

Aha! in the Brain

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The *Aha!* Moment

The Cognitive Neuroscience of Insight

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ABSTRACT—A sudden comprehension that solves a problem, reinterprets a situation, explains a joke, or resolves an ambiguous percept is called an *insight* (i.e., the "*Aha!* moment").

Psychologists have studied insight using behavioral methods for nearly a century. Recently, the tools of cognitive neuroscience have been applied to this phenomenon. A series of studies have used electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) to study the neural correlates of the "*Aha!* moment" and its antecedents. Although the experience of insight is sudden and can seem disconnected from the immediately preceding thought, these studies show that insight is the culmination of a series of brain states and processes operating at different time scales. Elucidation of these precursors suggests interventional opportunities for the facilitation of insight.

KEYWORDS—*Aha!* moment; creativity; EEG; fMRI; insight; neuroimaging; problem solving

Insight is a sudden comprehension—colloquially called the “*Aha!* moment”—that can result in a new interpretation of a situation and that can point to the solution to a problem (Sternberg & Davidson, 1995). Insights are often the result of the reorganization or restructuring of the elements of a situation or problem, though an insight may occur in the absence of any preexisting interpretation.

For several reasons, insight is an important phenomenon. First, it is a form of cognition that occurs in a number of domains. For example, aside from yielding the solution to a problem, insight can also yield the understanding of a joke or metaphor, the identification of an object in an ambiguous or blurry picture, or a realization about oneself. Second, insight contrasts with the deliberate, conscious search strategies that have been the focus of most research on problem solving (Ericsson & Simon, 1993); instead, insights occur when a solution is computed unconsciously and later emerges into awareness suddenly (Bowden & Jung-Beeman, 2003a; Smith & Kounios, 1996). Third, because insight involves a conceptual reorganization that results in a new, nonobvious interpretation, it is often identified as a form of creativity (Friedman & Förster, 2005). Fourth, insights can result in important innovations. Understanding the mechanisms that make insights possible may lead to methods for facilitating innovation.

AN APPROACH TO STUDYING INSIGHT

In our studies, we have used electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) to examine processes that would be difficult to detect using behavioral measurements alone. EEG has the benefit of high temporal resolution; fMRI complements EEG by affording the high spatial resolution necessary for precise localization of brain activity.

We used a type of problem called *compound remote associates* (Bowden & Jung-Beeman, 2003b) that affords two advantages. When a participant solves one of these problems, he or she can typically do so within 10 seconds; much longer time is often needed to solve classic insight problems (Fleck & Weisberg, 2004). This relatively short solution time allowed us to produce the large number of trials necessary for EEG and fMRI. In addition, compound-remote-associates problems can be solved either with or without insight, enabling researchers to compare insight and analytic solving without changing the type of problem. In our experiments, compound remote associates that were solved by insight and by analytic processing were sorted according to participants' trial-by-trial judgments of how the solution entered awareness—suddenly for insight, incrementally for analytic processing.

Each compound-remote-associates problem consists of three words (e.g., *crab*, *pine*, *sauce*). Participants are instructed to think of a single word that can form a compound or familiar two-word phrase with each of the three problem words (e.g., *apple* can join with *crab*, *pine*, and *sauce* to form *pineapple*, *crabapple*, and *applesauce*). As soon as participants think of the solution word, they press a button as quickly as possible. Participants are instructed to respond immediately and not take any time to verify this solution. They are then prompted to verbalize the solution and then to press a button to indicate whether that solution had popped into awareness suddenly (insight) or whether the solution had resulted from a more methodical hypothesis-testing approach. An example of a methodical strategy for solving the problem would be to start with *crab* and generate associates of this word, such as *cake*. *Crabcake* is an acceptable compound, as is *applecake*. But *pinecake* and *cakepine* are both unacceptable, leading to the rejection of *cake* as a potential solution. One might then try *grass*. *Crabgrass* is acceptable, but neither *pinegrass* nor *applegrass* works—and so on. Participants in our studies

immediately and intuitively understood the distinction between sudden insight and methodical solving.

