Towards a quantitative framework for sudden-insight problem solving and the feeling of 'Aha!'

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Introduction

Problem solving via Sudden-Insight has several qualities, notably the feeling of 'Aha!' and the seemingly instantaneous occurrence of fully formed solutions, which distinguish it from more incremental, methodological approaches. This corresponds to neural activity and dynamics with properties different than other types of problem solving, as shown by recent studies using fMRI and EEG (Kounios et al., 2008; Sandkühler and Bhattacharya, 2008; Low and Makeig, 2008). However, attempts to describe or predict high-level cognitive behaviors such as 'Aha!' problem solving with quantitative models have been lacking.

We hypothesize that a spatiotemporal resonance of cortical potentials generated by interacting neural populations supports a rapid rise of activity toward a threshold of conscious access (Del Cul et al., 2007), the crossing of which signifies the availability of an insight solution. We attempted to model the mechanism for achieving an 'Aha!' via resonance using P.A. Robinson's "continuum" model for EEG as a simple, archetype of distributed population behaviors which directly link neurophysiology to behavior (Robinson et al., 2005). Supporting preliminary data from high-resolution EEG in a semantic, phrase completion task suggests that activity in the theta and alpha bands reflects activity corresponding to sudden-insight solutions and consistent with the theoretical work.

What is 'Aha!'?

"The sudden appearance in conscious awareness of a really big new and useful relationship among previously known information."

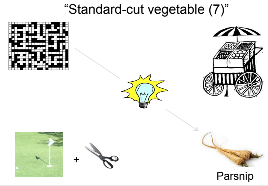
Stickgold, R., 2008
Insights into Insights UCSD/
Rancho Santa Fe

"…the clearest defining characteristic of insight problem solving is the subjective 'Aha!' or 'Eureka!' experience that follows insight solutions…"

Jung-Beeman, M. et al., 2004
Neural Activity When People Solve
Verbal Problems with Insight
PLoS Biology

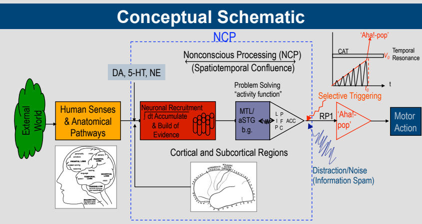
Priming or Insight?

"Standard-cut vegetable (7)"



Consider the anecdote of a cryptic crossword puzzle. Prior to working on the puzzle, the correct answer to a clue ("Standard cut vegetable (7)") was observed in a market and forgotten. Several weeks later and after unsuccessful attempts, the correct answer ("parsnip") was revealed in a flash of insight.

Conceptual Schematic



Information relevant to problem solving may originate from either the external world or within the brain. The use of such particularly relevant stimuli can be achieved both consciously and/or nonconsciously. It is the *selective triggering* of well-formed stimuli with the system kernel which leads to a resonance that rapidly brings the solution from "tip-of-tongue" to "top-of-mind".

Necessary Conditions

Rapid all-or-none solution – feeling of immediacy and fully formed solution, although not necessarily correct

Emotional response/appreciation – neuromodulators help determine the strength of the post-event 'Aha!' "feeling"

Impasse – a 'logical gap' exists at the final stage of solution processing…how close is the answer in emerging from 'tip-of-tongue' to 'top-of-mind'?

Accumulation process (over time), multiple areas (across space) – confluence of working memory and problem solving circuits (PFC, LIP, basal ganglia, ACC, aSTG/MTL, etc…)

Motivation and/or incentive – neuromodulation (e.g., DA, 5-HT) from start-to-finish of problem solving process

Noise dependence – minimal distraction or noise

Invariance – neural dynamics conserved across insights (mini- to macro-'Aha!')

