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WHERE DOES TAM RESIDE IN THE BRAIN? THE NEURAL MECHANISMS UNDERLYING TECHNOLOGY ADOPTION

*Où se loge le modèle TAM dans le cerveau ? Les mécanismes
neuronaux sous-jacents à l'adoption de technologie*

Completed Research Paper

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Abstract

Toward materializing the recently identified potential of cognitive neuroscience for IS research (Dimoka, Pavlou and Davis 2007), this paper demonstrates how functional neuroimaging tools can enhance our understanding of IS theories. Specifically, this study aims to uncover the neural mechanisms that underlie technology adoption by identifying the brain areas activated when users interact with websites that differ on their level of usefulness and ease of use. Besides localizing the neural correlates of the TAM constructs, this study helps understand their nature and dimensionality, as well as uncover hidden processes associated with intentions to use a system. The study also identifies certain technological antecedents of the TAM constructs, and shows that the brain activations associated with perceived usefulness and perceived ease of use predict self-reported intentions to use a system. The paper concludes by discussing the study's implications for underscoring the potential of functional neuroimaging for IS research and the TAM literature.

Keywords: NeuroIS, Cognitive Neuroscience, Technology Adoption, TAM, Brain Imaging, fMRI

Résumé

Ce papier aide à démontrer comment les outils d'imagerie neurofonctionnelle peuvent améliorer notre compréhension des théories en SI en mettant à jour les mécanismes neuronaux qui sous-tendent les construits d'adoption des technologies (utilité perçue et facilité d'usage perçue) en identifiant les zones du cerveau activées lorsque les utilisateurs interagissent avec des sites web qui diffèrent dans leur niveau d'utilité et de facilité d'usage.

Introduction

In recent years, there has been an explosion in the abilities of neuroscientists to study the functionality of the brain using functional neuroimaging tools that open the “black box” of the human brain by determining the location, frequency, and timing of brain activity with a high degree of accuracy. By directly asking the brain, not the person, functional neuroimaging tools allow an objective, reliable and unbiased measurement of thoughts, beliefs, and feelings and link them to human choices, decisions, and behavior. The field of cognitive neuroscience uses functional neuroimaging tools (e.g., fMRI, PET, MEG, EEG) to capture brain activations that underlie higher-order human functions (thoughts, beliefs, and decisions). The social sciences, such as economics, psychology, and marketing, have quickly adopted neuroimaging tools to make important advances in their understanding of social phenomena, and many interesting discoveries in these disciplines are rapidly emerging (e.g., Camerer, et al., 2005; Glimcher and Rustichini, 2004; Lee, et al., 2006; Zaltman, 2003). For example, Smith et al. (2002) challenged economic assumptions on the independence of payoffs and decisions, helping advance economic theory. In another study, Kuhnen and Knutson (2005) found that distinct neural circuits linked to anticipatory affect promote different types of financial choices and indicate that excessive activation of these circuits may lead to investing mistakes. Finally, Delgado et al. (2005) found that when subjects contrasted monetary gains and losses, the caudate nucleus was activated, which predicted the subject’s future behavior. In industry, Microsoft has started a research program on using EEG for task classification and activity recognition (Tan and Lee 2005). Also, the video gaming industry is using EEG-based headsets to observe the brain activity of users while playing video games (www.emotiv.com).

In the Information Systems (IS) discipline, there have been some recent attempts to explore the potential of cognitive neuroscience for IS research. Moore et al. (2005) and Randolph et al. (2006) used EEG to examine brain-computer interaction for handicapped patients. Dimoka, Pavlou, and Davis (2007) explored the potential of cognitive neuroscience for IS research, termed “NeuroIS.” The authors argued that the IS literature can first tremendously benefit by drawing upon the emerging cognitive neuroscience literature to inform IS phenomena. For example, Gefen and Pavlou (2008) drew upon the Neuroeconomics literature that showed that uncertainty and ambiguity span different areas of the brain to justify their hypothesized distinction between economic uncertainty and social ambiguity in online auction marketplaces. In particular, Dimoka et al. (2007) proposed how IS researchers can use functional neuroimaging tools to inform IS phenomena, offering the following set of opportunities for cognitive neuroscience to inform IS research:

- (1) Localize the neural correlates of IS constructs to better understand their nature and dimensionality;
- (2) Complement existing sources of IS data with objective brain data that are not subject to measurement biases;
- (3) Capture hidden (automatic) processes that are difficult to measure with existing measurement methods;
- (4) Identify antecedents of IS constructs by showing how IT stimuli (e.g., designs, systems) spawn brain activation;
- (5) Test the outcomes of IS constructs by showing how brain activation predicts decisions, choices, and behavior;
- (6) Infer causality among IS constructs by examining the timing of brain activations due to a common stimulus;
- (7) Challenge existing IS assumptions and enhance IS theories that do not correspond to the brain’s functionality;

Drawing upon these seven proposed opportunities (Dimoka et al. 2007), this paper focuses on the potential of cognitive neuroscience to inform the extensive literature on the Technology Acceptance Model (TAM) (Davis 1989) by examining how functional neuroimaging tools can enhance our understanding of technology adoption and use. There are many examples within the IS area of technology adoption and use for which cognitive neuroscience could offer valuable insights into relevant underlying brain structures and processes:

First, this study aims to identify where the two TAM constructs (perceived usefulness and perceived ease of use) reside in the brain. In doing so, it aims to shed light on their nature and dimensionality by examining how their neural correlates relate to what is already known in the cognitive neuroscience literature. As it is described later, the cognitive neuroscience literature has identified the role and functionality of many brain areas. Therefore, the neural mechanisms that underlie the TAM constructs can shed light on their nature and dimensionality if contrasted with what we already know from the cognitive neuroscience literature.

Second, this study aims to complement existing survey responses that measure the two TAM constructs with objective brain data. The purpose of this step is to identify the similarities and differences between survey responses

and objective brain data. Given that survey data may suffer from multiple measurement biases, such as subjectivity, social desirability, and common method bias, this study examines whether the objective brain data support the measurement of the TAM constructs. Neuroimaging data can complement self-reported data that may not fully reflect the underlying brain processes that underlie the TAM constructs, rendering a more complete and accurate picture of human behavior. Integrating survey and neuroimaging data gives the opportunity to triangulate among these two measurement methods. The study assesses the level of agreement in the classical survey responses of perceived usefulness and ease of use with the level of brain activation associated with the two TAM constructs.

