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Psychophysiological Measures of Human Cognitive States Applied in Human Computer Interaction

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Abstract

This paper reviews psychophysiological measures applied in Human Computer Interaction (HCI) by mainly focusing on studies related to human cognitive states. Although they have their own disadvantages, psychophysiological measures provide a promising way of user understanding to areas that seek "a sixth sense" for user psychological changes like HCI. We first briefly present the related literature and the major cognitive state assessment measurements. Then, fundamentals of psychophysiological measures are focused in-detail. We provide detailed information concerning their diagnosticity and sensitivity to human cognitive processes in table form. Finally, the paper discusses latest applications and point on the possible future directions.

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1. Introduction

We live in a ubiquitous computing age in which humans are surrounded by different computing systems such as computers, various interactive devices and embedded computing technologies. As well as its numerous advantages, such a life brings extra problems for humans. This might be attributed to the fact that traditional design approaches do not meet the cravings of modern information hungry devices anymore and managing information conveyed through these devices has been gradually becoming heavier [9]. Fortunately, we have advanced cognitive capabilities that enable us to cope with these problems. However, these capabilities show limited performance in reality and therefore they needed to be carefully exploited and even supported if possible.

In order to mitigate these problems, Human Computer Interaction (HCI) researcher focus on producing computing systems that are 1) more usable (cause lower mental workload and stress), 2) satisfactory (provide a pleasant user experience) and 3) adaptable (act according to user's needs and context). However achieving these purposes requires a deep and multidimensional user understanding. Research shows that psychophysiological measures, although they have their own limitations and weaknesses, have the potential to meet such a user

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understanding [19].

Psychophysiological measures provide an unobtrusive and implicit way to determine the user's affective or cognitive state on the basis of mind-body relations. Actually, they are physical signals of human body that are generated as a response to psychological changes and measured by special equipments in real-time.

There are numerous types of psychophysiological measures in the literature such as Electroencephalogram (EEG), Heart Rate Variability (HRV) and Electro Dermal Activity (EDA) [8]. In Table 1, we provide detailed information about the leading psychophysiological measures in the literature with their addressing cognitive states and selected strengths or weaknesses.

In this paper, we mainly focus on psychophysiological research related to human cognitive states in HCI. In Section 2, we review the literature concerning psychophysiological measures both in HCI and in different areas. Section 3 focuses on the fundamentals of psychophysiological measures and their relation with human cognitive states. Section 4 provides a brief introduction concerning the applications of psychophysiological measures in different fields of HCI. Finally, future directions and the conclusion are given in Section 5 and Section 6.

2. Related Literature

Psychophysiological measures have been receiving an increasing attention in different research and practice areas over the past decades, including Ergonomics, Human Factors, Automation Systems and Military or Life-critical Control Systems (power plants or warships). Most of the research pertaining to psychophysiological measures in these areas focuses on the mental workload assessment methodologies. Their findings are quite important for this study because mental workload is a concept directly related to human cognitive states.

Among these studies, Kramer's review is an important study that essentially focuses on psychophysiological aspects of mental workload assessment [5]. It contains in-depth information about the nature, selection criteria and the addressed psychological processes of the measures. Another useful review is the study of Farmer and Brownson [6]. It's a newer review than Kramer's study and includes highly practical information about mental workload assessment measures through a real project. Finally and as a recent study, Cain provides a detailed review that covers many aspects of metal workload assessment, including the detailed description of psychophysiological and other types of workload assessment methodologies in the literature and, previous remarkable reviews [7].

Especially since last decade, methods based on psychophysiological measures have also been popularized in different fields of HCI. These measures are also frequently named as physiological measures in the literature. In this paper, we chose to use the former term "psychophysiological" because we think it better expresses the measures by emphasizing on their psychological side with the prefix "psycho".

Today, a considerable literature exists concerning psychophysiological measures in HCI. If we first look for the important scientific proceedings; we see three recent workshops conducted within ACM SIGCHI conferences. The first one is the "Physiological Computing" workshop in 2002 [14] and the second one is the "Brain-Computer Interfaces for HCI and Games" workshop in 2008 [15]. The last workshop related to psychophysiological measures was conducted this year and had a meaningful name parallel to its purposes, "Brain, Body and Bytes: Physiological User Interaction" [10]. It aimed to attract researchers on an emerging area called Psychophysiological Computing and combine the findings of Physiological Computing and Brain-Computer Interfaces.

