$\mathbb{C}\times\mathbb{N}$: Investigating the Creative Proving Process Using Neuroscience Methods

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Background Literature – Incubation

Wallas (1926) four-stage creative process

- Preparation, Incubation, Insight, Verification
- Anecdotal evidence (e.g., Hadamard, 1945; Poincare, 1946; Burton, 1999; Liljedahl, 2004, 2014)
- Liljedahl (2004): "Upon reflection, I now see that the clinical interview is not at all conducive to the fostering of such phenomena [insight]..." (p. 49)

Savic (2015a) – Livescribe™ pens to research incubation

Background Literature - Proof

Proof production/Proving process (Weber, 2005; Savic, 2015b)

Key ideas (Raman, 2003)

- A key idea "gives a sense of **understanding** and **conviction**. Key ideas show why a particular claim is true" (p. 323)

Key ideas may have potential for insight

- "At the moment of insight, in the flash of understanding when everything seems to make sense and the answer is laid bare before you, you know it, and you call out – AHA!, I GOT IT!" (Liljedahl, 2004, p. 1)

Background Literature – Insight in Neuroscience

Bowden and Jung-Beeman (2003) – Insight moments occur within right-hemisphere

Kouinos et al. (2006, p. 887) – Insight preparation is extensive on the left bilateral temporal cortex

Remote association tasks

- Electric, High, Wheel
- Not remotely close insight to proving tasks

Research Questions

Can one obtain physical evidence of insight in proving?

Are there “predictors” of variance in brain activity?

Methods – Participants

3 graduate students in a department in a large university in the south central US

- Marshall – White male, Ph.D. candidate, passed qualifiers
- Francis – Native American female, Ph.D. candidate, pre-qualifiers
- Buzz – White male, Masters candidate

Methods – Days 1-2

Given two proving tasks for two days

- (ALG) Prove that no group is the union of two of its proper subgroups.
- (ANA) Prove that, if $a \in \mathbb{R}$ and $f: \mathbb{R} \to \mathbb{R}$ and $g: \mathbb{R} \to \mathbb{R}$ are functions continuous at a, then $fg: \mathbb{R} \to \mathbb{R}$ is continuous at a. [Here $(fg)(x) = f(x)g(x)$. Note that $fg \neq f \circ g$.]

Livescribe™ pens were used to capture proving process

Methods – Days 3-4

Creating slides for the EEG machine

- From Livescribe™ data with participants' handwriting
- Chunks – small excerpts of the written proof activity that indicate meaningful furthering of the proof (Savic, 2011)
- Also limited to size of slides (700 x 700 pixels)

Methods – Codes Used

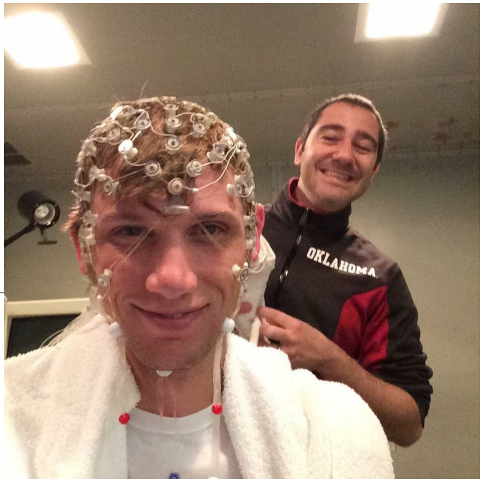
Coding chunks based on modification of Savic (2011)

- 14 codes: assumption, contradiction statement, delimiter, exterior reference, interior reference, relabeling, statement of intent, similarity in a proof, algebra, conclusion statement, definition, formal logic, use of exterior reference, use of interior reference
- Ex: "Let $\varepsilon > 0$." - Assumption
- Ex: "Since $A \subset B$, then $x \in B$."
  - "Since $A \subset B$" – interior reference
  - "then $x \in B$" – use of interior reference, use of definition

Additional codes: length of chunk, position, correctness, clean up, posing questions, example generation, statement to be proven, no code

Student-Reported Potential For Insight (SRPFI)

EEG Details



"Re-living" (Farah, 1988; Stavrinou et al., 2007)

EEG net – 128 Nodes

250 Hz sampling – 1 sample every 4 ms

Measure is variance from standard or steady activity

Chunks are combined together for analysis

- Investigation looked at all "original" and "canned" chunks from each participant from 0 – 1500 ms