Third, since functional neuroimaging tools can capture automatic processes that are not easily captured with verbal responses, this study aims to uncover brain areas associated with the two TAM constructs that are potentially “hidden.” The cognitive neuroscience literature promises to substantially expand the domain of applicability for TAM theories beyond controlled conscious processes to encompass the role of automatic unconscious processes. Functional neuroimaging tools can overcome blind spots in technology acceptance research regarding issues not easily studied through self-report questionnaire instruments, such as habit and automaticity, multitasking, attentional loads and switching, implicit learning, knowledge collaboration, and motivational goal self-regulation processes.

Fourth, it aims to examine how IT stimuli (specifically in this study, websites that differ on their manipulated level of usefulness and ease of use) can spawn activation in the areas associated with the TAM constructs, thus identifying potential TAM antecedents. This step can set the stage for identifying and testing additional TAM antecedents.

Fifth, this study aims to test whether the brain activation associated with the TAM constructs can explain intentions to use the system. This step can show whether the brain activations that underlie perceived usefulness and perceived ease of use can reliably predict intentions to use a system. This step can also set the stage for identifying additional consequences of the TAM constructs, such as decisions to use a system and actual system use.

Sixth, functional neuroimaging studies can examine the timing of the brain activations of the two TAM constructs to attempt to infer a causal interpretation between the two TAM constructs. While causality inference cannot be solely determined based on temporal precedence, the timing of the brain activations of the two TAM constructs can shed light on their timing in the brain.

Finally, this study aims to examine whether the findings from the neural correlates of the TAM constructs challenge TAM assumptions and help advance the TAM literature. In sum, we argue that the cognitive neuroscience literature and functional neuroimaging tools can advance knowledge of technology adoption and advance the TAM literature.

In terms of methods, the functional neuroimaging tool used is fMRI (functional Magnetic Resonance Imaging) because of its excellent spatial resolution that is vital for localizing the brain areas activated by the TAM constructs. The subjects were exposed to two websites that were manipulated to differ on their level of system usefulness and ease of use, and they were asked to respond to a set of measurement items on perceived usefulness and ease of use whilst in the fMRI scanner. These measurement items acted as the stimulus to induce the brain activation due to the manipulation of the two websites that differed on their level of usefulness and ease of use.

The results show that high levels of perceived usefulness activated the *caudate nucleus* and the *anterior cingulate cortex*, while low levels of perceived usefulness activated the *insular cortex*. In the cognitive neuroscience literature, the caudate nucleus and anterior cingulate cortex are activated due to the anticipation of a positive reward, while activation in the insular cortex is associated with intense negative emotions due to fears of loss. Also, perceived ease of use activated the *dorsolateral prefrontal cortex*. Higher levels of perceived ease of use correlated with the level of brain activation in the dorsolateral prefrontal cortex, an area involved with the sequential execution of operations during controlled processing. Finally, high intentions to use a website activated the ventrolateral prefrontal cortex (VLPFC) and the bilateral amygdala, while low intentions to use activated the left putamen. The VLPFC relates to intentions to engage in a behavior, while bilateral amygdala activation relates to prediction of a positive reward. Left putamen activation relates to realizing an error in reward prediction.

This study contributes to our knowledge and has implications for enhancing our understanding of technology adoption and use. It helps localize the neural mechanisms that underlie the TAM constructs, and it sheds light on their nature and dimensionality. It also complements existing survey responses with objective brain data, and it identifies hidden processes associated with intentions to use the system. The study also has implications for identifying antecedents of the TAM constructs, and also for showing that the brain activations due to the TAM constructs can adequately predict intentions to use a system. Finally, this study has implications for enhancing TAM theories by challenging assumptions about the linear and continuous measurement of the TAM constructs.

Literature Review

Basics of Cognitive Neuroscience

The field of cognitive neuroscience focuses on understanding the interaction between high-order human processes, thoughts, and behaviors with their underlying brain processes. The field focuses on the brain mechanisms and the localization of brain activity in response to certain stimuli that induce human processes, thoughts, and behaviors, measured with functional neuroimaging tools. Cognitive neuroscience covers individual and social perception, attention, memory, emotion, consciousness, executive functioning, and decision making. Most studies focus on identifying the functionality of specific brain areas that are activated by a specific stimulus, task, decision, or activity.

There are two major brain systems - the *prefrontal cortex* (higher cognitive processing), and the *limbic system* (emotional processing). The major areas of the prefrontal cortex are the dorsolateral (upper outer), ventromedial (lower middle), medial (middle), and orbitofrontal (above the eyes) cortices. The prefrontal cortex is activated in the planning of complex cognitive behaviors, such as problem solving, short-term memory, executive thinking, deciding between right and wrong, and orchestrating thoughts and actions in accordance with one's goals. The limbic system consists of the interior margins of the brain. The major regions of the limbic system are the amygdala, cingulate cortex, nucleus accumbens, and the hippocampus. The limbic system is primarily concerned with behaviors governed by emotional and affective responses (Lautin, 2001). It also shapes the formation of memory by integrating emotional states with stored memories of physical sensations.

Other important brain areas for human emotions are the dorsal striatum and the insular cortex. The literature has typically differentiated these two areas from the limbic system because they are considered more primitive. The dorsal striatum is formed by the caudate nucleus and the putamen. The *caudate nucleus* is innervated by dopamine neurons, which are activated when one receives an unexpected reward, with social cooperation, trusting intentions, and trust-building tasks. The *putamen* is activated for reinforcement learning and realization of error prediction. The left putamen relates to realizing that an error in a subject's prediction has occurred (e.g., McClure, et al., 2003; O'Doherty, et al., 2004). Finally, the *insular cortex* processes information to produce an emotional sensory experience, such as disgust, unease, and unfairness. It is also responsible for the integration of information about affective and reactive components of pain, and it belongs to the circuitry related to fear, loss, and anxiety. The anatomy and functionality of the prefrontal cortex and the limbic system is graphically illustrated in Appendix 1.

Review of Cognitive Neuroscience in the Social Sciences

Functional neuroimaging tools, such as fMRI have led to a better understanding of how humans make economic, social, and marketing decisions, deal with risk, uncertainty, ambiguity, and potential for loss, respond to rewards, search for and process product information, form utilities, respond to social influences, form product preferences, make purchasing decisions, trust or distrust, cooperate or compete, and predict others' behavior (theory of mind).

