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Resting-state brain oscillations predict trait-like cognitive styles

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ABSTRACT

Anecdotal reports suggest the existence of individual differences in peoples' cognitive styles for solving problems, in particular, the tendency to rely on insight (the "aha" phenomenon) versus deliberate analytical thought. We hypothesized that such stable individual differences exist and are associated with trait-like individual differences in resting-state brain activity. We tested this idea by recording participants' resting-state electroencephalograms (RS-EEGs) on 4 occasions over approximately 7 weeks and then tasking them with solving anagrams and compound remote associates problems that are solvable by either strategy. We found that peoples' tendency to solve problems consistently by insight or by analysis spans both tasks and time. Moreover, we discovered trait-like individual differences in the balance between frontal and posterior resting-state brain activity and in temporal-lobe hemispheric asymmetries that predict, at least weeks in advance, the tendency to solve by insight versus analysis. The discovery of an insight-analytic dimension of cognitive style and its neural basis in resting state brain activity suggests new avenues for the development of neuroscience-based methods for intellectual, educational, and vocational assessment.

1. Introduction

Two individuals may arrive at the same solution to a given problem through different cognitive strategies. *Insight* and *analysis* are two such strategies primarily distinguished by their reliance on unconscious versus conscious processing (Kounios and Beeman, 2014; Dehaene et al., 2017): Analysis involves the conscious manipulation of the elements of a problem, as in hypothesis testing; insight involves the sudden, conscious realization of a solution (“aha!”) associated with a burst of high-frequency brain activity following a period of unconscious processing (Jung-Beeman et al., 2004; Smith and Kounios, 1996). Though much progress has been made in understanding the neural mechanisms underlying analytic and insightful problem solving (Kounios and Beeman, 2014), little is known about whether and why some individuals may tend to rely more on one of these cognitive styles (Ovington et al., 2016). We tested the hypothesis that trait-like components of resting-state brain activity can predict, and may underlie, qualitative, trait-like individual differences in the tendency to solve problems by insight or analysis, thus signifying an insight-analysis dimension of cognitive style (Kozhevnikov, 2007).

Ongoing, resting-state brain activity is a plausible substrate of qualitative differences in trait-like cognitive style. It is highly consistent across recording sessions (Martín-Buro et al., 2016) and has a systematic relationship to task-related activity (Smith et al., 2009). It also predicts trait-like individual differences in psychopathology (John et al., 1988) and in the quantitative ability factor of fluid intelligence (Finn et al., 2015). Moreover, when recorded immediately before problem-solving, transient brain activity predicts solving strategy (Kounios et al., 2006, 2008).

Resting-state brain activity is, however, influenced by transient state changes as well as consistent, trait-like oscillations. To isolate trait-like brain activity, we recorded participants’ resting-state electroencephalograms (RS-EEGs) at the beginning of each of 4 sessions; the mean time between consecutive sessions was approximately 16 days. Averaging RS-EEGs recorded during sessions on different days allows transient state-changes to cancel out, thereby revealing trait-like patterns of activity (Hagemann et al., 2002, 2005). Additionally, participants performed a different task or filled out a questionnaire at the end of each session and were given no advance knowledge of these tasks. Thus, their resting-state brain activity could not have been influenced by specific anticipations. This report focuses on the relationship between the spectral content of participants’ RS-EEGs recorded during sessions 1–3 and their anagram-solving strategy during session 4 (Fig. 1).

Insight versus analytic solving strategy (or rarely, “not sure”) was assessed on a trial-by-trial basis with a validated self-report technique

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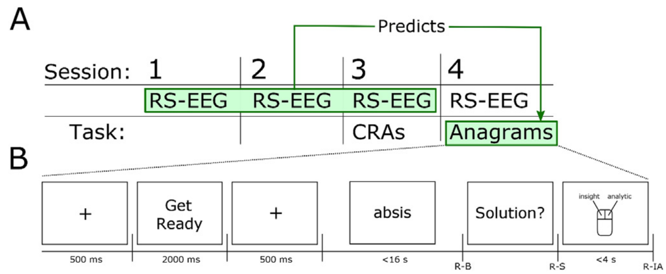

Fig. 1. Experimental design and procedure. (A) Subjects participated in 4 test sessions spanning about 7 weeks. Each session began with a resting-state EEG (RS-EEG) recording and ended with a task. The RS-EEG recordings from the first 3 sessions were used to predict a measure of cognitive style (insight versus analytic) obtained from the fourth session (B) The trial sequence of the anagram-task procedure consisted of a "+" fixation mark, a "Get Ready" prompt, a second fixation mark, and the anagram stimulus (in this example, "absis") displayed for 16 s until trial time-out or until the participant made a speeded bimanual button-press (R-B in the figure) to indicate that he or she had solved the problem. The participant was then prompted to verbalize the solution (here "basis," marked by R-S) after which the response was recorded as correct or incorrect. A visual reminder of the mouse-button response-mapping for insight- and analytic-strategy reporting was displayed for 4 s or until the participant responded with a left or right button-press to indicate that the solution had been derived by insight or analysis (R-IA in the figure).

