Measuring the Usability, Efficiency and Effectiveness of CAAD Tools and Applications

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Abstract. *Computer Aided Architectural Design (CAAD) decisions and judgments have been at the heart of architectural design practice. Despite the increasing popularity of computer aided design applications, measuring the decision making of designers empirically remains elusive. Past research claiming usefulness of the CAD has relied largely on anecdotal or case studies that are vulnerable to bias. The study reviews results of prior investigations. The relatively few laboratory experiments report hardly any empirical results regarding the measurement of CAD decision making. The study provides an overview of the literature of existing measurement methods that have been used in psychology and neuroscience to assess individual variations in design making, and highlight these different measurement methods' strengths and weaknesses. We conclude with a comparative evaluation of the different measures and provide suggestions regarding their constructive use in building realistic theories of designer's decision making measurement.*
Keywords. *Measurement; usability; efficiency; effectiveness; CAAD.*

INTRODUCTION

The last two decades have witnesses a proliferation of software, applications and interfaces of Computer Aided Architectural Design (CAAD) applications. One of the self-evident statements about CAAD applications is that their application in the design process can improve the design quality (Attia et al., 2013). During the concept development of architectural designs, complex systems, technologies and diverse disciplines come together as the concept develops. With the help of different CAAD applications, including Building Information Modeling (BIM) applications and Building Performance Simulation (BPS) applications and other applications, designers test their designs for their feasibility and take substantial decisions during their interaction with applications and interface technologies. The International Standards Organization (ISO) issued more than 50 standards related to software usability and Human Computer Interaction (HCI) (Bevan, 2006). Various other descriptive theoretical usability frameworks were also suggested by Nielsen and Mack (1994). To begin with, HCI-related ISO standards are primarily shaped around four topics: quality in use, product quality, process quality and organizational capability. Thus, there are many confirmatory references that support this statement in introductory section of most papers and books on the subject. But there is arguably less solid evidence for the claim that those applications are more likely to improve the quality and future performance of a building. There are few studies that demonstrate their utility by offering visible empirical evidence related to the integration of CAAD support into design practice.

Often, CAAD applications have been evaluated only as proofs of concepts. In fact, measuring the quality of use of CAAD applications has not been thoroughly addressed in the past in the AEC industry. There is insufficient investigation of quality of use and functionality in practice and research. Concerning the CAAD applications evaluation "quality in use" stands out as the most relevant quality characteristic described in ISO/IEC 25000 Series (2006). In this study (Figure 1), we adopt the definition of quality in use that states that "the extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use" (ISO/IEC 25062, 2006).

Therefore, a deeper understanding of this aspect may reveal promising opportunities for progress in the CAAD domain.

Current methods of measuring and evaluating the quality of use of CAAD applications include both subjective and objective techniques. However, the subject matter of usability and effectiveness measurement can be approached from three vantage points:

Behavior measures that track actions and decisions.

Physiological measures that tracks measures physiological manifestations of emotion and biomarkers (indicator of a biological state) during, and after each decision.

Self report measures are developed and applied by a middleperson. Researcher can ask subjects after the use of an application through quality of use evaluation methods.

The most common methods include self-reports through questionnaires, interviews, and think-aloud protocols, and objective reports through observational video analysis (Pak and Verbeke, 2011; Seffah et al., 2006). Despite the lack of sufficient case studies on self report measure in relation to CAAD applications this study in mainly focused on the second vantage point that addresses the physiological measures of CAAD usability, efficiency and effectiveness.

Physiological measurement is a research field that measure and monitor a range of physiological parameters usually in major organ systems. Physiological measures have the potential to be used as indicators of mental effort and stress (Wilson, 2001). Psychologists use physiological measures that enable researchers to get at participants states of mind- before, during and after each decisions (Mandryk et al., 2006). It aims to analyze the link between participants' physiology and their reactions to study stimuli. Revealing how biology changes in response to changes in probability and value options. Since there are many parameters to describe the usability, efficiency and effectiveness of CAAD applications – and many different ways to perceive such a complex subject, quality of use measurements derives generally by subjective intuition and experience – rarely based on objective parameters and scientific knowledge. However, physiological data have not been employed to identify user experience states such as efficiency effectiveness and satisfaction. Physiological measurements can fill this gap between subjectivity and objectivity by measuring and evaluating the quality of use of CAAD applications in practice.