The cognitive neuroscience literature in the social sciences focused on inferring the brain bases of decision making, aiming to provide accurate models of how people make decisions (Sanfey, et al., 2006). The literature has identified the prefrontal cortex (mostly the orbitofrontal and the dorsolateral brain areas) (Ernst and Paulus, 2005) and the limbic system (mainly the anterior cingulate cortex and the amygdala) (McClure, et al., 2004a) as the major decision-making areas. The prefrontal cortex is responsible for the cognitive (thinking) aspect of decision-making, and the limbic system is in charge of the emotional aspect (Sharot, et al., 2004). Realizing that decision making has both a cognitive and an emotional component, Bhatt and Camerer (2005) showed that subjects whose brain activity exhibited good cooperation between these two areas were the most successful in strategic decision-making.

The literature also offers insights of the mechanisms involved when people increase their utility (the subjective value of a reward), and shape their behavior (Walter, et al., 2005). Knutson and Cooper (2005) and McClure, et al. (2004b) described the brain's reward circuitry as the caudate nucleus, the limbic system (nucleus accumbens, anterior cingulate cortex, and amygdala), and the orbitofrontal cortex. Caudate nucleus activation is correlated with the magnitude of an anticipated reward (Hsu, et al., 2005). The anterior cingulate cortex has also been associated with reward anticipation (Bush, et al., 2000; Murtha, et al., 1996). The amygdala (activated by intense emotions) is activated in response to both a prediction of a large positive reward (Hommer, et al., 2003) and the devaluation of a

higher expected reward (Gottfried, et al., 2003), and it has also been linked to the dynamic interaction between emotion and cognition in the decision-making process (Phelps, 2006). The insular cortex is activated due to intense negative emotions (Wicker, et al., 2003). Several studies have investigated the brain area that is linked to higher behavioral intentions (Okuda, et al., 1998; Petrides, 1994; Petrides, 1996). The ventromedial prefrontal cortex (VLPFC) was found to be activated when subjects had higher intentions to perform a specific task versus others.

The literature also examined that the anticipation versus the experience of rewards activates different parts of the brain; during anticipation the nucleus accumbens is activated whereas while experiencing the outcome the medial prefrontal cortex is activated (O'Doherty, et al., 2002). These findings closely correspond to the behavioral decision making literature (Kahneman, 2000), which also distinguishes between anticipated and experienced utility.

Conceptual Development

Application of Cognitive Neuroscience to Technology Adoption and Use

This section proposes how the cognitive neuroscience literature and functional neuroimaging tools can advance the literature on technology adoption and use. Given that this is the first attempt, to the best of our knowledge, to employ functional neuroimaging tools in IS research and particularly to the TAM literature, we follow an exploratory approach without specifying explicit a priori hypotheses. This actually follows the “data-driven” spirit of the cognitive neuroscience literature that allows the objective brain data to “speak for themselves.” Accordingly, the inductive interpretation of the observed brain data derives implications, draws conclusions, and forms theories.

Below we discuss how the cognitive neuroscience literature and functional neuroimaging tools can inform theories related to technology adoption of use, based upon the guidelines prescribed by Dimoka, Davis, and Pavlou (2007).

1. Localizing the neural correlates of TAM constructs to better understand their nature and dimensionality

The neural correlates of the two TAM constructs can potentially shed light on the nature of perceived usefulness and perceived ease of use. As reviewed earlier, the cognitive neuroscience literature has identified the brain areas that underlie many human processes and functions. Therefore, certain brain activations can be associated with certain processes and functions already shown by extant empirical studies in the cognitive neuroscience literature. Identifying where the two TAM constructs reside in their brain and linking their localization to the cognitive neuroscience literature can enhance our understanding of the nature of these constructs. Martin (2007) showed that humans have a dedicated brain circuitry for perceiving and knowing about tools. Perceptions of technology attributes may rely on the cortical areas that mediate uncertain object classification based on perceived attributes (Aron, et al., 2004; Grinband, et al., 2006).

Also, since the two TAM constructs may reside in multiple areas in the brain, knowledge of their neural correlates can shed light on their dimensionality. The fundamental research question is to identify (map) the neural correlates of the TAM constructs to qualitatively assess how the observed brain activations relate to processes already identified in the cognitive neuroscience literature.

2. Complementing survey TAM responses with objective brain data

Given that the two TAM constructs are typically measured with subjective survey scales, TAM critics have argued that the measurement of perceived usefulness and perceived ease of use may be subject to measurement biases, such as subjectivity bias, common method bias, and social desirability bias. By comparing the survey responses with the objective brain data obtained when users respond to the corresponding survey items for perceived usefulness and perceived ease of use, this study can test the similarities and differences between the subjective survey responses and the objective brain activations, and help identify whether the TAM constructs suffer from measurement error.

Since there is substantial work on measuring the TAM constructs over the last 20 years, we expect to see significant correlations between the survey measurement items that have been shown in the literature to capture perceived usefulness and perceived ease of use and the corresponding brain data that underlie these constructs. However, it is a useful exercise to compare the two sources of measurement to identify potential similarities and differences that could infer potential biases or problems with measurement.

3. Capturing hidden (automatic) processes that are difficult to measure with existing measurement methods

Traditional IS acceptance theories, such as TAM emphasize conscious (controlled) perceptions and intentions as determinants of use behavior to the nearly complete exclusion of unconscious (automatic) perceptions. This reflects the fact that TAM was built upon the theory of reasoned action (Fishbein and Ajzen 1975) and the theory of planned behavior (Ajzen 1991), which theorize conscious control of behavior. However, recent IS research has begun to focus on the role of habit on the post-adoption stage of usage where the behavior becomes more automatic and can be executed with less conscious attention. As technology adoption and use research increasingly focuses on automatic and habitual behaviors that relate to the post-adoption use of IT tools, NeuroIS can expand the domain of applicability for technology adoption theories beyond controlled conscious processes to encompass the role of automatic unconscious processes. The cognitive neuroscience research has been instrumental in clarifying the distinct neural circuits that underlie controlled versus automatic processing modes (e.g., Lieberman, 2007).

Traditional self-report methods are severely limited for measuring these relatively unconscious processes as they are less accessible to introspection. Functional neuroimaging substantially overcomes the limitation of self-reporting by permitting more direct and objective measurement of the brain activity involved in automatic processes. TAM research has gone beyond purely cognitive aspects of system use to examine the roles of affective determinants such as enjoyment, playfulness, flow, and anxiety. Bagozzi (2007) stresses the need to strengthen the theories of the role of emotions in TAM research. As the complex interplay between emotion and cognition becomes better understood in the cognitive neuroscience literature, IS researchers may be able to examine and integrate the role of emotions in technology adoption and use. This study thus aims to uncover hidden or unconscious processes that underlie the TAM constructs, thus potentially uncovering components not adequately captured by survey measurement items.

