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An illustrated heuristic prototype facilitates scientific inventive problem solving: A functional magnetic resonance imaging study

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ABSTRACT

Many scientific inventions (SI) throughout history were inspired by heuristic prototypes (HPs). For instance, an event or piece of knowledge similar to displaced water from a tub inspired Archimedes' principle. However, the neural mechanisms underlying this insightful problem solving are not very clear. Thus, the present study explored the neural correlates used to solve SI problems facilitated by HPs. Each HP had two versions: a literal description with an illustration (LDI) and a literal description with no illustration (LDNI). Thirty-two participants were divided randomly into these two groups. Blood oxygenation level-dependent fMRI contrasts between LDI and LDNI groups were measured. Greater activity in the right middle occipital gyrus (RMOG, BA19), right precentral gyrus (RPCG, BA4), and left middle frontal gyrus (LMFG, BA46) were found within the LDI group as compared to the LDNI group. We discuss these results in terms cognitive functions within these regions related to problem solving and memory retrieval.

1. Introduction

Creativity is imperative for the progress of human civilization and is crucial throughout cultural life (Fink et al., 2010; Luo & Niki, 2003) and is characterized by the formation of something that is both novel and useful (Jung, Mead, Carrasco, & Flores, 2013; Runco & Jaeger, 2012; Stein, 1953). Throughout the history of insightful problem solving, creative behavior

Abbreviations: SI, scientific invention/innovation; HPs, heuristic prototypes; fMRI, functional magnetic resonance imaging; LDI, literal description with illustration; LDNI, literal description with no illustration; RMOG, right middle occipital gyrus; RPCG, right precentral gyrus; LMFG, left middle frontal gyrus; LPFC, left anterior prefrontal cortex; LIFG, left inferior frontal gyrus; LDLPFC, left dorsolateral prefrontal cortex; WCAT, Williams' creativity aptitude test; BOLD, blood oxygenation level-dependent.

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seems to appear when analogized from some heuristic knowledge when devising real-life, scientific innovations. One example was Rutherford's discovery of an atom's structure. In this case, Rutherford made a solar system analogy to devise an understanding of the atom. Other examples were Archimedes' discovery of the law of buoyancy and Kekule's discovery of benzene's molecular structure. Previous studies also have highlighted the important role of analogy during a scientist's insightful problem solving activities (Boden, 1993; Finke, 1990; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2010).

Recent investigations have utilized brain-imaging techniques, such as fMRI, to study the neural correlates associated with analogical problem solving. Luo and Niki (2003), using different types of analogical tasks, found that bilateral activation in prefrontal regions (right BA 11/BA 47 and left BA 45), the hippocampus, the left postero-superior temporal area, and the fusiform gyrus were involved during the integration of information. Krawczyk, McClelland, Donovan, Tillman, and Maguire (2010), using four-term analogical problems, found that the left inferior frontal gyrus (LIFG), left middle frontal gyrus (LMFG), and the left dorsolateral prefrontal cortex (LDLPFC) might be involved in this type of analogical reasoning. Green, Kraemer, Fugelsang, Gray, and Dunbar (2012), using analogical mapping with varied semantic distances, revealed frontopolar (BA9/10) activity during integration of semantically distant information in order to resolve analogical reasoning problems (similar findings can be found in Green et al. (2010).

Although these aforementioned findings aid an understanding of the analogical process, certain gaps remain. For instance, few studies have investigated insight problem solving during a scientist's insightful problem solving activities using real-life scientific innovations. Hence, we need to employ experimental methods to better assess this "knowledge-rich" field. In two recent studies, Luo, Li, et al. (2013) proposed heuristics were crucial to SI problem solving by way of bionic imitation. Using a brain imaging technique, (Luo, Li, et al., 2013) contrasted novel with older scientific innovations to explore the neural basis of SI induced by HPs. Hao et al. (2013) explored the neural basis of novel SI problem solving after learning the prototype. Although these studies dealt with actual innovations, until now, no study has examined the role of visual information processing during insightful problem solving, real-world SI problems. Sas, Luchian, and Ball (2010), using abstract and representational analogical cues, found representational cues were more beneficial when solving the "eight coin problem." This indicated that visual imagery facilitated problem solving during the scenario.

Dunbar (1997) noted that scientists frequently use biological analogies during innovative problem solving. This is an effective way to improve ecological validity among analogical research by combining abundant real-world SI examples and laboratory studies (Thomas, 2007). Real-life SIs (including technical problems and heuristic prototypes) in the present study included bionic cases in which insight is stimulated through activation of a related prototype. The term "prototype" here is distinct from its use in traditional cognitive psychology. We defined the term "heuristic prototype" as the object containing heuristic information to solve an insight problem but is superficially irrelevant to the insight problem (Ming, Tong, Yang, Qiu, & Zhang, 2014). Each scientific innovation consists of three parts: SI problem, HP, and the reference answer. Take the technical problem of how to design submarine as an example. The HP that the surface of the shark's skin has a unique

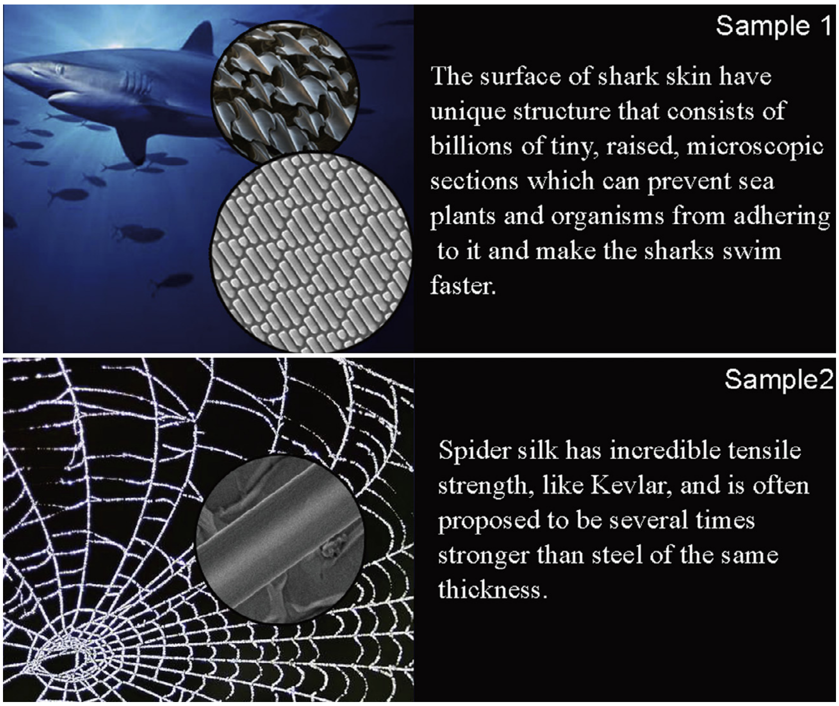

Fig. 1. Two examples of materials used for the LDI condition. Left, illustration of the heuristic prototype; right, corresponding literal description.