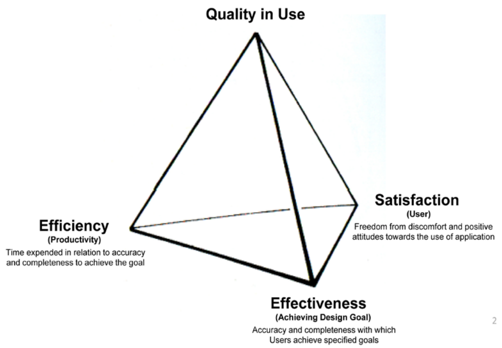

Figure 1
Illustrating the three metrics for measuring the quality of use of CAAD applications. Adapted from (Pak and Verbeke 2011) and (ISO/IEC 25062, 2006).

The use of physiological measurement in our field can help develop empirically ascertained knowledge in connection with experiences from architectural design practice (Emmett et al., 2011).

This paper provides an overview of the literature of existing measurement methods that have been used in psychology and neuroscience to assess individual variations in design making, and highlight these different measurement methods' strengths and weaknesses. Our ultimate goal is to create a methodology for the objective evaluation of CAAD, as rigorous as current methods for entertainment technologies. To provide an introduction for readers unfamiliar with physiological measures we review major studies research on using physiology to measure the usability, efficiency and effectiveness of applications and technologies in the field of HCI. Then we briefly introduce the physiological measures and describe how these measures are collected and explain their inferred meaning. Finally, we discuss the potential of applying physiological techniques and empirical measurement techniques on the quality of use of CAAD interfaces and applications.

METHODOLOGY

This paper first reviewed existing measurements techniques and relevant studies in the International Journal of Architectural Computing, the Cumulative Index of Computer Aided Architectural Design, the conference proceedings and International Journal of Building Performance Simulation. Then we conducted are review on the biomarkers tracking in the field of Human-Computer Interaction (HCI). This includes the publications of the International Journal of Human-Computer Studies, the Conference proceedings on Human Factors in Computing Systems. The second part of the review focuses on using psychophysiological techniques to measure user experience with computer technologies and applications. It classifies these various measurement techniques, equipment and physiological parameters. The paper then explains how these various techniques can be used for measuring the usability, efficiency and effectiveness of CAAD applications in the AEC industry.

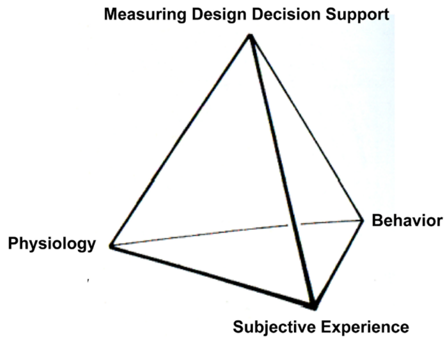

Figure 2
The three combined approach for measuring the quality of use of CAAD applications.

LITERATURE REVIEW

Although there is no previous research on using physiology to measure the quality of use of CAAD applications in architectural design, it has been used in other fields as a measure of assessment and evaluation.

The field of HCI has been concerned with optimizing the relationship between humans and their technological systems. By technological systems we mean applications and interfaces to geometrical modeling, rendering and performance simulation in particular real time, interactive, and highly realistic environments for design concept development and experimentation. The quality of the applications and interfaces is not only judged based on how it affects user performance in terms of productivity and efficiency but how it affects the decision making and leads to robust and high quality designs. Therefore, the emotional influences on judgment and choice and the well-being of the user in relation to the decision making are important. Psychophysiology demands that an understanding of human behavior is formed from the combination of three fundamental measures, shown in Figure 2: 1) behavior, 2) physiology, and 3) subjective experience (Wastell and Newman, 1996).

Wastell and Newman (1996) used the physiological measures of blood pressure (systolic and diastolic) and heart rate in conjunction with task performance and subjective measures (Likert scales) to determine the stress of ambulance dispatchers in Britain as a result of switching from a paper-based to a computer-based system. When normalized for job workflow, systolic reactivity showed that dispatcher stress increased more for increases in workload in the paper-based system than in the computer system. This was consistent with non-significant results obtained from the post-implementation questionnaires.