Triggered by 'well-formed' stimulus – an endogenous or exogenous trigger stimulates a rapid rise-to-threshold with sufficient energy to drive the consequent 'Aha!-pop'

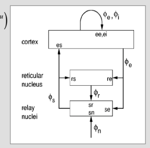
Mathematical Model

Robinson's 'continuum' model of population dynamics
(full, nonlinear)

$$V_a(t) = \int_{-\infty}^{\infty} L(t-t')P_a(t')dt' \qquad L(u) = \frac{\alpha\beta}{\beta-\alpha}\left(e^{-\alpha u} - e^{-\beta u}\right)$$

$$P_a(t) = \sum_b \nu_{ab}\phi_b(t) \qquad Q(x) = \frac{Q_{max}}{1+e^{\frac{-(V(x)-\theta)}{\sigma}}}$$

$$\left(\frac{1}{\gamma_a^2}\frac{\partial^2}{\partial t^2} + \frac{2}{\gamma_a}\frac{\partial}{\partial t} + 1 - r_a^2\nabla^2\right)\phi_a(\mathbf{r},t) = Q(V_a(\mathbf{r},t))$$



$$D_\alpha V_a(t) = \sum_b N_{ab}s_{ab}\phi_b(t-\tau_{ab}) \qquad D_\alpha = \frac{1}{\alpha\beta}\frac{d^2}{dt^2} + \left(\frac{1}{\alpha}+\frac{1}{\beta}\right)\frac{d}{dt} + 1$$

(space-clamped, linearized form)

"Fuzzy" Pole Resonance

$$D_\alpha V_a(t) = \sum_b N_{ab}s_{ab}\phi_b(t-\tau_{ab})$$

In time domain, we reduce the Robinson ODE to

$$\frac{d^2V_a}{dt^2} + (\alpha+\beta)\frac{dV_a}{dt} + \alpha\beta V_a = A\alpha\beta e^{-\gamma t} + \dots$$

The Laplace-transformed equation is

$$(s+\alpha)(s+\beta)V_a(s) = \frac{A\alpha\beta}{s+\gamma} + \dots$$

For $\gamma = \alpha$ (double pole), the $Ae^{-\gamma t}$ RHS forcing function yields a steady state solution with a **Real part:**

$$V_a(t) = \frac{A\alpha\beta}{\beta-\alpha}t\cos\alpha t$$

The near-resonant "fuzzy-pole" expansion for β or $\gamma = \alpha + \varepsilon$ (ε small), yields a transfer function kernel

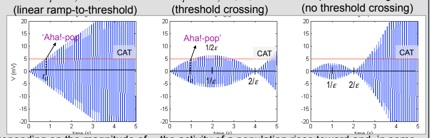
$$H_0(s) = \frac{1}{(s+\alpha)(s+\alpha+\varepsilon)} \approx \frac{1}{(s+\alpha)^2}\left(1 - \frac{\varepsilon}{(s+\alpha)} + \frac{\varepsilon^2}{(s+\alpha)^2} - \dots\right)$$

The real part of the inverse transform of the above equation is then of the form

$$h(t) \approx t\cos\alpha t\left(1 - \frac{\varepsilon t}{2} + \frac{(\varepsilon t)^2}{6} - \dots\right), \text{ so that } V_a(t) \approx \frac{A\alpha\beta}{\beta-\alpha}t\cos\alpha t\left[1 - \frac{\varepsilon t}{2} + \frac{(\varepsilon t)^2}{6} - \dots\right] \quad (\frac{(\varepsilon t)^2}{6} \to 0)$$

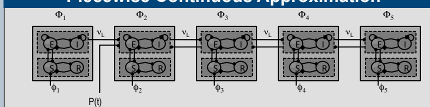
$$V_a(t) \approx \frac{A\alpha\beta}{\beta-\alpha}t\cos\alpha t\left[1 - \frac{\varepsilon t}{2}\right]$$

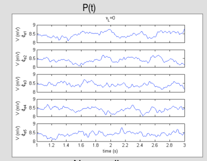
$\gamma = \alpha$; $\varepsilon = 0$ (linear ramp-to-threshold) | $\gamma = \alpha + \varepsilon$; ε small (threshold crossing) | $\gamma = \alpha + \varepsilon$; ε large (no threshold crossing)



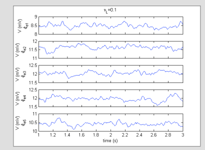
Depending on the magnitude of ε, the activity of a population rises toward and, in some cases (ε <<1), exceeds the threshold for conscious access. The shape of the activity envelope suggest potential hallmark features in EEG.

