A User Study of Visualization Effectiveness Using EEG and Cognitive Load

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User Studies

- Allow evaluation of visualization methods

- User studies in industry for ergonomics and optimization

- Almost every field makes use of user studies (100s of potential citations)
  - Allows *meaningful* comparisons to be made between methods/systems
Technology Evolution in User Studies

• Eye Tracking
  – Granka et al. SIGIR 2004
  – Duchowski Behavior Research Methods 2002

• Electroencephalography
  – Berka et al. SPIE 2004

• Cognitive Measures
  – Klingner et al. J. Psychophysiology 2011
  – Hitt et al. Human Factors and Ergonomics 1999
Thesis Statement

- Electroencephalography is a useful tool to employ in the analysis of visualization effectiveness.
  
  - Perform a user study examining different box plot style visualizations.
Electroencephalography

Emotiv EPOC EEG headset
Electroencephalography and memory

- Working memory is spatially organized
  [Baddeley Working Memory 1983]
  [Cohen Nature 1997]
Electroencephalography and memory

- Working memory is spatially organized
  [Baddeley *Working Memory* 1983]

- Working memory is spectrally organized
  [Eckhorn *Biological Cybernetics* 1988]
  [Klimesch *Brain Research Reviews* 1999]
Working memory performance

- Spectral dynamics linked to working memory performance
  [Gevins *Human Factors* 1998],
  [Stam *Neuroscience Letters* 2000], [Sauseng *IJPP* 2005]

  - Energy density change
Working memory performance

- Spectral dynamics linked to working memory performance
  
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  [Sauseng *IJPP* 2005]

- Energy density change
- Gravity frequency shift
Working Memory Spectral Dynamics

- Working memory located at the front of the brain
  - Dorsal-lateral Pre-frontal Cortices
- Working memory organized in the Theta and Alpha bands of frequencies
  - Theta: 3-8 Hz
  - Alpha: 8-13 Hz
Working memory and cognition

- Working memory performance and capacity goes down as cognitive load increases
- Working memory is independent of task and data.

What is Cognition, anyway?

- The process of conscious thought - often referring to information processing during the development of concepts, ideas, or decisions.
- Cognitive Load - The load imposed on working memory during instruction and reasoning.
- Cognitive Load Theory
  - Germaine load
  - Intrinsic load
  - Extraneous load

[Chandler and Sweller Cognition and Instruction 1991]
Germane Cognitive Load

“Learning arithmetic for the first time”

- Constant for the entire experiment
Intrinsic Cognitive Load

“Difficulty of 2x5 vs 382x8732”

- Dependent on task at hand
- Constant for each trial instance
Extraneous Cognitive Load

Dependent on how the data is displayed for the user.

$35 \times 30 = ?$

$35 \times 30 \underline{???}$
Cognitive Load in Box Plot Visualization

- Germane Load
- Intrinsic Load
- Extraneous Load
- Working Memory Capacity
- Working Memory Performance
User studies with cognition

- User studies use timing as a surrogate to measure difficulty
  - Time alone isn’t enough
  - Am I measuring efficacy of a visualization or familiarity with a specific user interface?
- A user study’s underlying goal is to answer the question “How hard must people think to complete a task?”
  - Subjective data is confounded by ego and uncertainty
- Cognitive measures enable exploration of working brain states
The User Study in Detail

- Given 2 randomly parametrized normal distributions, determine which has higher variance
  - Visualization method for each chosen randomly
A trial epoch

New Trial Onset  Epoch Start  Epoch End
Baseline  Trial

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A trial epoch
Data Acquisition

- Collected Data
  - 16 channel EEG @ 128 Hz
    - 10-20 sensor placement
  - Reaction Time @ ~10 kHz
    - Collected during interaction with high resolution timer
- Task difficulty
  - Computed based on parameters of distribution pair
  - All image types share a common difficulty distribution
Data Processing

- EEG
  - Segmentation via embedded marker trace
  - Trials separated into *resting state* and *trial epoch*
    - Resting state is first 1.0 sec of trial, stimulation epoch is the remainder
  
- Resting state and stimulation epoch transformed with Stockwell Transform to determine energy density change and frequency shift

[Stockwell, *DSP 2007*]
Cognitive Load

- Relies on gravity (weighted mean) frequency

\[ f(\omega) = \frac{\sum_{i=0}^{N-1} I_{\omega(i)} f_{\omega(i)}}{\sum_{i=0}^{N-1} I_{\omega(i)}} \]

- Combine change in gravity frequency and it’s power

\[ \omega \quad - \text{frequency band in question} \]
\[ f_{\omega(i)} \quad - \text{frequency at bin } i \]
\[ I_{\omega(i)} \quad - \text{energy density at bin } i \]
Cognitive Load

• Comparing to inter-trial baseline measurements helps eliminate practice effects

\[ \Delta |f(\omega)| = |f_t(\omega)| - |f_b(\omega)| \]

• Load-per-trial relies on the frequency shift modulated by the respective powers

\[ L(t) = \Delta |f_t(\alpha)| f_t(\alpha) - \Delta |f_t(\Theta)| f_t(\Theta) \]
Results

- Spatial location of the sensors is important!
Results

• Spatial location of the sensors is important!
  – Use gaussian weights to average sensor contributions

• Gaussian set to encompass closest sensors within the first std. deviation
Results
Conclusions

• Brain activity monitored by (wireless) EEG is capable of determining cognitive load.
  – Used for determining visualization efficacy.

• Complexity of the task and visualization methods in the study make experimental design difficult.
Future Directions

- Evaluate other visualization techniques
  - Color, dimensionality, etc.
- Investigate other cognitive controls
  - Confidence and certainty
  - “Visual” working memory - supplemental processing in visual cortex
  - Supplemental motor cortex activity - pre-cognitive motion planning and assessment
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• Questions?