Ward et al. (2002; Ward and Marsden, 2003) collected galvanic skin response (GSR), blood volume pulse (BVP), and hart rate (HR) while users tried to answer questions by navigating through both good and poorly designed web pages. No significant differences were found between users of the two types of web pages. However, different trends were found between the two groups when the data were normalized and plotted. Subjects of the good designed website tended to relax after the first minute whereas users of the poor designed website showed a high level of stress for most of the experiment. This was recorded through increasing GSR and level pulse rate. These discrepancies between physiological and subjective assessment support the argument for a three-combined approach.

These studies collected both subjective measures and physiological data. In the domain of HCI, a few other researchers have also used HRV as an indicator of mental effort (Rowe et al., 1998; Rani et al., 2002). Partala and Surakka (2004) and Scheirer et al. (2002) both used pre-programmed mouse delays to intentionally frustrate a computer user. Partala and Surakka measured EMG activity on the face in response to positive, negative, or no audio intervention, while Scheirer et al. (2002) applied Hidden Markov Models (HMMs) to GSR and BVP data to detect states of frustration.

In the domain of entertainment technology, Sykes and Brown (2003) measured the pressure that gamers exerted on the gamepad controls while participants played Space Invaders. They found that the players exerted more pressure in the difficult condition than in the easy or medium conditions. They did not correlate the pressure data with any type of subjective report.

Although very little research has been conducted in the CAAD domain, results from the few studies in HCI and the more plentiful studies in the field of human factors are encouraging. The studies presented in this section each reveal how different physiological measures were successfully used in different work-related domains. As such, comparison across studies is difficult. Building an amount of knowledge surrounding the use of physiological measures in HCI evaluation is occurring, even though gradually.

RESULTS

Based on the literature review we classified the responses found in literature under three main categories:

Physiological Responses & Emotions

There has been a long history of researchers using physiological data to try to identify emotional states such as boredom, challenge, ease, engagement, excitement, frustration, difficulty and expertise and fun. William James first speculated that patterns of physiological response could be used to recognize emotion (Cacioppo and Tassinary, 1990). Recent evidence suggests that physiological data sources can differentiate among some emotions (Levenson, 1992). Among the most measured physiological responses are the galvanic skin response (GSR), electrocardiography (EKG), electromyography of the jaw (EMG), and respiration. Heart rate (HR) could be computed from the EKG signal, while respiration amplitude (RespAmp) and respiration rate (RespRate) could be computed from the raw respiration data. According to literature blood volume pulse data (BVP) was less used because the sensing technology used on the finger is extremely sensitive to movement objects. As most architects and designers operate computer mouse and keyboards, it isn't possible to constrain their movements. The measures we found in literature are listed in Table 1 and will each be described briefly including reference

Table 1
The three combined approach (Mandryk et al., 2006).

Signal	**Feature**	**Measure**
GSR	Mean skin resistance	Estimate of general arousal
	Mean of derivative	Average GSR variation
	Mean of derivative for negative values	Average decrease rate during decay time
	Proportion of negative samples in the derivative vs. all samples	Importance and duration of the resistance fall
Blood Pressure	Mean value	Estimate of general pressure
	Standard deviation	Estimate of blood pressure (in)stability
Heart Rate	Mean of heart rate	-
	Mean of heart rate derivative	Estimations of heart rate variability
	Standard deviation of heart rate	Average heart rate variation
Respiration	Main frequency computed having the highest energy	-
	Standard deviation	Variation of the respiration signal
	Maximum value minus minimum value	Dynamic range
Temperature	Mean value	Estimate of general temperature
	Average derivative	Average temperature variation

to how they have previously been used in technical domains.

Galvanic skin response: GSR is a measure of the conductivity of the skin. There are specific sweat glands that cause this conductivity to change and result in the GSR. Located in the palms of the hands and soles of the feet, these sweat glands respond to psychological stimulation rather than simply to temperature changes in the body (Stern et al., 2001). For example, many people have cold clammy hands when they are nervous. In fact, subjects do not have to even be sweating to see differences in skin conductance in the palms of the hands or soles of the feet because the eccrine sweat glands act as variable resistors on the surface. As sweat rises in a particular gland, the resistance of that gland decreases even though the sweat may not reach the surface of the skin (Stern et al., 2001). Galvanic skin response is a linear correlate to arousal (Lang, 1995) and reflects both emotional responses as well as cognitive activity (Boucsein, 1992). GSR has been used extensively as an indicator of experience in both non-technical domains (Boucsein, 1992) for a comprehensive review), and technical domains (Wilson and Sasse, 2000a; Wilson, 2001; Ward et al., 2002; Ward and Marsden, 2003).

