Near to the Brain: Functional Near-Infrared Spectroscopy as a Lightweight Brain Imaging Technique for Visualization

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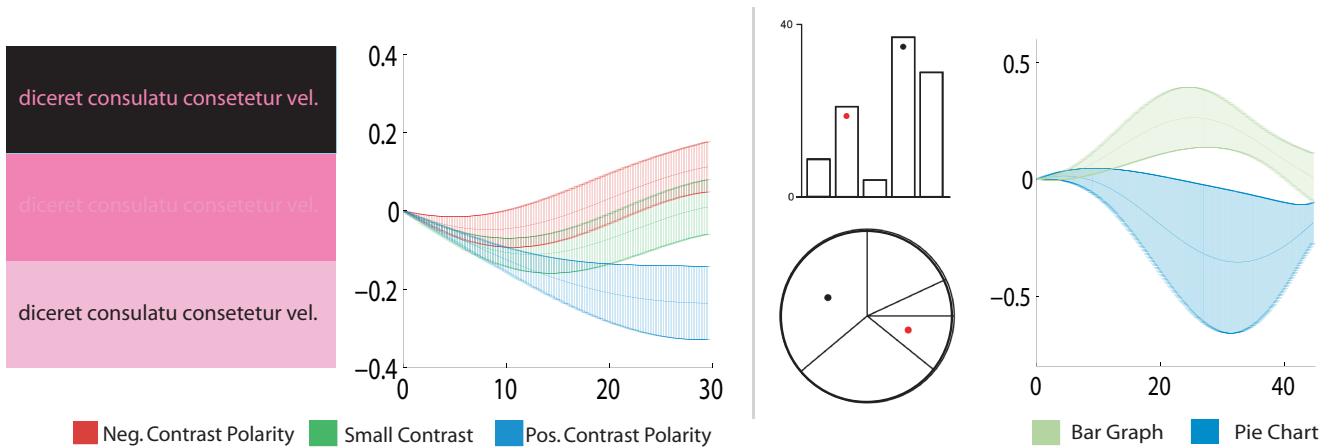Tufts University
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Figure 1: (Left) Activation in the prefrontal cortex while subjects performed a visual search task under different brightness contrast conditions. The brain activity plot is the mean change in deoxygenated hemoglobin over 130 trials of each condition (13 participants, 10 trials of each condition). The x-axis represents time (in seconds) over the course of a single trial. The y-axis is in micromolars and roughly represents activation levels. Finally, the width of the line represents standard error at each time point. (Right) Activation levels during angle and position judgment tasks in pie charts and bar graphs. The brain activity plot is the mean chance in deoxygenated hemoglobin over 36 trials of each condition (3 participants, 12 trials of each condition).

ABSTRACT

In order to better understand the user and visual interface, it is crucial to also understand human cognitive processes. Unfortunately, these processes are traditionally difficult to monitor without the use of cumbersome or expensive brain imaging equipment. In recent years, functional near-infrared spectroscopy (fNIRS) has emerged as a brain imaging technique that is both lightweight and easy to set up. In this paper, we demonstrate the potential of fNIRS to examine current visualization techniques and influence the design of visual interfaces. To validate fNIRS as a tool for visualization research, we present two studies based on previous work in brightness contrast in visual search and angle vs. position comparisons in form. Our results indicate there are significant and unintuitive cognitive differences in the prefrontal cortex during visual search tasks of positive and negative contrast polarity. Furthermore, we are able to differentiate between angle and position comparisons under specific experimental conditions. Finally, we outline the potential of fNIRS to give objective, continuous, and near real-time feedback of brain activity in future visualization research.

1 INTRODUCTION

Understanding human perceptual and cognitive processes has long been acknowledged by researchers in visualization and visual analytics as a core mission of the community. If one can observe a user's mental processes while viewing and interacting with a visualization, one can better evaluate the efficacy of visual interfaces, design new visual representations, and develop novel interaction techniques.

Unfortunately, observing a subject's cognitive processes when using a visualization has proven difficult. Use of successful brain sensing technologies such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) has been limited due to cost, cumbersome set-up, or movement artifacts that interfere with the signal.

Functional near-infrared spectroscopy (fNIRS) is an emerging technology for brain imaging being developed as an alternative to EEG and fMRI. It is lightweight, low-cost, non-invasive, easy to set up, and relatively robust with respect to movement artifacts. fNIRS uses near-infrared light to measure concentration and oxygenation of blood in the tissue at depths of 1-3cm [7]. Light is injected into the forehead in the near infrared range (650-900 nm), where it is diffusely reflected by the scalp, skull, and brain cortex. By measuring the light returned to the detector, researchers are able to calculate the amount of oxygen in the blood, as well as the amount of blood in the tissue. Since changes in blood flow and oxygenation indicate activation levels in the brain, much like fMRI, we can use fNIRS to measure activity in localized areas of the brain.

As a result, fNIRS has increasingly been used in the human-computer interaction (HCI) community for studying cognitive processes in real-world environments. Researchers have used fNIRS to identify verbal and spatial working memory [2], preference [3], emotion [6], interruption [5], and response inhibition [2].

We chose to replicate perceptual studies with quantifiable results to explore the fitness of fNIRS in a visualization context. By comparing our results with the known results of the studies, we believe that it provides a baseline for potential research with fNIRS and lends credibility to more exploratory studies in the future.

Figure 2: (Left) An fNIRS probe with five light sources and one detector. (Right) A headband holds two fNIRS probes in place on a study participant's forehead.