4. Identifying TAM antecedents by showing how IT stimuli spawn brain activation in identified TAM areas

This study examines how IT stimuli - websites that differ on their manipulated level of usefulness and ease of use - trigger activation in the areas associated with the TAM constructs, thus identifying how IT stimuli spawn activation in the identified TAM areas. TAM theorizes the role of cognitive appraisals of the IT artifact, such as judgments of relevance, quality and compatibility. This study examines how other antecedents of the two TAM constructs can be identified based on their potential to spawn activation in the areas where the TAM constructs reside in the brain.

Besides showing how experimentally manipulated IT stimuli induce activation in the brain areas that underlie the two TAM constructs, after identifying the neural correlates of perceived usefulness and ease of use, these brain areas can be the dependent variables that potential future IT stimuli will be tested on their potential to enhance perceptions of usefulness and ease of use. For example, IT designs and system prototypes can be tested on their potential to activate the "TAM" areas in the brain, thus objectively examining whether they have the desired effects.

5. Testing the outcomes of TAM constructs by showing how brain activation predicts behavioral intentions

The TAM literature has argued that perceived usefulness and perceived ease of use influence behavioral intentions to use a system. This study aims to test whether the brain activation associated with the TAM constructs can predict behavioral intentions to use the system under investigation, namely the website used to activate the TAM constructs. Besides showing that the brain activations associated with the TAM constructs predict behavioral intentions to use the system (measured with survey scales), this study aims to set the basis for identifying additional outcomes of the TAM constructs, such as actual behavior to use a system.

6. Inferring causality among IS constructs by examining the timing of brain activations

The TAM literature has also attempted to infer a causal interpretation between the two TAM constructs. While causality inference cannot be solely determined based on temporal precedence, the timing of the brain activations of the two TAM constructs can shed light on their timing in the brain.

7. Challenging TAM assumptions and enhancing TAM theories that correspond to the brain's functionality

Finally, the ultimate goal of this study is to integrate the empirical neuroimaging findings to examine whether any TAM assumptions are violated. By challenging existing TAM assumptions, this study aims to advance the TAM literature by shaping TAM theory to better correspond to the brain functionality.

Research Methodology

To identify the neural correlates of the two TAM constructs (perceived usefulness and perceived ease of use) in the context of e-commerce, we experimentally manipulated two commercial websites that differ in their utility and functionality and user friendliness. We used a real commercial website (Website 1) and a fictitious one (Website 2), and the experimental protocol was composed of three distinct stages (before, during, and after the fMRI session). Six normal individuals at the ages of 20-30 years old (mean=23) (4 male and 2 female) were recruited to participate.

First, before the fMRI session, the subjects were asked to browse each website for 15 minutes with the goal to purchase a specific digital camera. Website 1 is a popular, well-regarded, high-quality website with many products, extensive product descriptions and reviews, and superior product search capabilities. The fictitious Website 2 was custom designed with a few product offerings, lack of product search capabilities, and reduced product descriptions. To further manipulate the degree of perceived usefulness and ease of use, the subjects also received fictitious customer and expert reviews for each website that described Website 1 as a superb website with state-of-the-art search capabilities, sophisticated technical capabilities, and professional product descriptions; Website 2 was characterized as difficult-to-use website with few pictures and poor product descriptions. These ex ante experimental manipulations aimed at creating substantial contrast between the two websites in terms of their perceived usefulness and perceived ease of use. Manipulation tests conducted a priori with 12 respondents clearly showed that Website 1 was substantially superior to Website 2 in terms of perceived usefulness and perceived ease of use (both at $p < .01$).

Second, during the fMRI session in which the subjects were lying down inside the fMRI scanner, the IT stimuli were presented on a computerized digital projection screen placed in front of the subjects through a mirror. The subjects were randomly shown each of the two websites for 2 seconds, followed by a randomly-selected measurement item for perceived usefulness, perceived ease of use, and intentions to purchase (Table 1). The measurement items for both websites were randomly intermixed to more precisely target the corresponding constructs without causing halo or carry-over effects. Such intermixing has not been found to erode psychometric reliability and discriminant validity (Davis and Venkatesh, 1996). The website images were presented to subjects to induce the manipulations of the referent IT stimuli, while the measurement items were administered to induce brain activation specifically for each of the three focal constructs. Five seconds later, the subjects were shown the anchors of a 3-point Likert-type scale below the measurement item, and they were asked to select one of the three choices (1=Strongly Disagree; 2=Neutral; 3=Strongly Agree) by clicking on the corresponding button of a 3-button custom-made fiber-optic device. The measurement items (Table 1) were based on Davis (1989), and they were adapted to an e-commerce context (Gefen, et al., 2003; Pavlou, 2003). After the subjects clicked on their choice, the next randomly-selected measurement item was shown. Ten measurement items were used for each construct and each website.

Table 1. Sample Measurement Items for the Study's Focal Constructs for each Website

Perceived Usefulness
Website X was useful in purchasing this digital camera.
Website X was useful for getting valuable information about this digital camera.
Using Website X enabled me to find information about this digital camera quickly.
Website X improved my performance in searching this digital camera.
Using Website X enhanced my effectiveness in learning about this digital camera.
Perceived Ease of Use
Learning to use Website X would be easy for me.
My interaction with Website X would be clear and understandable.
Getting information about this digital camera from Website X would be easy.
It was easy to become skillful at using the Website X.
Overall, I found Website X to be easy to use.
Intentions to Use Website
Given the chance, I intend to purchase this digital camera from Website X.
Given the opportunity, I plan to purchase this digital camera from Website X.
If I wanted this digital camera, I would purchase it from Website X.
Given the need, I would buy this digital camera from Website X.

An important component of functional neuroimaging studies is to have appropriate control variables to “cancel out” irrelevant brain activation due to the visual stimuli, hand movement, and other sources of noise, and thus identify brain activation only associated with the intended stimuli. For the control variables, the subjects were shown each website for 2 seconds, and they were instructed to specifically press one of the three buttons of the custom-made fiber-optic device using a statement that closely resembled the study’s measurement items in terms of format type and length. Similar to the focal constructs, ten control statements were used for each website that were used to cancel out spurious brain activations, such as those associated with visual, auditory, motor, and other stimuli.

Third, after the fMRI session, subjects responded to the exact same measurement items on a traditional paper format on a traditional 7-point Likert-type scale. The purpose of this step was to compare the subjects’ survey responses during the fMRI session with their corresponding survey responses in a traditional paper format to test whether the unique fMRI environment or the required 3-point Likert-type format altered their responses (Phan, et al., 2004).