These workshops are like huge papers that give us the ability to see both the state of the art of technology and future potentials. Besides, there are important review papers that address the psychophysiological measures in HCI like Allenson and Fairclough's study. This is a comprehensive review that provides detailed information about previous research and contains a research agenda [19]. Another important and recent study is the review of Fairclough that addresses the fundamentals of psychophysiological measures [18]. It focuses intensively on the different aspects of psychophysiological computing system development.

However, a good understanding of these two studies (especially the second one) requires a piece of background knowledge about the psychophysiological research. As an alternative, Park's study may be a suitable preliminary reading to understand the basic characteristics and potential of psychophysiological measures for HCI studies [1]. There are also different reviews that focus on the applications of psychophysiological measures in specific fields of HCI such as Ganglbauer et al.'s review in User Experience Evaluation [2], Kivikangas et al.'s review in Game Research [3], and Bethel's et al.'s review in Human Robot Interaction [4]. These reviews are important information sources for future works because they spark new research challenges by specializing the subject into specific fields.

3. Psychophysiological Measures and Cognitive State Assessment

This section is concerned with the fundamentals of psychophysiological measures and cognitive state assessment. We first briefly explain other methods that are used for cognitive state assessment in the literature and then discuss the bases of psychophysiological measures, including definitions, advantages, disadvantages and application guidelines. There are three types of measurements that are used in cognitive state assessment, performance measures, subjective measures and psychophysiological measures [5].

These measurements are generally mentioned with cognitive load [2] or mental workload assessment in the literature [6, 7]. According to the point of view, as well as they can be used in the same meaning, their meanings may show differences. For example, cognitive load is a concept associated with working memory in cognitive load theory [20]. Mental workload, on the other hand, is a more problematic and multidimensional concept that does not have a widely accepted definition. It is both related to task demands and the capabilities, motivation and state of user [5]. In this paper, by means of the term "cognitive state" we indicate the state of human cognitive processes and resources such as perception, attention, cognitive effort, engagement, working memory, arousal, stress and fatigue.

Table 1. Psychophysiological measures and addressed psychological processes

Measures	Diagnosticity & Sensitivity	Strengths & Weaknesses
Event Related Brain Potentials (ERP)	• The P300 component is sensitive to variations in mental workload [5]. • ERP has a high temporal precision and sensitive to phasic and stimulus or response-related changes.	• ERP is sensitive to electrical fields produced by other physiological systems such as heart, eyes and muscles.
Electroencephalography (EEG)	• EEG is able to determine low or high perceptual and cognitive processes [2]. It can also be used to monitor the state of alertness and task engagement [5, 19]. • It has a high temporal precision and sensitive to phasic and tonic changes [3, 5].	• Very sensitive to biological and electrostatic artifacts as well as hardware related interferences (electrodes) and it's not very suitable for user experience evaluation [2].
Electro Dermal Activity (EDA)/Galvanic Skin Response (GSR)	• GSR is linearly correlated with arousal [2]. It's also a measure of stress [1] and frustrations [4]. • Its temporal sensitivity is poor, only tonic changes [3, 4, 5]	• Less sensitive to noise and less ambiguous than facial muscle (facial EMG) and heart activity (ECG) [3].
Cardiovascular Measures/Heart Rate (HR) and Heart Rate Variability (HRV)	• HR is sensitive to cognitive demands, time restrictions or uncertainty [19]. It's also sensitive to attention and correlated with arousal [1] • HRV is used as a measure of mental workload [1]. It also is used for assessing the positive or negative valence of an experience [2].	• Because the heart and circulatory system is regulated by many different bodily processes, interpreting the signal's relevance to the game context can be challenging [3].
Blood Pressure (BP)	• BP tends to increase under conditions of active coping and patterns of ECG and BP may be used to differentiate between humans in a state of challenge and a state of threat [19]	• It may be used in the evaluation of critical system interfaces and the design of computer games.
Electromyrogram (EMG)	• EMG is a good indicator of motor preparation for movements [19]. • Facial EMG is able to identify emotional valence [1].	• EMG is sensitive to noise such that bad contact between skin and electrodes and confounding sources of muscle activity, speaking and other social communication [1].
Eye Movements (fixations, saccades, gaze and blinks)	• Eye blink rates and duration yield meaningful information about task demands and level of fatigue [19]. • Eye gaze is a direct measure of cognitive interest [9].	• It's a good metric for interface evaluation and usability testing.
Pupil Diameter	• Pupil dilation is corralled with mental workload [2]. • It's an index of global changes in information processing [5]. • It also responds to emotional valance [19].	• Hard to apply in practical context because eye reacts to different light conditions, which almost impossible to anticipate and difficult to calculate outside of the controlled environments [2].
Respiration	• It's a measure of task demands [19]. It's also used for negative valance and arousal [1].	• Respiration changes affect EDA and cardiac measures. This change can be controlled using appropriate preparation and analysis steps within a well controlled setting [1].