Cardiovascular measures (Heart Rate): The cardiovascular system includes the organs that regulate blood flow through the body. Measures of cardiovascular activity include heart rate (HR), interbeat interval (IBI), heart rate variability (HRV), blood pressure (BP), and BVP. EKG measures electrical activity of the heart. HR, HRV, and respiratory sinus arrhythmia (RSA) can all be gathered from EKG. HR reflects emotional activity. It has been used to differentiate between positive and negative emotions with further differentiation made possible with finger temperature (Winton et al., 1984; Papillo and Shapiro, 1990). HRV refers to the oscillation of the interval between consecutive heartbeats. When subjects are under stress, HRV is suppressed and when they are relaxed, HRV emerges. Similarly, HRV decreases with mental effort, but if the mental effort needed for a task increases beyond the capacity of working memory, HRV will increase (Rowe et al., 1998). There is a standard medical configuration for placement of electrodes; two electrodes placed fairly far apart will produce an EKG signal (Stern et al., 2001), for example, placing pre-gelled surface electrodes in the standard configuration of two electrodes on the chest and one electrode on the abdomen of the user.

Respiratory measures: Respiration can be measured as the rate or volume at which an individual exchanges air in their lungs. Rate of respiration (RespRate) and depth of breath (RespAmp) are the most common measures of respiration. Emotional arousal increases respiration rate while rest and relaxation decreases respiration rate (Stern et al., 2001). Although respiration rate generally decreases with relaxation, startle events and tense situations may result in momentary respiration cessation. Negative emotions cause irregularity in the respiration pattern (Stern et al., 2001). Because respiration is closely linked to cardiac function, a deep breath can affect cardiac measures. Respiration is most accurately measured by gas exchange in the lungs, but the sensor technology inhibits talking and moving (Stern et al., 2001). Instead, chest cavity expansion can be used to capture breathing activity using either a Hall effect sensor, strain gauge, or a stretch sensor (Stern et al., 2001).

Electromyography: Electromyography (EMG) is a technique for evaluating and recording the electrical activity produced by skeletal muscles. EMG is performed using an instrument called an electromyography, to produce a record called an electromyogram. An electromyograph detects the electrical potential generated by muscle cells when these cells are electrically or neurologically activated. The signals can be analyzed to detect medical abnormalities, activation level, and recruitment order or to analyze the biomechanics of human or animal movement (Stern, 2001). The use of EMG on the face using surface electrodes has been used to distinguish positive and negative emotions.

In conclusion, each physiological response can identify different emotions. The best practice is to combine various physiological responses to evaluate the quality of use of CAAD applications. Another result of the literature review is the classification of the features and metrics extracted from different experimental physiology studies. We found the most important measurement techniques found in literature are:

Eye tracking systems: analysis and evaluation of visual perception;

Flashlight systems: analysis and evaluation of visual perception;

Biofeedback-Systems: survey of physiological data: (Impedance cardiographs, heart rate/variability, bio amplifiers, and transducer modules).

Subjective Responses

The literature review reveals that there is a variety of subjective evaluation methods that measures the quality of use of CAAD applications (Pak B., Verbeke, J., 2011). Some of these methods may be considered as more suitable to be utilized in the early stages of CAAD software development as they are relatively easy to conduct, efficient, effective and reliable; thus satisfactory.

Questionnaires and surveys: Questionnaires and surveys can be utilized for various purposes related to usability (ISO/IEC 25062, 2006). A common practice is the user satisfaction assessment. In the last thirty years, numerous user satisfaction questionnaires are developed and tested by established researchers. Most of these questionnaires are well-documented and publicly available. Therefore, conducting such studies is not so difficult. In addition, questionnaires are efficient tools for collecting information on user characteristics; which is essential for profiling the users and determining the possible influence factors. Furthermore, questionnaires can be conducted online, saving plenty of resources and making this method even more cost-effective.