NEURAL CORRELATES OF THE “*AHA!* MOMENT”

Our first neuroimaging study included separate EEG and fMRI experiments that examined brain activity during a time interval beginning shortly before the derivation of the solution (Jung-Beeman et al., 2004). Brain activity corresponding to analytic solutions was subtracted from activity corresponding to insight solutions, to show brain areas whose level of activity differed while solving problems with insight relative to solving problems analytically. EEG showed that insight solutions were associated with a burst of high-frequency (i.e., 40-Hertz gamma-band) activity starting about 300 milliseconds before the button-press signaling that a solution was derived. This burst of EEG activity was detected at electrodes located over the right anterior temporal lobe, just above the right ear (Fig. 1). The only insight effect reliably detected with fMRI in this initial study occurred in a brain region called the right anterior superior-temporal gyrus, which was underneath the electrodes showing the corresponding EEG effect.

There was one additional insight effect present in the EEG data. Immediately prior to the burst of gamma-band EEG activity was a burst of slower, alpha-band (approximately 10-Hertz), activity measured over right occipital cortex (i.e., the right side of the back of the head; see Fig. 2). Though this finding was unexpected, the EEG literature, and common experience, suggested an interpretation.

In everyday circumstances, when asked a difficult question, a person often will look away from the questioner, or even close his or her eyes, in order to avoid distractions and to concentrate on thinking of the answer. In our EEG experiment, the participants were instructed to

keep their eyes open and focus on a fixation marker in order to minimize electrical noise from eye movements and blinks. These instructions strongly discouraged the tendency to look away or close their eyes. This restriction on their overt behavior apparently led to a type of covert compensation.

Alpha-band oscillations are the brain's dominant rhythm and are understood to reflect idling or inhibition of brain areas (Kounios et al., 2006). In particular, such oscillations measured over the occipital or visual cortex at the back of the head reflects a reduction in the amount of visual information passed from visual processing areas to higher areas that perform more abstract computations (i.e., sensory gating; Payne & Kounios, 2009). This insight-related burst of alpha may represent the brain's covert alternative to closing the eyes or looking away.

Taken together, the alpha and gamma effects suggest that when a weakly activated problem solution is present in the right temporal lobe, a temporary reduction in interfering visual inputs facilitates the retrieval of this solution, allowing the solution to pop into awareness.

THE PREPARED MIND

Our initial study of the neural substrates of insight suggested that the brain response associated with the *Aha* was the culmination of a series of neural events, such as the alpha “brain blink.” A subsequent study (Kounios et al., 2006) sought to trace the origins of insight farther back in time to answer a more fundamental question—namely, why are problems sometimes solved with insight and sometimes analytically? Inspired by Louis Pasteur's famous comment “Chance favors only the prepared mind,” we examined brain activity immediately preceding the display of each problem. The logic of this study was that the pattern of brain activity already present when a problem is displayed may bias cognitive processing, increasing the chances of

either insight or analytic solving. On each trial of the EEG experiment, participants signaled readiness for the next problem with a button-press. One second later, the three words of a problem were displayed on the monitor in front of them. We examined the 2-second interval preceding the presentation of each problem (i.e., starting 1 second before the button-press and ending the instant the problem was displayed) and sorted the trials into those that were subsequently solved with insight and those subsequently solved analytically. (Because of the technical requirements of fMRI, the onset of the problem display was a random rest interval not controlled by the participants in the fMRI experiment.)

We found distinct patterns of brain activity preceding problems solved with insight versus those solved analytically (Fig. 3). Before the presentation of problems to be solved with insight, EEG revealed greater neural activity over the temporal lobes of both cerebral hemispheres (i.e., around the ears) and over mid-frontal cortex. Before the presentation of problems to be solved analytically, there was more neural activity measured over posterior (visual) cortex. The results of the fMRI experiment closely mirrored those of the EEG experiment. The activations of both the right and left temporal lobes suggest priming of brain areas that process lexical and semantic information. fMRI showed that the mid-frontal activity originated in the anterior cingulate, a brain area that a number of neuroimaging studies have implicated in the control of cognitive processes like detection of inconsistent or competing activity, attention switching, and so on (e.g., Botvinick, Cohen, & Carter, 2004). We therefore hypothesized that, in this situation, the anterior cingulate may be involved in the readiness to detect weakly activated, subconscious solutions and to switch attention to them when they are detected. The greater neural activity measured by EEG over visual cortex preceding problems solved analytically was hypothesized to reflect the amount of visual information passed along to

higher cortical areas. In this case, preceding the display of problems to be solved analytically, the increase in neural activity suggests that participants were preparing for analytical solving, in part, by directing attention outwardly—that is, to the monitor on which the next problem was about to be displayed. Conversely, preparation for solving an upcoming problem with insight involved directing attention inwardly—priming for lexical-semantic processing and the detection and retrieval of weakly activated potential solutions rather than focusing attention outwardly toward the monitor.