(Bowden et al., 2005; Kounios and Beeman, 2014) similar to the "remember-know" paradigm widely used in memory research (Wixted and Mickes, 2010). This procedure has revealed differences in brain activity, eye-blinks, and eye-movements between insight and analytic solutions. These differences occur leading up to the point of solution, just before problems are presented, and in resting-state activity recorded immediately before a block of problems (Kounios and Beeman, 2014; Salvi et al., 2015). Furthermore, this technique has revealed different patterns of errors and timeouts predicted by the hypothesis that insight solutions become available suddenly while analytic solutions accrue incrementally (Kounios et al., 2008). Each participant's predominant solving style, independent of quantitative differences in solving ability, was quantified by calculating the log ratio of his or her number of insight solutions (I) to the number of analytic solutions (A) during a series of anagram problems in which a participant had to unscramble a letter sequence to discover a word (Kounios et al., 2008).

As reported below, the tendency to solve problems by insight versus analysis, independent of solving ability, shows stability over tasks and time. Moreover, it can be predicted, weeks in advance, by trait-like resting-state brain oscillations.

2. Materials and methods

2.1. Participants

This work was carried out in accordance with The Code of Ethics of the World Medical Association (Declaration of Helsinki). Experimental protocols were approved by the Drexel University Institutional Review Board. Fifty-one right-handed, native English-speakers (27 male, 24 female) gave informed written consent before participating. They ranged in age from 18 to 29 years of age (M = 20.69, SD = 2.97). Of these, 5 were excluded for failing to follow directions during the tasks; 3 were excluded for solving fewer than 20% of the problems; 2 were excluded for excessive EEG artifact; and 1 was excluded for abnormally high focal EEG alpha activity (i.e., more than 3 SD greater than the mean of the sample). Insight and analytic groups were constructed from the remaining pool of 42 participants (23 female) prior to analyses of the EEG data; however, these groups were not gender balanced because females, on average, had higher log I/A ratios (males: mean = 1.39, SD = 0.98; females: mean = 6.17, SD = 9.27; $t = -2.29$, $p = .027$). Instead, gender was explored as a covariate in an SPM flexible factorial model, as described below.

Participants filled out the Edinburgh Handedness inventory (Oldfield, 1971) on the first day of testing. All subjects were right handed, and the groups did not significantly differ in the degree of handedness (insight: mean = 4.63, SD = 0.50; analytic: mean = 4.39, SD = 0.67; $t = -1.18$, $p = .248$).

According to pre-planned analyses, we initially excluded participants with I/A ratios in the middle quartile (n = 10) of the distribution because participants who do not exhibit a distinct or consistent cognitive style are thought to be qualitatively different from participants who do exhibit a cognitive style (Kozhevnikov, 2007). The remaining 32 participants from the tails of the distribution of I/A ratios were included in the initial analyses (3 sessions each, for a total of 96 sessions of RS-EEG data). Some analyses involved group contrasts between participants with relatively high (insight group, n = 16) versus relatively low (analytic group, n = 16) I/A ratios. Subsequent regression analyses reinstated the middle quartile of the distribution of I/A ratios to test the generalizability of the model to the entire range of I/A ratios (n = 42).

2.2. Experimental design

Each person participated in 4 sessions on different days; the mean time between consecutive sessions was approximately 16 days. Each session lasted approximately 2 h. At the beginning of each session, 10 min of resting-state EEGs were recorded (see Electroencephalograms). This was followed by administration of the PANAS mood questionnaire (Watson et al., 1988). The remaining questionnaires and tasks varied across sessions.

During the first session, participants filled out 3 additional questionnaires (see Questionnaires): The Morning-Eveningness Questionnaire (Adan and Almirall, 1991) the Edinburgh Handedness inventory (Oldfield, 1971), and a demographics questionnaire. On the second day, participants completed a computer-based attention task and two other questionnaires as part of another study. On the third day, participants solved a series of compound-remote associates (CRA) problems (Bowden et al., 2005) while EEGs were recorded (see Compound Remote Associates). On the fourth day, EEGs were recorded while participants completed a set of anagrams (see Anagrams).

2.3. Tasks and procedures

2.3.1. Compound remote associates

The session-3 CRA task was implemented with E-Prime 2.0 (Psychology Software Tools, Sharpsburg, PA) and displayed on a ViewSonic Graphics Series G790 monitor. Participants sat approximately 1.5 m away from the monitor. A fixation cross was displayed until participants initiated each trial by making a bimanual button-press with their thumbs on a computer mouse. At that time, crosshairs appeared around the fixation cross. After 1000 ms, 3 CRA problem words (e.g., pine, crab, sauce) were displayed in a column replacing the fixation cross within the cross hairs. The words were displayed in yellow Courier New 14-point font against a black background for up to 14 s. Participants were instructed to try to read all of the words without moving their eyes and to think of a single solution word that forms a compound or familiar phrase with each of the problem words (in this case, apple, as in pineapple, crabapple, applesauce). If they found an answer, their task was to immediately indicate this by making another bimanual button press. Then "Solution?" appeared on the screen to signal participants that they should verbalize the solution after which the experimenter recorded whether or not the solution was correct. Participants indicated whether they had solved the problem by insight, that is, with the solution popping into awareness suddenly and seemingly disconnected from ongoing thoughts, or whether they had solved it analytically, that is, by working it out in a conscious, deliberate manner. Half of the participants indicated insight judgments with