Data Analysis and Reporting

The analysis of the fMRI data was performed with the SPM2 freeware.¹ Whole-brain 3Tesla MRI data were acquired in a time-series of approximately 14min 20s to provide 20 contiguous 6mm thick brain slices and 430 images per slice state allowing the subjects to respond to approximately 60 measurement items with a gap of approximately 10s between measurement items.

In the first step of the data analysis, we contrasted the brain activations for each construct relative to the control variables for each website, aiming to localize the neural correlates of each construct while minimizing confounds. All brain activations were measured at the time the subjects were reading each measurement item (before posting their response). fMRI data are graphical images with a resolution of 256x256 pixels with each pixel reflecting activation on a continuous scale. The difference between the ‘experimental’ and the ‘control’ image reflected the activation due to the experimental scenario. As a first step, the brain images were analyzed and localized for each individual subject. Then, second-level one-sample t-tests were performed on the aggregate results to create random-effect group analyses for each construct. For each construct at the group level, statistical parametric maps were generated that displayed the t-value of each voxel (3D pixel) that met a $p < .05$ threshold.

In the second step of the data analysis, we tested the correlation of each subjects’ level of observed brain activation (measured in terms of t-scores obtained from the SPM software) for each construct with the subjects’ perceptual responses to each construct’s corresponding 3-item Likert-type measurement items (during the fMRI session), aiming to test whether each subject’s level of agreement to each construct correlates to the level of brain activation.

Table 2. Descriptive Statistics and Reliability of TAM constructs (Measurement Items during fMRI session)

Construct	Mean	STD	Reliability
Ease of Use (Website 1)	2.90	0.19	1
Ease of Use (Website 2)	2.35	0.81	0.93
Usefulness (Website 1)	2.92	0.18	0.83
Usefulness (Website 2)	1.56	0.59	0.94
Intentions to Purchase (Website 1)	2.98	0.04	1
Intentions to Purchase (Website 2)	1.03	0.24	0.76

In the third step of the data analysis, the level of the subjects’ agreement with the measurement items during the fMRI session was correlated with their responses on the paper format after the fMRI session, aiming to examine whether the responses during and after the fMRI session are highly correlated.

¹ The fMRI images were realigned to correct for motion artifacts. The resulting images were normalized to a standard stereotaxic space (Montreal Neurological Institute), and spatially smoothed with a 8mm full-width half maximum isotropic Gaussian kernel. The data were submitted to an event-related General Linear Model analysis, fitting a reference hemodynamic response function (hrf) to each event in the observed time-series data.

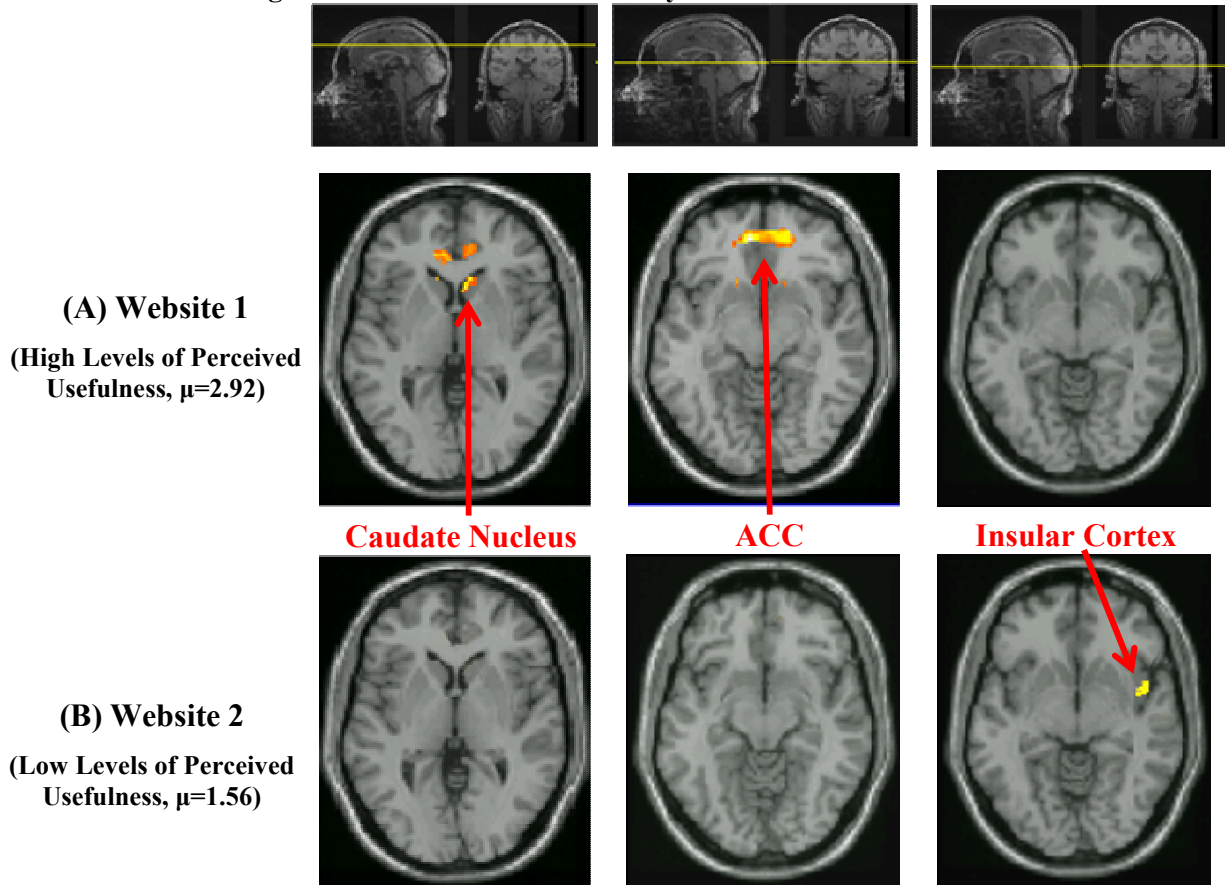
Results

The first stage of the analysis was to identify the neural correlates of perceived usefulness, perceived ease of use, and intentions to use a website. This stage included the comparison between the objective brain data and the survey measurement items, and the identification of potential hidden processes associated with the TAM constructs.

Neural Correlates and Findings for Perceived Usefulness

The manipulation of perceived usefulness was also successful with the subjects' responses since the self-reported perceived usefulness for Website 1 had a mean of 2.92 (3=Strongly Agree) while the mean for Website 2 was 1.56 (1=Strongly Disagree) ($p<.01$). The reliability scores for all constructs are shown in Table 2. As shown in Figure 1, the high levels of perceived usefulness for Website 1 activated the *caudate nucleus* and the *anterior cingulate cortex*, while the low levels of perceived usefulness for Website 2 activated the *insular cortex*.

