Using Passive Input to Adapt Visualization Systems to the Individual

Daniel Afergan
Tufts University
afergan@cs.tufts.edu

Evan M. Peck
Tufts University
evan.peck@tufts.edu

Remco Chang
Tufts University
remco@cs.tufts.edu

Robert J.K. Jacob
Tufts University
jacob@cs.tufts.edu

Abstract
Personalizing the design of an interface to the individual has emerged as a difficult problem. People are composed of long-term personality traits and short-term cognitive states that can both positively and negatively influence interaction with an interface. In this paper, we propose the use of performance metrics and physiological measures to evaluate the user's interaction with an interface and adaptively calibrate its design to the individual. We then identify three types of visual display systems that could benefit from this adaptation.

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Adaptive interfaces, visualization, fNIRS, visual design

ACM Classification Keywords
H.5.m [Information interfaces and presentation (e.g., HCI)]: Miscellaneous.

Introduction
Designers typically create one standardized interface template, even though their final product may have a target audience that spans a wide range of cultures, experiences, and skills. While many interfaces attempt to address this diversity through customization options, a general audience often lacks the expertise to know which set of selected options will maximize his or her experience

given a unique set of abilities, skills, and needs. While there are few tools that aid users in aligning these individual needs with the design of the interface, we believe that an intelligent system could monitor behavior and cognitive state to assess which presentation formats are most effective and cater the visual design to the individual's strengths.

The idea of calibrating the user interface to accommodate an individual's skillset has existed for decades in HCI. For example, Gajos et al. [2] found improvements in performance by adapting to the user's preferences and physical abilities. While the system built by Gajos et al. catered to users with differing physical capabilities, our objective is to cater to users' mental traits or states which may cause them to perceive and process the user interface differently from other users. Additionally, many systems hinge on accurate elicitation of user preference or ability *before* interaction with the interface. We believe that these adaptations could also be made passively during the course of natural interaction with the system.

Unfortunately, behavioral metrics do not always reflect the user's mental processes, which renders observing cognitive state during interaction difficult. Obtaining psychological profiles of users can also be challenging, as they require an explicit time-investment from the user and surveys may lose their relevance as the user's cognitive state changes over time. As a result, we propose that the use of physiological sensors may circumvent some of these problems by accessing the body's natural response to mental state. For example, brain oxygenation, heart rate variability, and galvanic skin response have been correlated with user states such as cognitive load and engagement.

When coupled with performance metrics, we propose that these sensors can be used as passive input to three types of systems that adapt and personalize visual content to the user: 1) **fixed display systems** that modify the visual representation of information on the screen, 2) **adaptive back-end systems** that modify the interaction mechanism of design elements already on the screen, and 3) **dynamic visualization systems** which do not impact the current design, but cater future visual displays for the individual. In this paper, we discuss work in HCI and Visualization that builds toward personalized visual interfaces and expand on our categorization of adaptive systems.

Individual Differences and Performance

User performance with an interface can be impacted by a number of individual cognitive differences. Cognitive load, the amount of short-term working memory engaged during a task, affects how much visual information a user can process. Cognitive traits such as spatial and perceptual abilities may affect how a user interprets and understands a visualization. Toker et al. [6] found that perceptual speed, verbal working memory, visual working memory, and user expertise all affect efficiency and satisfaction for users interacting with bar graphs and and radar graphs. In addition, personality traits have been linked to changes in performance in visual systems. For example, Ziemkiewicz et al. [7] showed that locus of control, a user's sense of control over external events, affected adaptation to visual layouts with containment metaphors and list-like menus.

Physiological Sensors and User State

Physiological measures can be used as passive input to an adaptive system by unobtrusively assessing the user's mental state. While traditional brain-computer interfaces (BCIs) or biocybernetic systems use physiological signals as input to directly control an application (to move a cursor/object, select an option, or other intentional action), these signals can also be used to passively modify

a scenario by determining a user's level of mental effort, emotional state, and motivation [1]. Fairclough et al. found that brain measures (via EEG) correlate with mental load and systolic blood pressure (SBP) correlate with engagement. Other research has shown that frustration and boredom correlate to features of heart rate variability (HRV) and galvanic skin response (GSR), while immersion and concentration correlate to features of HRV [3].