Piecewise Continuous Approximation

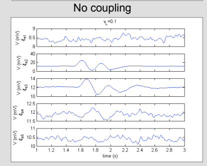




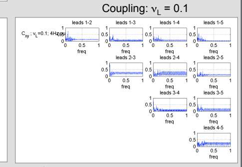
No coupling



Coupling: ν_L = 0.1



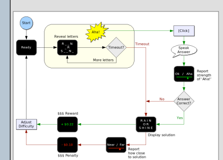
Coupling: ν_L= 0.1; P(t): 4Hz pulse



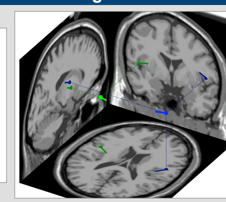
Spectral coherence between leads

Increased lateral coupling (ν_L) tends to increase coherence in the theta band. Furthermore, a brief sinusoidal pulse at a resonant frequency in one population leads to increased coherence between other populations in the network.

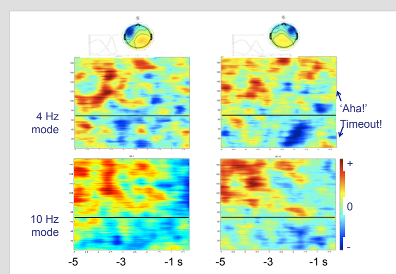
Experimental Findings



A phrase completion paradigm was used to study 'Aha!'/insight problem solving using hi-res EEG.



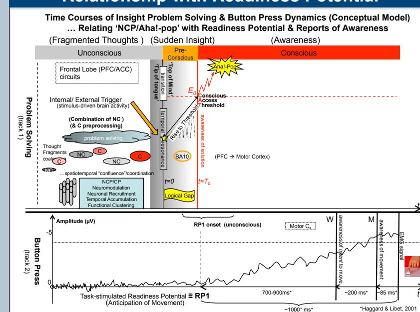
Dipole source localization suggests involvement of temporal areas (also see Kounios et al., 2008 and Jung-Beeman et al., 2004.



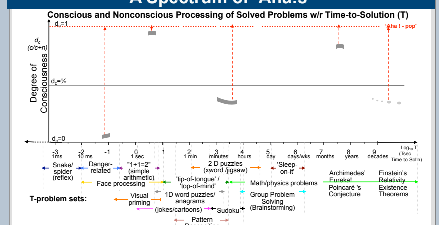
Significant differences in both the theta and alpha bands are evident in successful vs. unsuccessful trials several seconds prior to reporting solutions by subjects.

(See poster 682.5 RR78 11/18/08 1:00PM R. Low & S. Makeig)

Relationship with Readiness Potential



A Spectrum of 'Aha!s'



Conclusion

•Spatiotemporal resonance is a candidate dynamical mechanism that explains the phenomenon of insight/'Aha!' solutions and may be derived mathematically from neural population models.
•The concept of a "fuzzy" pole or "closeness" to an ideal clue suggests characteristic waveforms in neuroelectric fields.
• Piecewise approximations of Robinson's model support the hypothesis of "fuzzy" pole resonance for an 'Aha!'.
• Pilot studies of a semantic task (Phrase Completion) confirm a role of frontal and temporal lobe structures in 'Aha!' problem solving including relevant activity in the alpha and theta bands.

Literature Cited

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