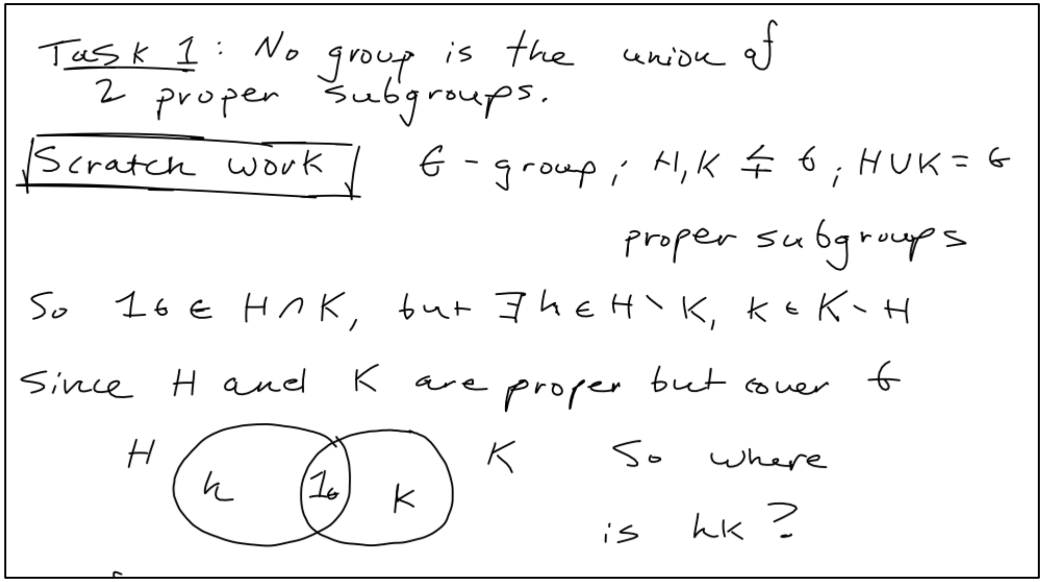
Which codes can "model" the variance in brain activity?

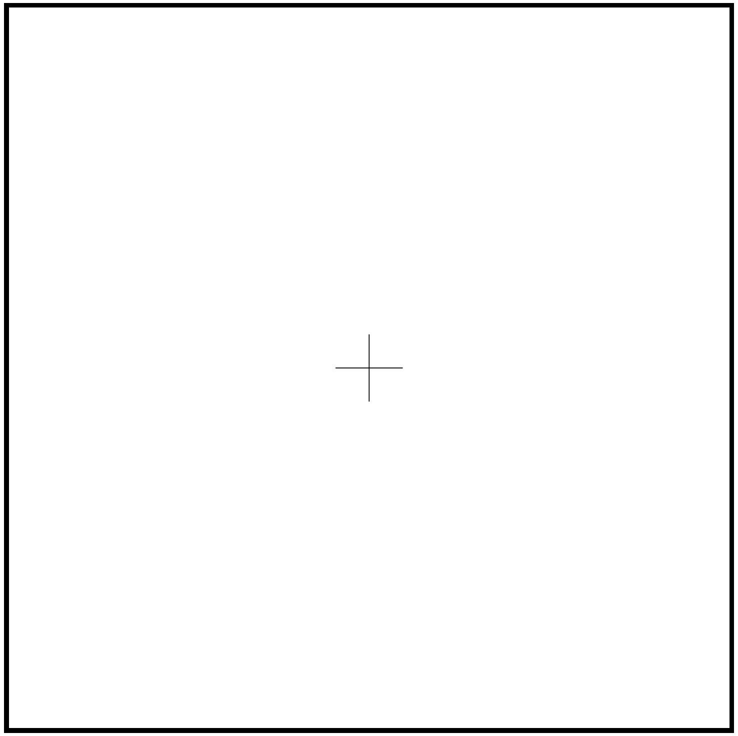
Methods – Day 5

EEG and exit interview

- EEG included their proofs and two comparable "canned" proofs
  - (ALG) Suppose G is a group such that $G/Z(G)$ is cyclic (where $Z(G)$ is the center of the group). Prove that G is commutative.
  - (ANA) If $a \in \mathbb{R}$ and $f: \mathbb{R} \to \mathbb{R}$ and $g: \mathbb{R} \to \mathbb{R}$ are functions continuous at a, then $f + g: \mathbb{R} \to \mathbb{R}$ is continuous at a.
- Interchanged: ALG Original, ALG Canned, ANA Original, ANA Canned
- Interview asked questions about their proving process and the key ideas of their own proofs and the canned proofs
  - Generally, what does it mean to be a key idea in a proof?
  - What is/are the key idea/s in this proof?
  - Why do you say this is a key idea in the proof?
  - Which of these parts of the proof do you think is most important?