2 STUDY 1: CONTRAST AND VISUAL SEARCH

Studies suggest that increasing the contrast in first-order perceptual features improves performance on search tasks [4]. As an example, light text on a dark background is more difficult to read than dark text on a light background and the minimum luminance contrast between foreground and background color should be about 27 units (CIELAB lightness) [8]. Because contrast and visual search have such widespread implications in visualization, we believe that it is a prime research area to test the experimental validity of fNIRS in visualization research.

Following work by Zuffi et al., we used a visual search task in which participants search for occurrences of a character within a body of text (in this case, the letter 'e'). Text and background colors were selected for specific differences in brightness levels, using the HSB color model, to create three contrast conditions for visual search: *small contrast, large contrast with positive polarity, and large contrast with negative polarity*.

- **Hypothesis:** fNIRS can measure differences in visual search between the small and large brightness contrast conditions, as well as the positive and negative contrast polarity conditions.

During the course of one 30 second trial, participants saw 10 phrases of pseudo-text, each for a 3 second interval. The phrases, which consisted of 5 words each, were randomly selected from a body of *lorem ipsum* text. Participants were asked to visually scan each phrase as it was presented to them and press the space bar on the keyboard each time they saw the letter 'e'. Participants were shown 10 trials of each condition.

Our results, demonstrated in Figure 1, indicate that there are measurable differences in activation in the prefrontal cortex between the three conditions. Although these differences were expected, it is surprising to observe that the cognitive footprints vary most dramatically between positive and negative polarity conditions, with lesser distinction between small and large contrast levels. It is important to note that it is difficult to compare task workloads exclusively from looking at fNIRS readings. We can make observations about *activation* in the prefrontal cortex, but that activation might not correlate to overall workload in the brain.

3 STUDY 2: FORM AND SPATIAL WORKING MEMORY

In their landmark paper, Cleveland and McGill [1] demonstrated that judgment tasks relying on position along a common scale are more accurate than judgment tasks that rely on angle. Their experiment, based on comparisons in bar graphs and pie charts, created a baseline for visualization work in the study of form.

- **Hypothesis:** fNIRS can measure differences in spatial working memory between percentage judgments in bar graphs and in pie charts.

In our version of Cleveland and McGill's experiment, participants were shown slides with a pie chart or bar graph every 3.75 seconds. However, instead of making percentage estimates of a smaller graph section (marked by a red dot) to a larger graph section (marked by a black dot) in the current slide, participants compared a smaller section in the current slide, to a larger section in the *previous* slide. This variation of the 1-back task - a test used by psychologists to induce working memory - requires participants to maintain the mental image of graph sections between slides. By taxing their spatial working memory, it gives us a better opportunity to observe differences in activation between conditions. Each trial lasted 45 seconds and showed 12 slides, resulting in 12 comparisons over the course of the trial. Participants were shown 12 trials of each condition - pie chart and bar graph.

Early results indicate that our hypothesis holds. By looking at Figure 1, we can see that there are significant differences in fNIRS signals during participant interaction with bar graphs vs. pie charts that are likely caused by varying loads on spatial working memory.

4 CONCLUSION AND DISCUSSION

In the first study, we used fNIRS to capture contrast differences in visual search conditions. We found differences between negative contrast polarity and positive contrast polarity which were significantly more striking than difference in high contrast and low contrast conditions. These results raise interesting questions about the impact of contrast polarity in visualizations. Are there cognitive effects that could impact a user's experience with a visualization, either positive or negative, that have not been aptly captured in behavioral studies? In addition, we believe that this study can be extended to investigate other visualization questions about optimal design for legibility, visual search, and reduction of visual clutter. In the second study, we saw evidence that we can distinguish between angle and position judgments in bar graphs and pie charts. We believe that similar setups can be used to examine interactions in more complex graphical layouts and forms where behavioral measures may be difficult to extract.

Based on our findings, we propose that fNIRS can offer similar benefits to visualization researchers and practitioners as those experienced by the HCI community. fNIRS can give passive information about users as they perceive, cognitively digest, subjectively experience, and interact with visualizations.

REFERENCES

[1] W. S. Cleveland and R. McGill. Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods. *Journal of the American Statistical Association*, 79(387):531, Sept. 1984.

[2] L. M. Hirshfield, R. Gulotta, S. Hirshfield, S. Hincks, M. Russel, R. Ward, T. Williams, and R. J. K. Jacob. This is Your Brain on Interfaces : Enhancing Usability Testing with Functional Near-Infrared Spectroscopy. In *CHI 2011*, 2011.

[3] S. Luu and T. Chau. Decoding subjective preference from single-trial near-infrared spectroscopy signals. *Journal of Neural Engineering*, 6, 2008.

[4] J. Robson. Spatial and Temporal Contrast-Sensitivity Functions of the Visual System. *Journal of the Optical Society of America*, 56(8):1141–1142, 1966.

[5] E. T. Solovey, F. Lalooses, K. Chauncey, D. Weaver, M. Scheutz, A. Sassaroli, S. Fantini, P. Schermerhorn, and R. J. K. Jacob. Sensing Cognitive Multitasking for a Brain-Based Adaptive User Interface. In *CHI 2011*, 2011.

[6] K. Tai and T. Chau. Single-trial classification of NIRS signals during emotional induction tasks: towards a corporeal machine interface. *Journal of neuroengineering and rehabilitation*, 6:39, Jan. 2009.

[7] a. Villringer and B. Chance. Non-invasive optical spectroscopy and imaging of human brain function. *Trends in neurosciences*, 20(10):435–42, Oct. 1997.

[8] S. Zuffi, C. Brambilla, G. Beretta, and P. Scala. Human Computer Interaction: Legibility and Contrast. In *14th International Conference on Image Analysis and Processing (ICIAP 2007)*, number Iciap, pages 241–246. Ieee, Sept. 2007.