Interviewing: Interviewing is another beneficial method which is often used as a follow-up measurement tool in combination with other methods (Shuy et al., 2001). When performed rigorously, interviews are useful for collecting information on users' experiences and ideas. In particular, follow-up interviews are highly complementary with task observation and questionnaire methods.

Think-aloud: Think-aloud is a reliable but not so cost-effective research method. It can provide critical insight into the users' thinking processes (Ericsson and Simon, 1993) and help evaluators to identify misconceptions. On the other hand, it takes a lot of effort and time to make a pilot study, design the experiment and build a coding scheme, conduct the real experiment, transcribe, segment and codify the verbalizations and perform statistical analysis.

In conclusion, each self reporting method can detect different user responses. The best practice is to combine various evaluation methodologies to evaluate quality of use of CAAD applications (ISO/IEC 25062, 2006).

Behavioral Responses

Task observation: To begin with, task observation is an effective method for evaluating how well the software facilitates users to accomplish a number of tasks. In this method, the evaluators choose around ten vital tasks to be completed by the representative users. These tasks are then given to the users in a preferably controlled space (such as a fixed test labs or rooms) and they are observed by the evaluator and/or a video camera. The evaluator times and records the specific indicators either during the test or after the test. This method can be performed with a limited number of participants. In an experimental study, Lewis (1994) found that only eight evaluators are sufficient to detect 95% of the problems with an individual detection rate of 0.45. In this context, task analysis is an easy-to-use method for evaluating the user and software performance, observing how the interactions are related to the relevant tasks and prioritizing possible functionalities.

Logging Users: Logging users' interactions is another effective usability evaluation method. The strength of this method comes from the fact that it can be applied to a large number of actual users (although analyzing them may take some time). In this sense, through logging, it is possible to find usability issues which cannot be revealed through observation. Moreover, use logs are valuable sources especially when combined with task observations and other collected data (Pak and Verbeke, 2011).

Observational video analysis: Observational video analysis is an observational technique that uses a naturalistic perspective relying upon material drawn from the first-hand experience of a software user, rather than in artificial or experimental conditions. It seeks to understand software environments and activities as they naturally occur, from the point of view of the users who use those applications, and usually involves quite lengthy periods of time using software. It is a useful approach to find out how a tool is used and how task are executed.

DISCUSSION AND CONCLUSION

Given the tremendous potential of CAAD applications substantial research efforts are justified with a focus on one major research challenge: Highly interactive, intuitive and attractive interfaces can facilitate the creative architectural design process required.

CAAD applications are meant to facilitate creative design and educational processes through concept testing and experimentation. Promising concepts must be tested for their feasibility, performance and ability of realization. At this point decisions may have a substantial impact design. Therefore, it is crucial to base such decisions on validated and user friendly interfaces. With current interface technology, however, participants often spend a substantial part of their cognitive resources on understanding and controlling interfaces. Therefore, the effect of combing physiological, behavioral and subjective assessment support measures is significant. The ideas of possible research initiatives that can apply physiological measures in correlation to subjective measures for the usability, effectiveness and effectiveness of CAAD applications:

- Emotional influences on judgment and choice
- Performance of CAAD decision making
- Trust in CAAD decision making

In the future work, we are looking to conduct experimental subjective and physiological tests for users using CAAD applications. It is expected that users' physiological responses correspond to their physiological responses. Studying the relationship between a physiological measure and subjective measure would be an empirical evidence to measure the quality of use an application or tool.

In conclusion, the field of human factors has been concerned with optimizing the relationship between humans and their technological systems. The quality of a system has been judged not only on how it affects user performance in terms of productivity and efficiency, but on what kind of effect it has it on decision making of the CAAD tool users. Although very little research has been conducted in the CAAD domain, results from the few studies in HCI and the more plentiful studies in the field of human factors are encouraging. The studies presented in this paper reveal how different physiological measures were successfully used in different work-related domains, however, the emerging nature of this technique means that there has been no standardization of task, domain, or measures in the CAAD domain. As such, comparison across studies is difficult. Building a corpus of knowledge surrounding the use of physiological measures for CAAD applications evaluation is occurring, albeit slowly. There is still a need for researchers from the AEC industry, who are interested in physiological techniques for CAAD applications evaluation, to create a research community in order to advance the fledgling field.

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