Figure 1. Brain Areas Activated by Perceived Usefulness



In the cognitive neuroscience literature, the caudate nucleus is activated proportionately with the magnitude of an anticipated reward (Hsu, et al., 2005; Knutson, et al., 2005). The anterior cingulate cortex is related to reward anticipation (Bush, et al., 2000; Murtha, et al., 1996) and linking actions with their outcomes (Rushworth, et al., 2004). The insular cortex is activated by intense negative emotions due to the fear of loss (Wicker, et al., 2003).

The level of brain activation in the anterior cingulate cortex and caudate nucleus highly correlates ($p<.001$) with the subjects' responses to the measurement items of perceived usefulness for Website 1 (mean=2.92) versus Website 2 (mean=1.56). The level of activation in both the right (-.57, $p<.01$) and left (-.46, $p<.01$) insular cortex is negatively correlated with the subjects' low levels of agreement with the measurement items for perceived usefulness.

The responses to the measurement items of perceived usefulness during and after the fMRI session are very similar ($r=.92$, $p<.001$), implying no differences due to the fMRI setting and the number of anchors in the Likert-type scale.

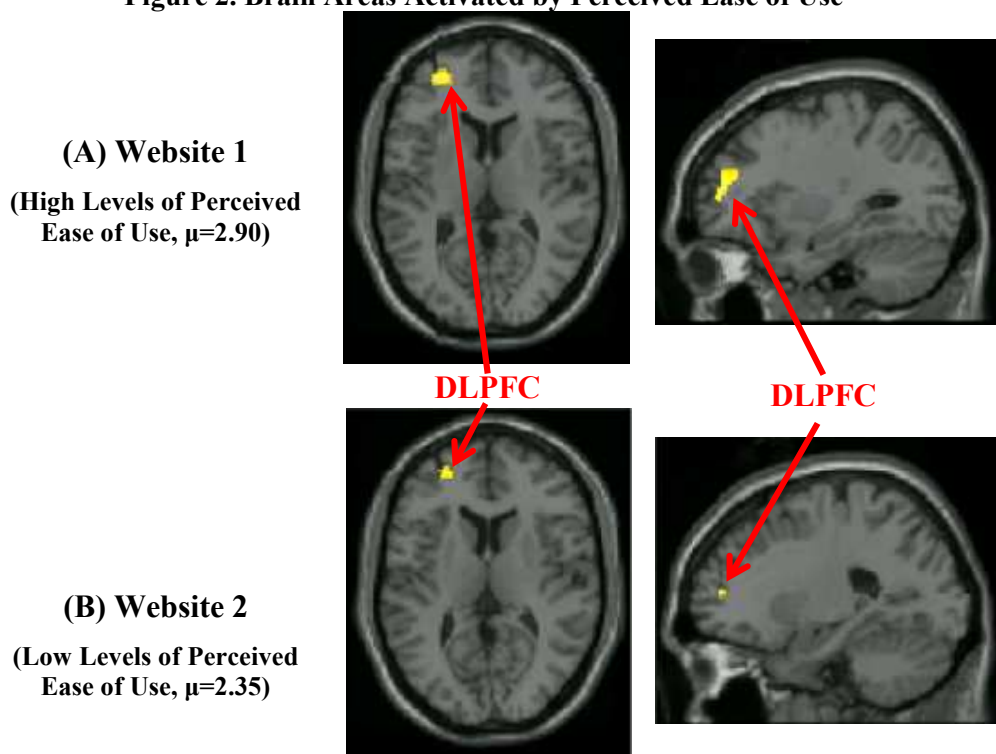
Neural Correlates and Findings for Perceived Ease of Use

The manipulation of perceived ease of use was successful since the self-reported perceived ease of use for Website 1 had a mean of 2.90 (3=Strongly Agree) while the mean for Website 2 was 2.35 (1=Strongly Disagree) ($p < .05$).

As shown in Figure 2, higher levels of perceived ease of use for Website 1 activated the *dorsolateral prefrontal cortex*, while lower levels of perceived ease of use for Website 2 also activate the same area in the prefrontal cortex, but at a lower level of activation. The dorsolateral prefrontal cortex is involved with the sequential execution of operations during controlled processing (Schneider and Chien, 2003). Both Website 1 and Website 2 have similar areas of activation, consistent with the subjects' similar responses on ease of use (Website 1: mean=2.90, Website 2: mean=2.35). Still, there is a higher level of activation for Website 1 in the dorsolateral prefrontal cortex ($p < .01$). Also, the perceptual responses to the survey measurement items of perceived ease of use are significantly correlated ($r = .58$, $p < .01$) to the measured level of brain activation in the dorsolateral prefrontal cortex.

In terms of the responses on perceived ease of use during and after the fMRI session, those were highly correlated ($r = .90$, $p < .001$), again implying no differences between the responses in and outside the fMRI scanner.