3.1. Performance Measures

Performance measures are based on the overt performance of users like error ratio and task completion time. They can be classified into two major types: primary-task measures and secondary-task measures. These measures provide an objective and real-time assessment for user cognitive state. However, they are one-dimensional and should be customized according to the task. Although secondary-task measures are widely used, they may suffer from intrusiveness and lack of user acceptance [22].

3.2. Subjective Measures (Rating Scales)

Subjective measures depend on the user's perception on tasks [5]. They are influenced directly from the user characteristics like answering style, social desirability, interpretations of questionnaire or limits of memory [3]. Their real-time usage is not possible because they usually taken after the activity. Subjective measures can be one-dimensional or multi-dimensional.

3.3. Psychophysiological Measures

Psychophysiological measures are physiological responses of human body to psychological manipulations [8]. Actually, these responses are physical signals that make possible to determine humans' psychological processes by monitoring their bodily changes. Thus, psychophysiological measures provide a new way of user understanding for research and practice areas that seek "a sixth sense" for users' (or operators') psychological state (affective or cognitive) like Human Computer Interaction (HCI).

There are numerous psychophysiological measures in the literature. In this paper, by combining the findings of different studies and especially related reviews (Section 2), we present the leading psychophysiological measures in Table 1 with their sensitivity and diagnosticity information and, their major weaknesses or strengths.

Psychophysiological measures are grouped according to the controlling nervous system. Human nervous system falls into two parts, Central Nervous System (CNS) and Peripheral Nervous System. CNS consists of brain, brain stem and spinal cord. The leading measures related to CNS are Electroencephalography (EEG), Event Related Brain Potentials (ERP) and Electrooculography (EOG). Peripheral nervous system, on the other hand, contains all the remaining parts of the human nervous system. It has two subsystems, somatic and autonomic.

While somatic nervous system is responsible for the activation of voluntary muscles, autonomic nervous system (ANS) is responsible for controlling the involuntary muscles and internal organs. The leading measures of the ANS are Heart Rate (HR), Heart Rate Variability (HRV), Pupil Dilation, Eye Movements, Galvanic Skin Response (Skin Conductance) and Electromyogram (EMG). Autonomic nervous system also has two components, Sympathetic (SNS) and Parasympathetic Nervous Systems (PNS). SNS is responsible about the mobilization of body for emergencies and PNS maintain bodily resources.

3.3.1. Advantages

Psychophysiological measures have 6 important advantages. These are objectivity, multidimensionality, unobtrusiveness, implicitness, continuity and responsiveness.