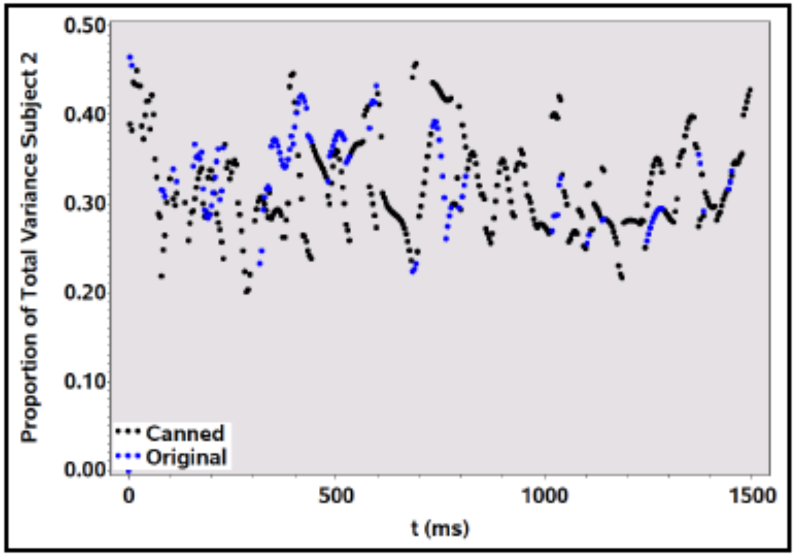
Sample DATA


Task 1: No group is the union of 2 proper subgroups.
Scratch work
G - group; H, K ⪇ G; H ∪ K = G
proper subgroups
So 1G ∈ H ∩ K, but ∃ h ∈ H ∖ K, k ∈ K ∖ H
Since H and K are proper but cover G
H
h
1G
k
K
So where is hk?