It is not yet clear to what extent these forms of preparation may be conscious and volitional or automatic and anticipatory. The fact that subjects in the EEG experiment initiated the display of each problem when ready suggests a volitional substrate. An alternative hypothesis that we explored is that there are slow fluctuations in resting-state brain activity that are associated with insight versus analytic processing; perhaps participants press the button to indicate readiness for the next problem when these fluctuations put them in a target state for tackling the problem. However, examination of possible sequential dependencies in solving strategies across trials yielded no evidence of clusters of insight or noninsight solutions at any time-scale, weighing against the notion that subjects initiated trials to coincide with uncontrolled variation in brain states.

THE CREATIVE BRAIN AT REST

The study just described shows how problem-solving strategy can be influenced by the prior preparatory state. This, however, naturally raises the question of what determines the preparatory state. A recent study examined the possibility that the adoption of problem-solving strategies may have its origins in yet more fundamental processes—specifically, in individual differences in resting-state brain activity (Kounios et al., 2008). In this study, we recorded

participants' EEG while they sat comfortably with no task to perform and no specific expectation of what would happen next. After this resting-state activity was recorded, they were given a series of anagrams to solve, using the same insight-judgment procedure used in our compound-remote-associates studies. We divided the participants into two groups based on the proportion of their anagram solutions that resulted from insight versus analytic processing. We then analyzed their initial resting-state EEG activity (collected before they even knew what task they would be performing) separately for these high-insight and high-analytic groups.

Based on prior research, we predicted two general differences between these groups. One prominent view of creativity is that it is based on the processing of remote or loose associations between ideas (Mednick, 1962). Recent research implicates the brain's right hemisphere in the processing of remote associates and the left hemisphere in the processing of close or tight associations (for a review, Jung-Beeman, 2005). We therefore predicted greater activity in right-hemisphere regions associated with lexical and semantic processing. Second, based on previous findings suggesting that individuals high in creativity habitually deploy their attention in a diffuse rather than a focused manner (Ansburg & Hill, 2003), we predicted greater diffuse activation of the visual system in high-insight participants (corresponding to less posterior alpha-band and beta-band EEG activity). Both of these predictions were supported by the data, demonstrating that task-related problem-solving strategies have their origins in individual differences in resting-state brain activity.

As interesting as these findings are, they raise as many questions as they answer. For example, this experiment did not ascertain whether these insight-related differences in resting-state activity are stable. It is possible that the relevant aspects of resting-state activity vary over a time-course of hours or days, resulting in slow fluctuations of cognitive style. And if the insight-

related aspects of resting-state EEG are relatively stable, the question arises whether this stability has a genetic basis (though stability could result from nongenetic causes, such as practice). In general, individual differences in resting-state EEG are fairly stable and have been shown to have a genetic basis (Smit, Posthuma, Boomsma, & de Geus, 2005), though it is not yet known whether these insight-related differences are a subset of the stable, genetically related individual differences in resting-state EEG. This question is important, because it suggests the possibility of genetically determined individual differences in cognitive style.

Nevertheless, even if the tendency to have insights is genetically influenced, the fact that preparation for insight or analytic processing can vary from problem to problem shows that insight is not a fixed ability. Our research has begun to examine how various factors can influence this tendency. For example, a recent fMRI study showed that people are more likely to solve problems with insight if they are in a positive mood when they arrive at the lab than if they are in a neutral or negative one (Subramaniam, Kounios, Parrish, & Jung-Beeman, 2009). Moreover, positive mood was associated with greater activity in the anterior cingulate during the preparation period prior to each problem, suggesting that positive mood biases cognitive control mechanisms in ways that facilitate insight, with anxiety having the opposite effect. Similarly, work in progress suggests that when positive mood is induced by having participants watch comedy videos, they solve more problems, and solve more of them with insight, than they do after they watch neutral or anxiety-inducing films.