Figure 2. Brain Areas Activated by Perceived Ease of Use

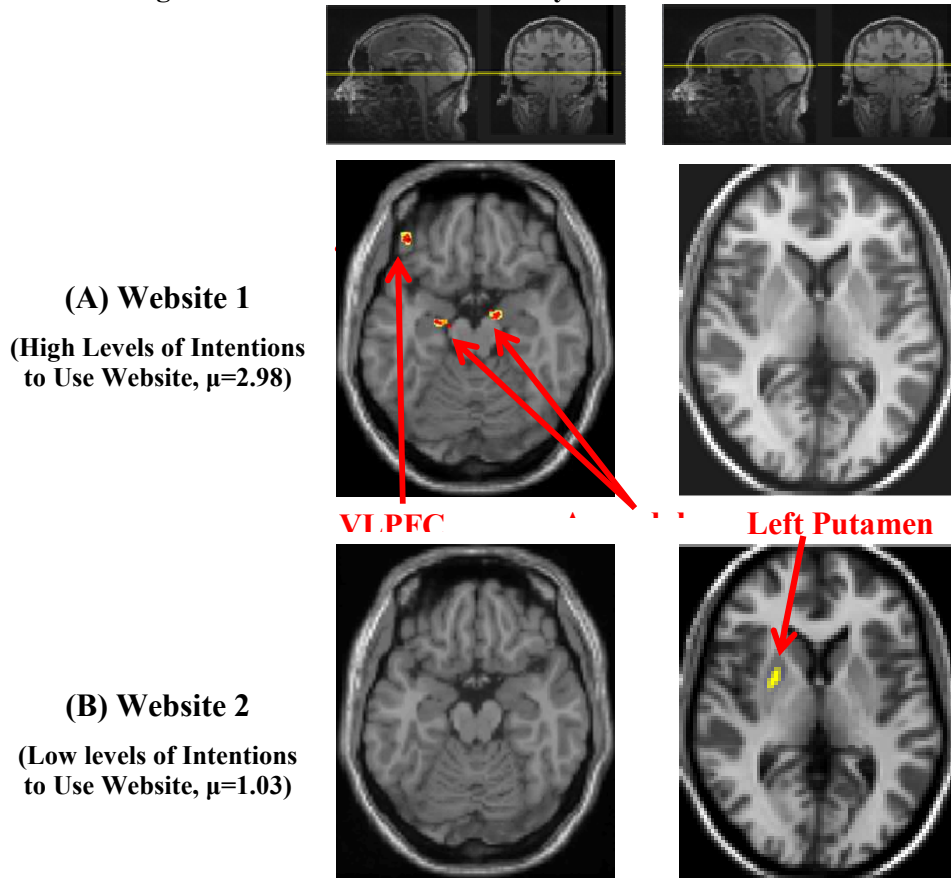


Neural Correlates and Findings for Intentions to Use Website

The self-reported intentions to use Website 1 for purchasing had a mean of 2.98 (3=Strongly Agree) while the corresponding mean for Website 2 was 1.03 (1=Strongly Disagree) ($p < .001$). As shown in Figure 3, intentions to use Website for purchasing activated the *ventrolateral prefrontal cortex* (VLPFC) and the *bilateral amygdala*, while intentions to use Website 2 for purchasing only activate the *left putamen*.

In the cognitive neuroscience literature, VLPFC activation relates to the higher intentions to engage in a behavior (Okuda, et al., 1998; Petrides, 1994; Petrides, 1996). The bilateral activation in the amygdala is explained by the fact that this area is activated in response to intense emotions when predicting a positive reward (Hommer, et al., 2003). The amygdala was also linked to the dynamic interaction between emotion and cognition in decision-making (Phelps, 2006). In terms of intentions to use Website 2 for purchasing, the left putamen is activated (Figure 3). The left putamen relates to realizing that an error in a subject's prediction occurs (e.g., McClure, et al., 2003; O'Doherty, et al., 2004). This activation implies that people realize it may be an error to purchase from Website 2.

Figure 3. Brain Areas Activated by Purchase Intentions



Antecedents and Consequences of TAM Constructs

To test whether the high/low manipulation of the two websites that differed on their degree of usefulness and ease of use predicted the brain activation identified for the two TAM constructs. In terms of the areas associated with perceived usefulness, the binary manipulation of website usefulness was correlated with the activations in the caudate nucleus ($r=.49, p<.05$), anterior cingulate cortex ($r=.69, p<.01$), and insular cortex ($r=-.64, p<.01$). These results suggest that the IT stimulus for usefulness adequately predicted the brain activation for perceived usefulness. In terms of the area associated with perceived ease of use (DLPFC), the correlation of the binary manipulation of website ease of use with activation in the DLPFC was modest ($r=.14, p<.10$). This relatively weak correlation is due to the weaker manipulation of website ease of use since Website 2 was not perceived as difficult to use (mean=2.35 where 3=Strongly Agree compared to Website 1 (mean=2.90), albeit still being significantly different ($p<.05$). Thus, it is possible to show how IT stimuli can be viewed as antecedents of the two TAM constructs.

Table 3. Predicting Intentions to Use based on the Observed Brain Activations using Linear Regression

Observed Brain Activation	Regression Coefficient	Significance
Dorsolateral Prefrontal Cortex (Ease of Use – Both Websites)	.33	$p<.05$
Anterior Cingulate Cortex (Usefulness – Website 1)	.42	$p<.05$
Caudate Nucleus (Usefulness – Website 1)	.02	N/S
Insular Cortex (Usefulness – Website 2)	-.52	$p<.01$
Dependent Variable: Intentions to Use Website - $R^2 = 48\%$		

In terms of the consequences of the observed brain activations and whether they can predict intentions to use the website, we regressed the four observed activations with the subjects' intentions to purchase from each website, as obtained from the subjects' survey responses on the 7-point Likert-type scale after the fMRI session.

As shown in Table 3, it is possible to predict intentions to use the website for purchases based on the observed brain activations in the areas activated from perceived ease of use (DLPFC) ($\beta=.33$, $p<.05$) and perceived usefulness (anterior cingulate cortex) ($\beta=.42$, $p<.05$) and insular cortex ($\beta=-.52$, $p<.01$). However, the caudate nucleus has an insignificant effect on intentions to use, perhaps because it is associated with brain activation due to high levels of perceived usefulness (Website 1). Most important, the proposed model does a good job predicting intentions to use the website ($R^2=48\%$), suggesting that brain activations can predict behavioral intentions to use the system.

The subjects were also asked to respond whether they would purchase from each website on a binary (yes/no) scale, and the brain activations in the four areas (DLPFC, anterior cingulate cortex, caudate nucleus, insular cortex) were used to predict whether the subject will purchase from each website using logistic regression (Table 4).

Table 4. Predicting Intentions to Use based on the Observed Brain Activations using Linear Regression

Observed Brain Activation	Logistic Beta Coefficient	Significance
Dorsolateral Prefrontal Cortex (Ease of Use – Both Websites)	4.16	$p<.01$
Anterior Cingulate Cortex (Usefulness – Website 1)	5.21	$p<.01$
Caudate Nucleus (Usefulness – Website 1)	.01	N/S
Insular Cortex (Usefulness – Website 2)	-11.63	$p<.001$
Dependent Variable: Intentions to Use Website - Cox & Snell $R^2 = 66\%$ - Nagelkerke $R^2 = 78\%$		

As shown in Table 4, the same brain areas (DLPFC, anterior cingulate cortex, and insular cortex) can adequately predict whether a person would purchase the product from each website. As shown by the logistic regression R^2 (Cox & Snell $R^2 = 66\%$ - Nagelkerke $R^2 = 78\%$), the observed brain activations have substantial predictive power.

Discussion

Key Findings

High levels of perceived usefulness (Website 1) activated the caudate nucleus and the anterior cingulate cortex, while low levels of perceived usefulness (Website 2) activated the insular cortex. These findings correspond to the cognitive neuroscience literature since the caudate nucleus and anterior cingulate cortex are activated due to anticipated rewards while activation in the insular cortex is associated with intense emotions due to fears of loss. Perceived ease of use activated the DLPFC, an area involved with the sequential execution of operations during controlled processing. Higher levels of perceived ease of use (Both Websites) correlated with the level of brain activation in the DLPFC. Finally, high intentions to use Website 1 activated the VLPFC and the bilateral amygdale, while low intentions to use Website 2 activated the left putamen. According to the cognitive neuroscience literature, the VLPFC relates to intentions to engage in a behavior, while bilateral amygdale activation relates to prediction of a positive reward. Left putamen activation relates to realizing an error in reward prediction.