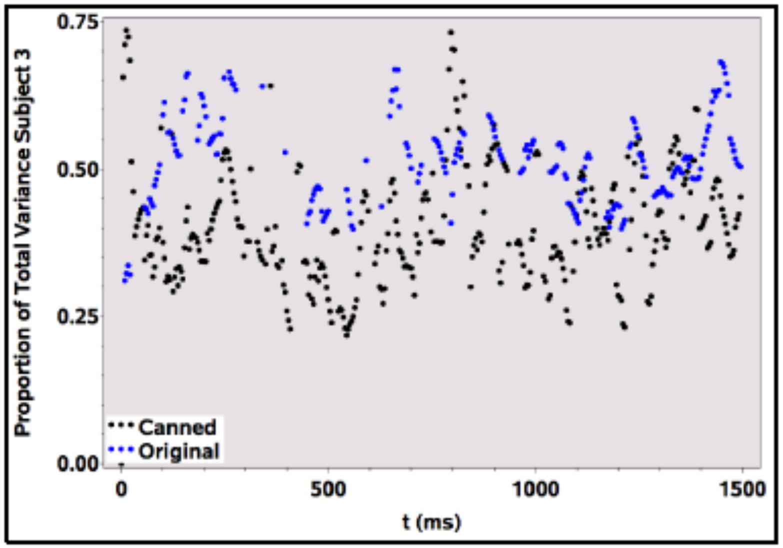
Results

Models created from codes explain quite a bit of variance in brain activity

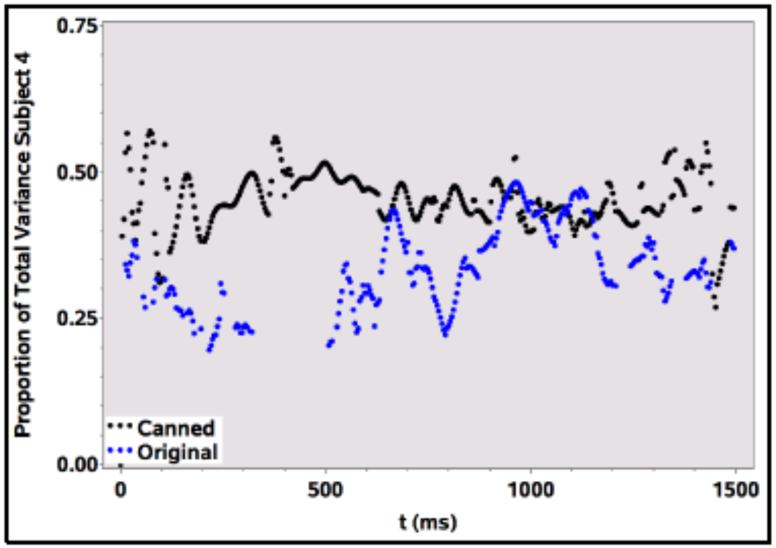


(a) Marshall

Results (cont.)



(b) Francis

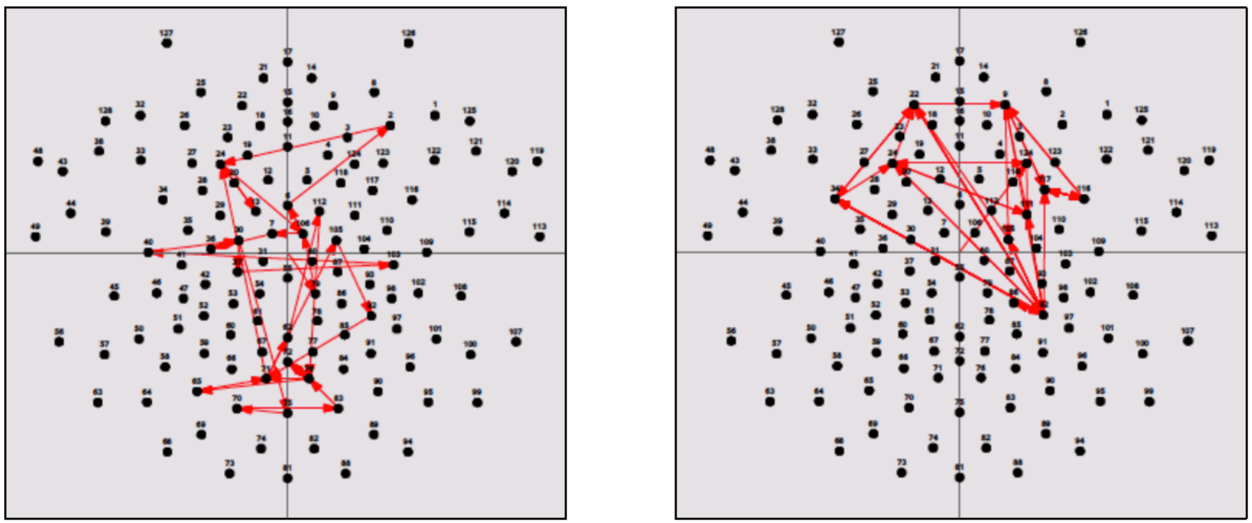


(c) Buzz

Results (cont.)

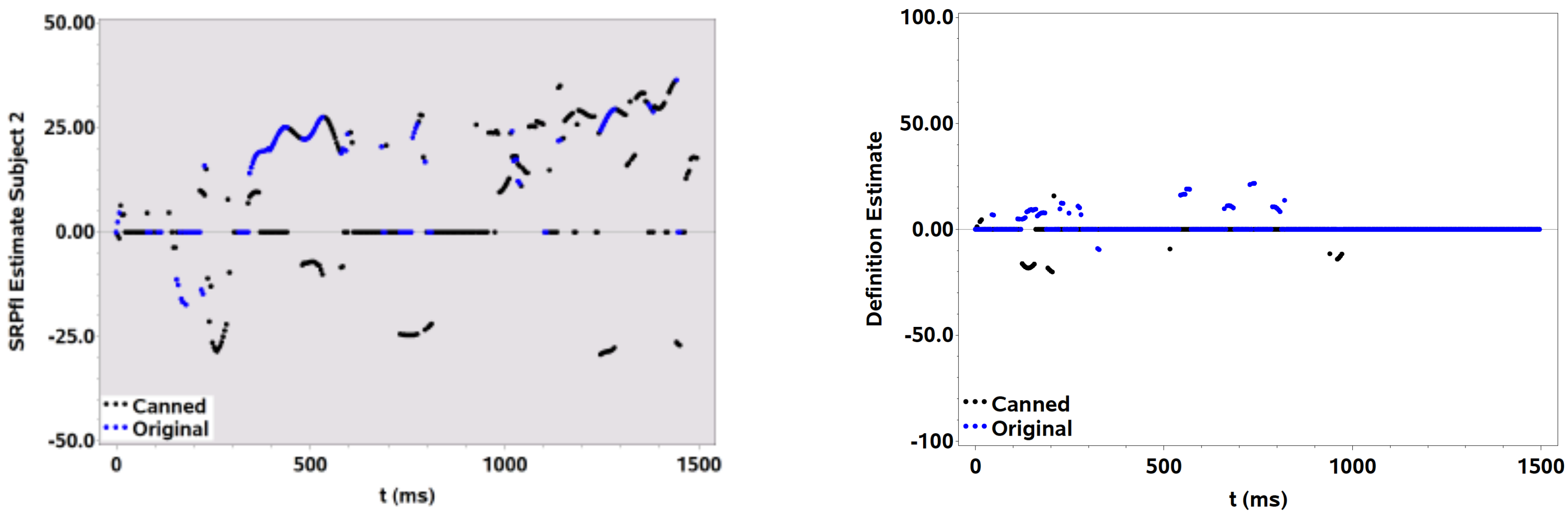
Following the path of electrodes with most variance explained

