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Neural correlates of *Eureka* moment

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ABSTRACT

Insight processes that peak in "unpredictable moments of exceptional thinking" are often referred to as Aha! or Eureka moments. During insight, connections between previously unrelated concepts are made and new patterns arise at the perceptual level while new solutions to apparently insolvable problems suddenly emerge to consciousness. Given its unpredictable nature, the definition, and behavioral and neurophysiological measurement of insight problem solving represent a major challenge in contemporary cognitive neuroscience. Numerous attempts have been made, yet results show limited consistency across experimental approaches. Here we provide a comprehensive overview of available neuroscience of insight, including: i) a discussion about the theoretical definition of insight and an overview of the most widely accepted theoretical models, including those debating its relationship with creativity and intelligence; ii) an overview of available tasks used to investigate insight; iii) an ad-hoc quantitative meta-analysis of functional magnetic resonance imaging studies investigating the Eureka moment, using activation likelihood estimation maps; iv) a review of electroencephalographic evidence in the time and frequency domains, as well as v) an overview of the application of non-invasive brain stimulation techniques to causally assess the neurobiological basis of insight as well as enhance insight-related cognition.

Contents

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1. Introduction

Although research on insight processes began over a century ago with Köhler's observations on the problem-solving abilities of chimpanzees (Kohler, 1925), a comprehensive definition of "insight processes" remains elusive. During the last twenty years, several theories have been proposed to explain the insight phenomenon. Over the past decade, experimental support for some of these theories has been gathered thanks to recent advances in neuroimaging and neurophysiological techniques. In the present review, we provide a comprehensive summary of the neuroscience of insight. We first provide an overview of the most relevant theoretical definitions and the most commonly used tools for the investigation of insight moments. Second, we present original results from a quantitative meta-analysis of available functional magnetic resonance imaging (fMRI) data, as well as a summary of the evidence collected with electroencephalography (EEG), focusing on brain oscillations and event-related analysis. Third, we critically discuss emerging evidence from perturbation-based and neuromodulatory approaches, such as repetitive transcranial magnetic stimulation (rTMS) and transcranial electrical stimulation (tES), which add a causal dimension to traditional neuroimaging mapping data, allowing for the transient modification of regional brain dynamics underlying insight processes. Finally, we address the possibility of using non-invasive neuromodulation as a tool to enhance insight problem-solving abilities.

2. Defining the topic: definitions, theories, and tasks

2.1. An insight into insight

Many great scientific discoveries have relied on insight moments (e.g., Newton's finding of the law of gravitation, Kekulé's discovery of the structure of benzene, Poincaré's discoveries in mathematics, Einstein's first theorization of the General Relativity theory; Sandkühler & Bhattacharya, 2008). The first known *Aha!* moment typically refers to Archimedes of Syracuse, who, after discovering the principle of displacement while taking a bath, reportedly ran naked down the street shouting "*Eureka*!". This funny anecdote highlights the unpredicted, unfettered nature of *Aha!* moments, thought of as "a special gift of Muses" by the Greek. While solid theory has been proposed for the biological network of intelligence (Jung & Haier, 2007), valid scientific explanations are largely lacking for insight. This leaves the *Eureka* moment as one of the most intriguing and unexplained processes of the human mind (Sternberg & Davidson, 1995), despite many relevant correlations with fluid intelligence (Paulewicz, Chudersky, & Necka, 2007; Sternberg & Davidson, 1995), switching ability and working memory (WM) capacity (Murray & Byrne, 2005). It was not until the beginning of the 20th century that Gestalt psychologists attempted to create a proper definition of insight (Dietrich & Kanso, 2010), describing it as "a process based on reconstructing the core of a problem, rethinking its basic assumptions and originating a new and creative solution, a process usually occurring in an unexpected and unpredictable manner" (Kohler, 1925).

To better characterize the *Aha!* moment, a valid heuristic approach might be to discard what is *not* considered insight problem-solving. In general, problem-solving strategies can be divided into three types: analytical problem-solving, memory retrieval, and insight (Novick & Sherman, 2003). Analytical problem-solving is characterized by three main features: (i) it is deliberate and predominantly conscious, (ii) it advances step by step from the initial processing of information to the resolution and (iii) its steps are available to WM, so that subjects are able to explain in details how they were able to approach the solution. In contrast to analytical problem-solving, which is marked by a deep understanding of the problem, memory retrieval processes can be described as a simple mental retrieval of previously acquired knowledge, which fits to the problem at hand (Aziz-Zadeh, Kaplan, & Iacoboni, 2009).

Insight problem-solving is thought to be very different from these other two strategies. The *Aha!* moment consists of a sudden, unexpected, and somehow "obvious" solution that cannot be explained by a sequential solution process. Unlike analytic problem-solving, the subjects cannot readily explain the exact path they followed to reach