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Neural dynamics of idea generation and the effects of priming

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ABSTRACT

Idea generation is a fundamental attribute of the human mind, but the cognitive and neural mechanisms underlying this process remain unclear. In this paper, we present a dynamic connectionist model for the generation of ideas within a brainstorming context. The key hypothesis underlying the model is that ideas emerge naturally from itinerant attractor dynamics in a multi-level, modular semantic space, and the potential surface underlying this dynamics is itself shaped dynamically by task context, ongoing evaluative feedback, inhibitory modulation, and short-term synaptic modification. While abstract, the model attempts to capture the interplay between semantic representations, working memory, attentional selection, reinforcement signals, and modulation. We show that, once trained on a set of contexts and ideas, the system can rapidly recall stored ideas in familiar contexts, and can generate novel ideas by efficient, multi-level dynamical search in both familiar and unfamiliar contexts.

We also use a simplified continuous-time instantiation of the model to explore the effect of priming on idea generation. In particular, we consider how priming low-accessible categories in a connectionist semantic network can lead to the generation of novel ideas. The mapping of the model onto various regions and modulatory processes in the brain is also discussed briefly.

1. Introduction

The ability to generate relevant ideas in familiar and novel contexts is a central characteristic of the human mind, and has been studied extensively through behavioral experiments in the context of brainstorming (Osborn, 1957). These experiments have uncovered various social and cognitive factors that influence idea generation (Coskun, Paulus, Brown, & Sherwood, 2000; Dugosh & Paulus, 2005; Nijstad & Stroebe, 2006; Paulus & Brown, 2003; Paulus & Dzindolet, 1993), and have shown that priming with hints during brainstorming can enhance both the number and the quality of the generated ideas (Coskun et al., 2000; Dugosh, Paulus, Roland, & Yang, 2000; Nijstad, Stroebe, & Lodewijkx, 2002). Understanding these factors is crucial to developing better brainstorming protocols, and for explaining the idea generation process in human cognition.

Several brainstorming models based on associative memory have been developed (Brown, Tumeo, Larey, & Paulus, 1998; Nijstad & Stroebe, 2006; Paulus & Brown, 2003), and while they account for results observed in behavioral experiments, they provide limited insight into the underlying neural processes. The SIAM model by Nijstad and Stroebe (2006) is a flow-chart diagram of the search process for ideas, and is based on the free-recall model (SAM) by Raaijmakers and Shiffrin (1981). While the model describes the logical interplay between search cues, associative semantic memory, learning of retrieved ideas and storage in working memory and episodic memory, it is a high-level model that does not explain the process of how new ideas are generated. The associative model by Brown et al. (1998) and Paulus and Brown (2003) represents semantic knowledge as a network of categories and the retrieval of ideas from it as a stochastic Markov-type process. This model has been very successful in explaining brainstorming experiments (Coskun et al., 2000; Dugosh & Paulus, 2005; Dugosh et al., 2000; Paulus, Nakui, Brown, & Putman, 2006) and in predicting factors that would enhance brainstorming productivity. The model is able to emulate short-term memory effects and attention to others' ideas, and can model different styles of ideation (e.g. divergent and convergent thinking). The main shortcoming of this model too is the abstract representation of individual ideas, precluding the explicit consideration of ideas,

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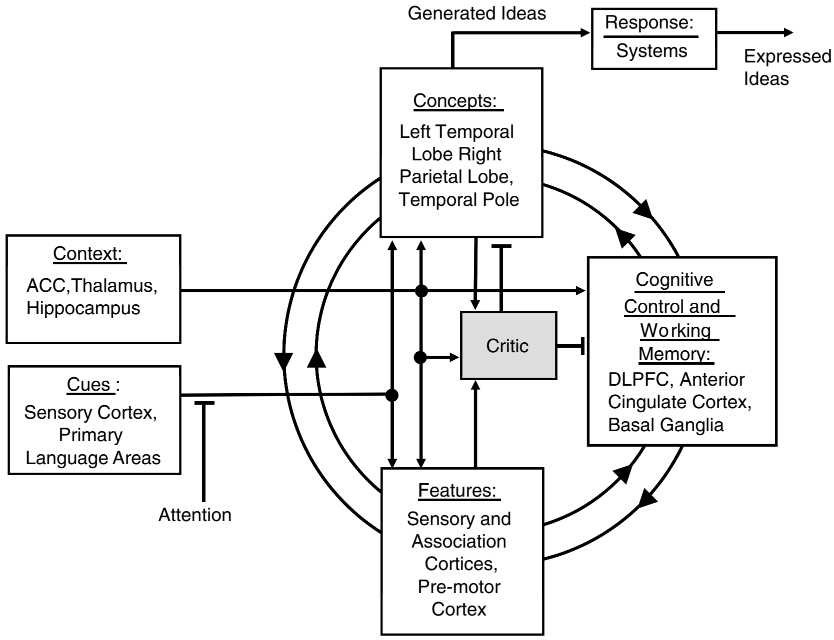

Fig. 1. Architecture of the hypothesized model for idea generation and its approximate mapping onto brain regions (Abbreviations: VLPFC — ventrolateral prefrontal cortex; DLPFC — dorsolateral prefrontal cortex; ACC — anterior cingulate cortex).

assessing their quality or novelty, and modeling the dynamics of the idea generation process.

