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Improving HCI with Brain Input: Review, Trends, and Outlook

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ABSTRACT

In the field of HCI, researchers from diverse backgrounds have taken a broad view of application domains that could benefit from brain signals, both by applying HCI methods to improve interfaces using brain signals (e.g., human-centered design and evaluation of brain-based user interfaces), as well as integrating brain signals into HCI methods (e.g., using brain metrics in user experience evaluation). Recent advances in brain sensing technologies, new analysis methods, and hardware improvements have opened the door for such research, which will accelerate with the increased commercialization of wearable technology containing brain sensors. In this monograph, we examine brain signals from an HCI perspective, focusing on work that makes an HCI-related contribution. We pursue three main goals. First, we give a primer for HCI researchers on the necessary technology, the possibilities, and limitations for using brain signals in user interfaces. Second, we systematically map out the research field by constructing a taxonomy of applications, input paradigms, and interface designs. For this purpose, we reviewed more than 100 publications in major HCI conferences and journals. Finally, we identify gaps and areas of emerging work to lay a foundation for future research on HCI for and with brain signals.

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Introduction

Emerging research is providing more practical brain measurement tools as well as greater understanding of brain function. This process will continue through international investments in brain research as well as the commercialization of wearable technology containing brain sensors. These developments open up many research directions that until recently seemed unachievable, but that could soon drastically change our relationship with technology and with each other.

People have been imagining this future for decades. As long as there have been computers, there has been a desire to integrate one's thoughts directly with them. This integration promises improvements in numerous facets of life (e.g., communication, memory, mobility, learning, entertainment, etc.).

As the technology progressively comes into contact with human users, new challenges and opportunities arise that are central to human–computer interaction (HCI). Available brain sensing technology allows us to draw conclusions about a person's cognitive states and processes, for example by providing non-invasive access to the electrical activity measured through sensors on the skull. Thus, brain sensing offers a window into the user's internal cognitive processes that could inform the design of interactive systems.

In this review, we use the term *brain input* to refer to the use of brain signals as input to an interactive system (to be differentiated from input going into the brain). Continuous brain signals can augment interface evaluation metrics such as task completion time, error rate and subjective feedback to provide a fuller picture of the dynamic state of an individual during HCI. They can also be used in real-time as input to an interactive system, but have characteristics that are fundamentally different from conventional input devices. New input paradigms and interaction techniques are needed for effective and worthwhile use of brain signals that also preserve user values such as privacy, security and safety. These important design considerations will play a key role in future adoption of brain sensing for solving real-world problems and for use by a wider audience.

Consequently, since 2008, brain-related publications have had a stable presence at the ACM CHI conference and in the broader set of primary HCI conferences and journals. To date, over 100 articles employing brain sensor data have been published in HCI-focused venues, tackling HCI questions related to brain sensing and brain interfaces. These papers are diverse in goals, methods, analysis, and reporting practices, due to the interdisciplinary nature of HCI research and the fact that the use of brain signals as computer input is still in its infancy.

Despite this, there is insight to be gained by looking back at the path this research has taken thus far and to identify areas where the studies share common ground. Of particular interest is how these papers build on, but collectively differ, from the more established field of traditional brain-computer interfaces (BCIs), which have historically focused on technical aspects, such as signal processing and machine learning, to provide a communication channel for patients unable to communicate otherwise. As HCI work expands and broadens the reach of brain signals to new application areas, it is a good time to identify common practices and themes that have emerged in this work and that will drive the future research paths in HCI.

In existing HCI work on using brain signals, there are clusters of frequent application domains, control paradigms, and neural processes used, as well as unique examples that stand out. An underlying challenge is that such investigations require knowledge about recording and processing neural signals, real-time processing and classification of the data, integration into a non-trivial application, as well as experimental paradigms to train and test the systems under realistic conditions. Accordingly, a considerable number of publications concentrate only on parts of this chain, such as the mental state assessment, but leave out others, such as the actual testing of a quantifiable usability improvement. Surprisingly, while many groups are working on similar aspects of this research, there are still only limited shared resources, such as executable paradigms, data sets, and processing pipelines.

The goal of this review is to bring together resources and insights about this evolving field from an HCI perspective. Because its foundations come from diverse disciplines (neuroscience, biomedical engineering, machine learning, traditional BCIs, as well as human–computer interaction), it can be difficult to find resources all in one place for gaining necessary background, or for discovering the state-of-the-art. We aim to provide an entry point on the diverse approaches and methods, and to synthesize the body of existing work to identify trends and emerging research questions that would be of interest to HCI researchers and students. Over the course of this review, we will outline the fundamentals of designing, building and evaluating interactive systems using brain signals. We will discuss steps to improve methods of re-using and reproducing existing results to unlock new and more complex designs for brain input paradigms. Where applicable, we will provide pointers to work that thoroughly covers relevant topics and will give more attention to areas where such resources do not yet exist.

In particular, with the rise of research on brain signals in computing, other recent reviews have covered related areas. Because the field is complex and heterogeneous, these unsurprisingly focus on different areas than this review. Ramadan and Vasilakos (2017) concentrate on using brain input for active control, mostly for the support of disabled individuals. Similarly, Rezeika *et al.* (2018) focus on active control interfaces for text entry. In contrast, Aricò *et al.* (2018) review systems which focus on user state monitoring in the wild. The Brain–Computer Interfaces Handbook (Nam *et al.*, 2018) is a comprehensive textbook that brings together many aspects of real-time brain input for active control and passive user state monitoring. All of these books and reviews are written from the perspective of the traditional BCI community. Early steps to connect the BCI research to HCI were taken in Tan and Nijholt (2010), but much work has emerged in the ten years since that was written. Our monograph will refer the reader to relevant sections of these related surveys and reviews, instead of providing redundant resources.

The rest of the monograph is organized as follows. Sections 2–4 review and characterize existing literature on the foundations and broader context of using brain signals, discussing different HCI application domains that use these methods, and finally presenting definitions and examples of the main paradigms used in HCI for brain input. Section 5 explains many of the cognitive processes measured and used in HCI research. Sections 6 and 7 are technology-centered and introduce different architectures and development tools to design applications which use brain signals. They also present the fundamentals of the most important brain sensing technologies. Section 8 introduces HCI-centered evaluation methods, as well as generalizability and reproducibility considerations of using brain signals in a scientifically sound and sustainable way. Sections 9 and 10 then discuss future research directions and the strengths and limitations of brain signals as input with currently available technology.

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