THIS PASSAGE, from Ayn Rand’s *Atlas Shrugged* (1957), signifies an important aspect of memory that we all have experienced at one time or another: recalling (or reconstructing) memories that seem to have come out of nothing,

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Perspectives in Biology and Medicine, volume 47, number 42 (spring 2004):176–80

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without any attempt to force or retrieve them. For example, one day one of us (PAT) was eating watermelon in his house in Dayton, OH, when suddenly a scene from his childhood came to his mind. It was himself inside a little store in Eleusis, Greece, where he had spent most of his childhood summers. This particular store did not sell fruits, and he had only visited it briefly one or two times in his life. This memory is of course personal and helped us to formulate our hypothesis, but is something common in everyone's experiences and is reflected well in the literature. To quote Marcel Proust (1922): "Then the memory of a new position would spring up, and the wall would slide away in another direction; I was in my room in Mme de Saint-Loup's house in the country" (7). Proust's narrator describes how different positions while sleeping evoked different and seemingly unrelated memories. Obviously, unrelated memories can be brought back at any time and without any apparent association to present conditions.

Memories (specifically, long-term memories) are associated to one another and to the environmental cues that accompanied the events that gave rise to them. This association consolidates memories. We are more likely to remember something that is associated with a particular condition. For example, walking a street full of shops during Christmas is more likely to evoke memories of family gatherings during that period or an event that happened during Christmas. The more a particular memory is associated with an event, the more likely it is to bring back another memory related to that event. We can assume, therefore, that there is a probability that dictates the likelihood for a memory to be recalled. This probability must depend on how closely the two memories are related (topic, place, event) or how strongly (impression, emotion) they are represented in the repertoire of the brain.

In recent years the "small-world" theory has made spectacular contributions to the understanding of how networks interact and exchange information. The roots of small-world networks go back to the American psychologist Stanley Milgram (1967). Milgram was interested in the web of human connections, and in the 1960s he designed the following experiment. He sent letters to a random sample of people in Nebraska and Kansas, asking the recipients to forward their letters to his friend, a stockbroker who lived in Boston, but he did not provide the address of his friend. Milgram hoped that the recipients would not toss the letters into the wastebasket, but would give them to friends whom they thought were socially "closer" to the stockbroker. One might think that it would take many such steps before—if ever—any of the letters found their way back to Milgram's stockbroker friend. Surprisingly, though, not only did most of the letters reach the stockbroker, but it took only about six steps for each letter to arrive. This incredible result came to be known as "the six degrees of separation" and vindicated the expression "It's a small world."

A network is a set of interconnected and interacting points. Until recently, the study of networks was restricted either to regular (ordered) networks, where each point has the same number of links connecting it in a specific way to a small

**FIGURE 1**

An ordered (left panel), random (middle) and small-world (right) network.

SOURCE: COURTESY DR. S. H. STROGATZ.

number of neighboring points (Figure 1, left panel), or to random networks, where each point is haphazardly connected to a few points that can be anywhere in the network (Figure 1, middle panel). Regular networks are highly clustered, which means that it takes many steps to go from a point to another point away from its immediate neighborhood. Such networks show a high number of degrees of separation between any two distant points. As a result, regular networks do not transfer or process information efficiently. In addition, because of the high degree of local clustering, each step is between highly correlated points. In contrast, random networks do not exhibit local clustering. Far away points can be connected as easily as nearby points. Thus the number of degrees of separation between any two faraway points is very small. Random networks are efficient in transferring and processing information, but because of their architecture, a step usually involves highly uncorrelated points. A new class of networks, called small-world networks, were discovered a few years ago (Barabasi 2002; Strogatz 2003; Watts 2003; Watts and Strogatz 1999). Small-world networks exhibit a high degree of local clustering, but they contain a small number of long-range connections, which makes the number of degrees of separation between faraway points as small as if the network were random (Figure 1, right panel). Thus, small-world networks are as efficient in transferring information as random networks, but they maintain a large degree of “order” and local correlations. Since their original discovery, such networks have been found to pervade biological, social, ecological, and economic systems, the Internet, and other systems (Albert, Jeong, and Barabasi 2001; Bouchaud and Mezard 2000; Jeong et al. 2000, 2001; Liljeros et al. 2001; Pastor-Satorras and Vespignani 2001; Watts and Strogatz 1999).

We suggest that memory associations form a small-world network. In such a network the points are the individual memories. In the example of the watermelon memory, we may speculate on six plausible steps that may have connected the initial action to the long-term memory: (1) eating watermelon in Dayton; (2) watermelon brings up memory of summer; (3) summer brings up memory of vacation; (4) vacation brings up memory of childhood vacation in Eleusis;

(5) Eleusis and vacation memories bring up familiar houses or relatives visited; (6) the memory of the store is recalled because it was close to a house of a relative. Even though this example does not mean that every memory recall can be traced to an origin in six steps, it is clear that the number of steps will not be large. On the average, strongly connected memories would more likely correspond to some local cluster and would be associated with fewer degrees of separation. For example, a hometown memory will be connected to another memory related to it, such as old friends or different locations, with fewer degrees of separation. These memories are strongly associated. By contrast, highly unrelated memories, which are far apart in the network, would need more steps to be connected. Due to the small-world property, however, the number of steps required still would not be very high.

The small-world hypothesis might also explain some of the peculiar features of dreaming. Dreaming has been linked to memory processing; specifically, it is believed that sleep participates in memory consolidation, during which memory traces are analyzed and incorporated into the long-term memory. The so-called hypnagogic dreams at the onset of non-rapid eye movement (non-REM) sleep show incorporation of daytime experiences; this kind of dreaming has been linked to learning and memory processing, and such processes have been experimentally controlled. However, REM sleep is associated with bizarre dreams and with increases in emotions and stress, and its use in memory consolidation is often disputed (Maquet 2001; Siegel 2001; Stickgold et al. 2001). Usually, these dreams are complex and incoherent, and their construction is difficult to ascertain. However, it seems plausible that there are two types of networks involved in dreaming: during conscious states and non-REM sleep, the network has a small-world architecture; during REM sleep, the parameters change and the network becomes a random one.

To our knowledge no such hypothesis for dreams and memories has previously been formulated. Studies of neural networks suggest that neurons are connected as small-world networks (Latora and Marchiori 2001; Watts and Strogatz 1999). Although the relationship between neural function and mental processes is not yet understood, a small-world neural network might underlie a small-world network of memory association. We hope that this hypothesis provides a fresh new look at memory reconstruction and might lead to further understanding of the basis of such an important problem in neurobiology.

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