Our group has recently proposed a connectionist model for the dynamics of idea generation (Brown & Doboli, 2006; Doboli & Minai, 2005; Doboli, Minai, & Brown, 2007; Iyer, Minai, Doboli, & Brown, 2007, 2008), motivated by experimental results on the neurobiology of semantic cognition (Caramazza & Mahon, 2003; Damasio, 1989; Damasio, Grabowski, Tranel, Hichwa, & Damasio, 1996; Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004; Kellenbach, Brett, & Patterson, 2001; Martin, 2007; Patterson, Nestor, & Rogers, 2007; Warrington & Shallice, 1984), and theories of semantic organization (Andrews, Vigliocco, & Vinson, in press; Blei, Ng, & Jordan, 2003; Burgess & Lund, 1997; Griffiths, Steyvers, & Tenenbaum, 2007; Landauer & Dumais, 1997; McRae, de Sa, & Seidenberg, 1997; Mueller & Shiffrin, 2006; Steyvers & Tenenbaum, 2005; Verguts, Ameel, & Storms, 2004; Vigliocco, Vinson, Lewis, & Garrett, 2004), as well as insights from other connectionist models of semantic information processing (Kruschke, 1992; McClelland & Rogers, 2003; Moss, Hare, Day, & Tyler, 1994). The model is now being extended to simulate and explain actual data from behavioral experiments. In this paper, we apply the model to explain experimental effects of priming during the ideation process (Coskun et al., 2000; Dugosh & Paulus, 2005; Dugosh et al., 2000; Nijstad et al., 2002).

2. The idea generation process

Semantic information in the brain is represented at several levels, ranging from combinations of sensorimotor features (Martin, 2007; Warrington & Shallice, 1984), through amodal concepts (Kellenbach et al., 2001; Patterson et al., 2007), to semantic categories (Caramazza & Mahon, 2003). Considerable evidence now supports the idea that semantic processing involves several cortical functional networks that process and integrate information at all these levels (Damasio, 1989; Damasio et al., 1996, 2004; Martin, 2007). The areas involved include the left temporal lobe, the prefrontal cortex, the anterior cingulate cortex, the orbitofrontal cortex and parts of the occipital cortex. Regions of the right hemisphere temporal and parietal cortices are also involved (Bowden, Jung-Beeman, Fleck, & Kounios, 2005), and may provide a crucial non-linguistic component needed for the intuitive generation of novel ideas (Bowden et al., 2005; Duch, 2007; Heilman, Nadeau, & Beversdorf, 2003; Schilling, 2005). The flow of information in these cortical networks is controlled by switching processes in the basal ganglia (Graybiel, 1995; Houk, 2005), and is modulated by dopaminergic (Apicella, 2007; Schultz, 2000) and noradrenergic (Aston-Jones & Cohen, 2005) signals reflecting judgments of value.

The organization and use of semantic knowledge has also been studied extensively by researchers in linguistic cognition and computational linguistics. Several models of meaning have been developed based either on sensorimotor experiential features (Andrews et al., in press; McRae et al., 1997; Verguts et al., 2004), or on more abstract features derived from the distribution of words in text corpora (Blei et al., 2003; Burgess & Lund, 1997; Griffiths et al., 2007; Landauer & Dumais, 1997). Both approaches typically use multi-level representations of semantic knowledge in terms of features, concepts, categories, topics, etc.

Following the semantic networks approach (Boden, 1995; Mednick, 1962), we postulate that concepts are the key elements of the semantic space, and that ideas are *combinations of concepts* that arise through the dynamics of networks linking them with each other based on previous learning. This dynamics is modeled as an itinerant flow (Tsuda, 2001) where groups of co-activated concepts arise as resonant metastable patterns of activity in concept space (Doboli, Brown, & Minai, 2009; Iyer, Minai, Doboli, Brown, & Paulus, 2009; Minai, Iyer, Padur, & Doboli, 2009), and the itinerant dynamics generating them can be seen as a self-organized search process. This dynamics is modulated over time by factors such as external context, recently generated ideas and evaluative feedback from a critic to make the search more efficient.

The broad architecture of our idea generation model is shown in Fig. 1. Motivated by results from neuroscience and theories of semantic cognition, the model represents semantic knowledge in terms of features, concepts and categories. It also incorporates ideas from reinforcement learning (Sutton & Barto, 1998) and selection-based control (Graybiel, 1995; Houk, 2005). The figure indicates how the system's components might map qualitatively to specific brain regions: The encoding of features