- *Objectivity:* By means of objectivity it's possible to make assessments that do not depend on the user's perception [3]. Objectivity is an important property that increases the reliability of a measurement technique.
- *Multidimensionality:* Multidimensional measures are able to provide different faces of user state [5]. You can clearly observe in Table 1 that psychophysiological measures are sensitive to different cognitive processes of humans with changing levels.
- *Unobtrusiveness:* Although psychophysiological measures require the placement of electrodes on the body, they don't directly interfere with user tasks like "secondary task measures". Therefore, they are considered as unobtrusive measures.
- *Implicitness:* By comparing the "primary task measures", psychophysiological measures do not require the measurement of overt performance [12]. They provide the necessary information implicitly (covertly).
- *Continuity and Responsiveness:* Psychophysiological measures are continuous signals and therefore they can be

used in real-time [5]. They allow researchers to examine both short-term (phasic) and long-term (tonic) bodily reactions [11]. Thus, observing psychophysiological changes when they occur in response to manipulations of user is possible.

3.3.2. Disadvantages

Psychophysiological measures have several disadvantages. We categorize them under three groups such as special equipment disadvantages, data quality and interpretation disadvantages and, unnaturalness disadvantages.

- *Special Equipment Disadvantages:* Psychophysiological signals are measured by using special equipments and these equipments may be costly according to capabilities of the purchased system. Besides, different electrodes attached to body are used in these measurements. The selection and correct placement of them are crucial to acquire noise free data. Therefore, sufficient attention and time should be given to personnel training and device maintenance [3].
- *Data Acquisition and Interpretation Disadvantages:* Psychophysiological measures are mostly weak electrical signals and may be highly susceptible to noise [13]. Therefore suitable filtering techniques should be selected and applied to data. Besides a number of them are very vulnerable to confounding factors like ambient lightning (pupil dilation), power grid (ERP), and body movement (ECG). These factors should not be omitted; otherwise misleading results will be inevitable. Data interpretation is another problem for researcher and engineers. It's because of that psychophysiological measures produce large amount of hard-to-analyze data.
- *Unnaturalness Disadvantages:* Especially in laboratories, the environment is sufficiently artificial and unnatural. With advances of recent technologies portable and wireless solutions are possible for some measures like EEG, GRS and HR. if not; electrodes are attached to user by cables and this causes the user movements to be constrained and break the naturalness of the interaction

3.4. Application Guidelines

When psychophysiological measures are applied either in controlled laboratory or in real environments, there are many issues that must be considered. Especially in real environments, problems are much more complicated because of the disadvantages given in the previous section, particularly the ones regarding the data quality. Controlled environments, on the other hand, cause the interaction to be artificial (unnaturalness). While the users are asked to behave naturally when they are connected to electrodes, experimenters hope to obtain results that show their natural/real behavior [2].

Generally, the first problem of a psychophysiological application is selecting one or possibly more psychophysiological measure suitable to the desired cognitive state. Kramer proposes five fundamental criteria in order to make this selection, including sensitivity, diagnosticity, intrusiveness, reliability and generality of application [5]. You can find a larger list in Cain's study. Besides, Zwaag et al. provide several guidelines for the implementation of psychophysiological methods [13]. Fairclough, on the other hand, provides a detailed study about the development of computing systems based on psychophysiological measures [18].

4. Applications of Psychophysiological Measures

Psychophysiological measures have been applying to many types of application in HCI. Girouard et al. categorize these types under three groups, 1) evaluation applications, 2) adaptive interface applications and 3) direct (or natural) input mechanisms [10]. Psychophysiological measures as direct input mechanisms, especially for physically disabled people, have been the major concern of Brain-Computer Interfaces (BCIs). Much of the work in BCIs aimed to improve the life of patients with neuro muscular disorders [14]. This situation has started to change recently. The idea of controlling computers with thought and its potential applications for healthy people seem to be an attractive area of research in the future.

Actually, psychophysiological measures are implicit interaction channels that provide plenty of information about the user internal processes. In their interesting study, Ikehara and Crosby used this information and presented a "psychophysiological authentication" method that enables to continuously verify the user's identity without interrupting him or her [12]. They propose to use the pressure level applied to a computer mouse as an authentication modality. In their design, first authentication is approved as usual by one of classical authentication methods (passwords or biometrics). After that, users' identity continuously verified by means of mouse pressure patterns. Users are asked to reenter the password only if anomalies are detected in these patterns.