An Example: fNIRS in Visual Design

To demonstrate how physiological sensors can help illuminate personal preferences or performance differences in a visual interface, we used fNIRS brain sensing to explore interaction in benchmark visual designs - bar graphs and pie charts [4]. In a memory-intensive task, we observed that half of all participants believed that pie charts were more mentally demanding, while the remaining participants believed that bar graphs were more mentally demanding, and that these workload differences are reflected in the fNIRS signal.

Although we did not investigate the underlying cause of the differences observed between participants, we were able to identify which visual design reduced workload for the user by analyzing the fNIRS data. This highlights an important advantage of physiological sensors: they allow evaluators to circumvent the psychological or demographic profiling of participants that might be necessary to fully optimize performance to an individual.

We also found that traditional performance metrics of speed and accuracy were not reflective of the user's mental demand. While performance was identical across graph types, it is very likely that participants were working harder to achieve the same level of accuracy on one of the two graphs. Physiological sensors may be able to record
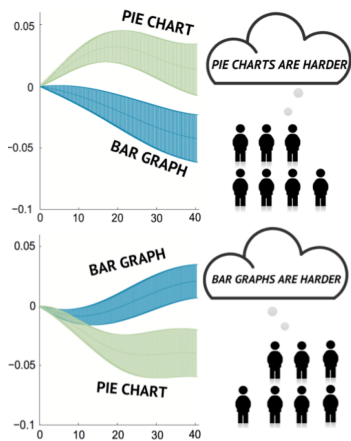

Figure 1: In a memory-intensive task, we found that graph difficulty differed between people and that fNIRS brain sensing captured this difference.

differences between people where traditional behavioral metrics may not.

Adapting Visualization Systems

We propose that there are three ways to combine an adaptive interface with performance and physiological metrics: fixed displays, adaptive back-ends, and dynamic views.

In a **fixed display**, we monitor a user's physiological data and use that to filter or emphasize the information on-screen according to a user's cognitive state. This can be done via methods such as changing the peripheral data or layering of information on a display, and may aid the focus of the user by highlighting critical information at critical moments. Constantly updating the entire interface and changing the display format would be jarring and unsettling for users, disrupting their ability to form cohesive mental models of the system.

Instead, we can subtly modify elements on screen which are inactive in order to clarify the display for the user. Here, we can leverage the high temporal resolution of physiological sensors. Rather than evaluating the interface as one cohesive unit, we can identify moments in time in which the user's cognitive state is modified and associate them with areas of the user interface. This allows for the adaptation of sections of the visualization that are no longer in use, thereby minimizing disruption.

In a static display with an **adaptive back-end**, the main display stays consistent, however, actions triggered by interacting with on-screen elements may be modified. The system may take control of elements such as timing, control, or actions of elements that are currently being displayed, change the effects of input devices, or change the meaning of future commands. Solovey et al. [5] used

fNIRS to detect when a user was in a state of multitasking and controlled a robot based on this signal, finding an increase in performance and decrease in measures of self-reported workload. Cognitive state can also be used to influence the format of query results or incoming data.

In a **dynamic visualization system**, the user is constantly being fed new information with little expectation of its incoming format (for example, the results of a search engine). In this scenario, physiological sensors would monitor user state as people naturally interact with information in their working environments, tagging visual designs with metrics such as workload or engagement. Over time, an intelligent system could compare the user's state across different visual designs, and slowly gravitate towards interfaces that elicit better performance and cognitive measures.

For applications where users manually select the display of information (such as Excel or Tableau), the system could recommend visualizations that would maximize the user's engagement or performance, prioritizing their placement in the user interface [7]. The system would also try to infer the user's preference and performance for interfaces that the user had not interacted with yet and use this as a guide. In addition to changing the overall format of visual designs, methods such as low-pass filters or edge bundling can help reduce the complication of a data visualization.

Creating a general framework that allows user interface designers to personalize a visual system regardless of the type of display allows greater personalization and can increase performance. By monitoring the user in all three types of systems, one can create passive adaptive systems that adapt in real-time to the user's cognitive abilities, personality, and cognitive state.

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