FUTURE DIRECTIONS

These research findings raise many issues to be tackled by future studies. One question is to what extent these results are specific to verbal-reasoning problems or whether insight in other

domains (e.g., visual-object identification) involves somewhat different neurocognitive mechanisms. Another question is whether differences in resting-state brain activity between high-insight and high-analytic participants are relatively stable over time, possibly being influenced by genetics, or whether these differences reflect transitory, though slowly changing, states.

Finally, the real-world implications of these findings are potentially of substantial importance. The fact that the tendency to solve problems with insight is influenced by multiple processes operating at varying time-scales suggests that there are a number of “vulnerable” points in the cascade of processes that result in an insight. These points potentially represent opportunities for influencing the course of reasoning. We expect research will eventually result in a systematic technology for facilitating or entraining creative insight.

Recommended Reading

- Jung-Beeman, M., Bowden, E.M., Haberman, J., Frymiare, J.L., Arambel-Liu, S., Greenblatt, R., et al. (2004). (See References). A study using EEG and fMRI to isolate the main neural correlate of the “*Aha!* moment.”
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Subramaniam, K., Kounios, J., Parrish, T.B., & Jung-Beeman, M. (2009). (See References). A study showing that participants' mood upon entering the laboratory predicts whether they will subsequently solve problems with insight or analytically.

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Fig. 1. High-frequency *gamma-band* (approximately 40 Hertz) electroencephalogram (EEG) activity associated with problem solution. Panel A shows a plot of gamma-band activity as a function of time. The *y*-axis represents EEG power (squared microvolts); the *x*-axis represents time (seconds) with the yellow *R* signifying the point in time at which a subject presses the button to indicate that he or she had just derived the problem solution. The blue line (NI) represents gamma activity for noninsight (analytic) solutions; the red line (I) represents gamma activity for insight solutions. The burst of gamma activity for insight solutions relative to noninsight solutions beginning approximately 300 milliseconds prior to the button-press response (about the amount required to make a manual response) is hypothesized to be the primary neural correlate of the “*Aha!*” experience. Panel B shows the topographic distribution of this gamma-band activity for the insight solutions minus the activity for the noninsight solutions. The view is of the right side of the head, with each red dot signifying the location of an EEG electrode. The yellow region over the right anterior temporal lobe (i.e., the area above the right ear) is the spatial focus of the insight effect (i.e., insight solutions minus noninsight solutions).

Panel C shows the corresponding insight effect for the functional magnetic resonance imaging (fMRI) experiment. This activation is in the right anterior superior temporal gyrus. From “Neural Activity When People Solve Verbal Problems With Insight,” by M. Jung-Beeman, E.M. Bowden, J. Haberman, J.L. Frymiare, S. Arambel-Liu, R. Greenblatt, et al., 2004, *PLoS Biology*, 2, pp. 502 and 505.

Fig. 2. The alpha-band (10 Hertz) insight effect (i.e., insight solutions minus noninsight solutions). Panel A shows a plot of electroencephalogram (EEG) alpha power for the insight effect in relation to the gamma insight effect (see Fig. 1). The *x*-axis represents time (seconds) leading up to the button-press response (the yellow *R*) that indicated that a participant had derived a solution to the problem. The *y*-axis represents EEG power (squared microvolts—note the different scales for alpha and gamma). The purple line represents the alpha insight effect (measured at a right posterior electrode); the green line represents the gamma insight effect (measured at a right temporal electrode). Note that the alpha burst precedes the gamma burst. Panel B shows the topographic distribution of the alpha insight effect (back view of the head). This panel uses the same conventions in Figure 1, Panel B.

Fig. 3. Areas involved in preparation for insight versus those involved in analytic solving. The topographic maps of electroencephalogram (EEG) alpha power (8–10 Hz) show a display head from four angles. Yellow-orange regions are areas in which neural activity during the 2 seconds immediately preceding presentation of the compound-remote-associate problems was greater for trials on which the subsequently presented problem would be solved with insight. Blue regions reflect areas in which the neural activity during the same preparatory phase was greater for trials

on which the subsequently presented problem would be solved without insight (i.e., analytically).

The color scale reflects scalp regions yielding significant t -scores.