Evaluation applications of psychophysiological measures consist of two major types including usability evaluation and user experience evaluation [2]. Mental workload assessment studies are good examples of in-depth usability evaluation applications in the literature. Besides, there are specific studies that focus on the relation between traditional usability metrics and psychophysiological measures [17]. User experience evaluation, on the other hand, focuses on the emotional aspects of user interfaces.

Bellur and Sunder observe user's psychophysiological responses to specific structural features of user interfaces [11]. They measure the cognitive activity caused by these interface features using EEG (to detect attention), IBI (to detect mental workload), GSR (to detect arousal) and EMG of facial muscles (to detect valance). Their results suggest that more interactive features does receive less attention from the users (effects of interactivity), slow download speed cause higher arousal (arousal from slow refresh speed) and also drag cause phasic shifts in mental workload with respect to sliding and rollover.

The applications of psychophysiological measures in adaptive systems are quite numerous including interruptibility estimation and regulation of notifications, adaptive avatars, adaptive learning systems etc. Badly timed notifications or interruptions causes stress, anxiety and performance lost [9]. Therefore, they are needed to be regulated according to the user's availability to communication or interruptibility. Chen and Vertegaal use HRV (to detect mental workload) and EEG (to detect physical activity) to regulate notifications come from a mobile phone [16]. They specify four cognitive states for users and allow them set up their mobile phone, instant messenger and email program accordingly.

Wray et al., in their adaptive learning system, aim to tailor the practice through student cognitive states in different ways [20]. They address the motivational aspects of the learning or improving the diagnosis of student behavior. If an inappropriate load, arousal or affect that do not match to the expected pattern of student behavior is detected, the system will be able to warn the teacher or the student. For example, they investigate the engagement of students by using student's arousal level as a measure of cognitive engagement by using ECG. If a low level arousal is detected, it is considered as a cue of students' low cognitive load and attention. That means the student is not sufficiently engaged in the practice.

Additionally, psychophysiological measures have applications in specific fields of HCI like Game Research [3] and human robot interaction [4]. Game research focuses on the gamers' experience with a game or aims to adapt the game according to the gamers changing affective or cognitive state. In human robot interaction, on the other hand, it's aimed to understand humans' approaches to robots (their experience and reactions) or to offer different services appropriate to psychological states of humans.

5. Future Directions

Psychophysiology investigates the mind-body relations of humans and provides a large literature about physiological bases of human psychological processes [8]. Most of the findings of this literature have not been applied in Human Computer Interaction (HCI) yet [10]. We think that analyzing these findings from an HCI point of view and looking for ways to apply them in HCI are challenging and also promising research areas. Besides, there are many psychophysiological measures available in the literature. Investigating their suitability for different HCI problems is another future study.

Unfortunately, there are no one-to-one relations between psychophysiological measures and human psychological processes. Each measure has its own ability to represent different psychological processes, advantages and disadvantages. For accurate measurements and successful applications, psychophysiological measures are needed to be combined most of the time. This is particularly important for real life applications. Consequently, seeking appropriate measure combinations, overcoming implementation shortcomings and developing new interaction methods based on these combinations may be given as important future studies.

The number of applications that exploits psychophysiological measures in HCI is in a constant flux. As well as the usability and user experience evaluation, they have been receiving an increasing attention from specific fields of HCI like mobile interaction, game research, human robot interaction and ambient intelligence. Naturally, each field has its own problems and promises future works special to these problems. Psychophysiological measures may be used to understand the characteristics of a particular problem, to optimize a product or software, and to provide adaptive solutions in these fields.

6. Conclusion

This paper has provided a review on psychophysiological measures that are used for cognitive state assessment in Human Computer Interaction (HCI). Modern HCI applications like user experience evaluation and adaptive user interfaces requires unobtrusive, implicit and real-time methods that provide multidimensional information about user affective or cognitive state. A great deal of studies shows that psychophysiological measures have the potential to meet these requirements. They are able to present different dimensions of human psychological processes with changing levels. However, psychophysiological measures are needed to be carefully implemented. Especially, data acquisition and interpretation disadvantages prevent them to be implemented in real environments. We think that, although they do not completely disappear, these problems will be alleviated in time and psychophysiological measures will be easier to research and more applicable.

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