Marshall – Canned (L) and Original (R)



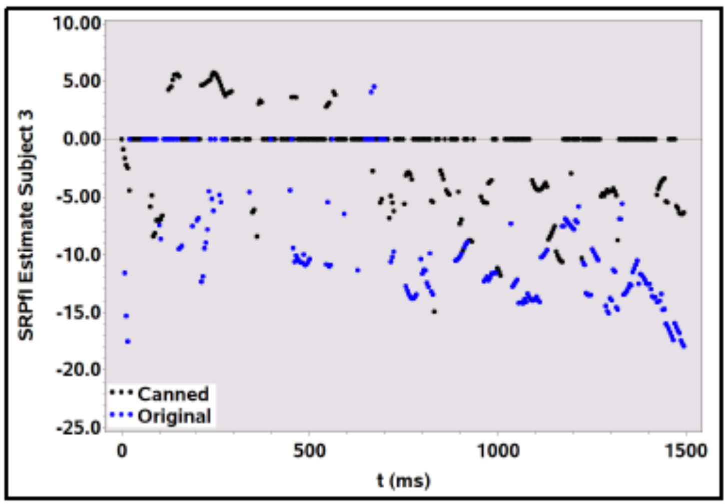
Importance of SRPFI

SRPFI was included in many models explaining variance

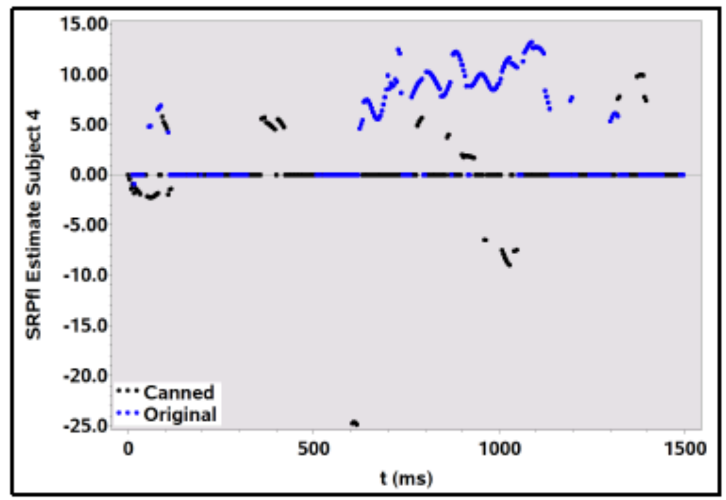


(a) Marshall

Importance of SRPFI



(b) Francis



(c) Buzz

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Future Work

Exploring interpretations of our current data and the theoretical implications, including changing many of the proof codes themselves

Collecting data with more participants, including undergraduates

Exploring different neural data collection techniques (e.g., alternative brain-computer interfaces such as fNIRS – functional near-infrared spectroscopy)

- Currently collaborating with Shiv Karunakaran, Abigail Higgins, and James Whitbread at Washington State University

THANK YOU!

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Questions for audience:

- What would be a sound way to code the importance of each chunk in the proving process?
- Would questions about insight in the post-interview be helpful?
- Could the problem-solving process be investigated in a similar manner? For example, could calculus tasks allow for similar results?