Implications for the Literature on Technology Adoption and Use

The examination of the neural correlates of the TAM variables in the context of website use has several interesting implications for underscoring the potential of functional neuroimaging for IS research and the TAM literature.

1. Localizing the neural correlates of TAM constructs to better understand their nature and dimensionality

The measurement of brain activation associated with the two TAM constructs can also shed light on the nature and dimensionality of these constructs. First, perceived usefulness has three components that are associated with different levels of anticipation for utility (or loss). The negative aspects of utility activated due to low levels of usefulness of Website 2 corresponded to areas associated with a potential for loss (insular cortex). However, the positive aspects of utility can be broken down into the magnitude of an actual reward (caudate nucleus) and the

anticipation of a reward (anterior cingulate cortex). These findings have interesting implications about the nature and dimensions of perceived usefulness besides what the TAM literature has inferred from experiments and surveys. The nature of perceived usefulness is thus associated with expectations of increased utility, as expected. Moreover, perceived usefulness seems to have two distinct, yet related dimensions in the brain, one associated with the magnitude of the reward and one with the anticipation of the reward. To the best of our knowledge, this is the first study to suggest that perceived usefulness may be a multi-dimensional construct. Second, perceived ease of use is located in the prefrontal part of the brain (DLPFC) that is associated cognitive functioning. This is consistent with the nature of perceived ease of use, as noted in the TAM literature. Also, in contrast to perceived usefulness, perceived ease of use seems to be a unidimensional construct.

2. Complementing survey TAM responses with objective brain data

This study shows that the subjective responses to the TAM variables are consistent with the objective brain data obtained from the fMRI study. While this is expected since the measurement items for perceived usefulness and perceived ease of use were used to induce the corresponding brain activation as a result of the underlying IT stimuli (the two websites that differed on their degree of usefulness and ease of use), it is interesting to see that the two sources of measurement are quite consistent. The fact that the observed brain activations are significantly correlated with subjective responses to existing measures of these perceptual constructs testifies that these brain areas are indeed the neural correlates of these constructs. This has implications for the TAM literature in the sense that the subjective measurement of the TAM constructs closely corresponds to their objective measurement in the brain.

3. Capturing hidden (automatic) processes that are difficult to measure with existing measurement methods

The ability for the objective and unbiased measurement of perceptual constructs has the potential to identify hidden or unconscious processes that may be difficult to capture with self-reported measures. While no hidden processes were uncovered in terms of perceived usefulness and perceived ease of use, intentions to use the system (website) were associated with both a cognitive component (VLPFC) (confirming the cognitive focus of the literature on behavioral intentions), but it also associated with an emotional element (amygdala), which has been largely ignored in the literature. The identification of hidden affective processes in usage intentions has implications for TAM research to consider the emotional aspects of behavioral intentions that have been conceptualized as purely cognitive phenomena. As TAM research increasingly focuses on the automatic and habitual behaviors that characterize post-adoption use, it calls for better theories on the processes that govern habitual behavior. This finding has implications for IS research to uncover other hidden components of IS constructs that cannot be easily inferred by self-reported measurement scales.

4. Identifying TAM antecedents by showing how IT stimuli spawn brain activation in identified TAM areas

This study highlights the possibility to examine antecedents of the two TAM variables. The simple manipulation of two websites that differ on their level of usefulness and ease of use is shown to activate different areas of the brain that correspond to the TAM constructs. The website manipulation acted as the IT stimulus that spawned activations in different brain areas, induced by classic measurement items associated with perceived usefulness and ease of use. These findings have implications for identifying additional, less obvious antecedents of the TAM constructs, such as systems and prototypes that differed on their proposed levels of usefulness and ease of use. Knowing the neural correlates of the two TAM constructs can help test the usefulness and user friendliness of other IT systems and tools.

5. Testing the outcomes of TAM constructs by showing how brain activation predicts behavioral intentions

The TAM literature has argued that perceived usefulness and perceived ease of use influence behavioral intentions to use a system. This study showed that the brain activations associated with the two TAM constructs can predict behavioral intentions to use the two websites. Interestingly, the observed levels of brain activations (z-scores) associated with the TAM constructs can be used as independent variables in both a multivariate and also in a logistic regression to predict behavioral intentions to use the system (measured with continuous Likert-type scales) or use the website to purchase a product (measured with a binary variable). This study has implications for identifying additional consequences of the TAM constructs, such as ex post actual system usage.

6. Inferring causality among IS constructs by examining the timing of brain activations

The TAM literature has also attempted to infer a causal interpretation between the TAM constructs. While causality inference cannot be solely determined based on temporal precedence, the timing of brain activations can shed light on their timing in the brain. However, such study requires a common stimulus for both perceived usefulness and ease of use. Since this study had distinct stimuli for the two TAM constructs, this task is left for future research.

7. Challenging TAM assumptions and enhancing TAM theories that correspond to the brain's functionality

The fact that different areas of the brain are activated for low and high levels of perceived usefulness and intentions to use the system may suggest that these two constructs are not necessarily linear and continuous (as the traditional continuous measurement items for these constructs suggest), but they may exhibit non-linearities and discontinuities between high and low levels of usefulness and intentions to use a system. These findings seem to challenge the assumption in the TAM literature that the measurement of these two constructs is linear and continuous. While these findings must be verified by additional research, they underscore the insights and implications that neuroimaging studies may have in building superior theories that better correspond to the brain's functionality.

Limitations & Suggestions for Future Research

First, usefulness and ease of use were somewhat confounded in that the manipulated website was either designed to be either high or low in both constructs. Future research can orthogonally manipulate usefulness and ease of use (low-low, low-high, high-low, high-high) to tease apart the distinct effects of usefulness and ease of use.

Second, the number of anchors in the Likert-type scale was restricted to three anchors due to the technological limitations of the 3-button fiber optic device used in the highly magnetic fMRI scanner. Future research could adopt a custom-made 7- or 9-button fiber optic device to allow a higher variability in the respondent's choices.

Third, this study only focused on the classic TAM constructs (perceived usefulness and perceived ease of use). However, there are other potential determinants of intentions to use a system, such as subjective norm and perceived behavioral control. For example, the subjective norm construct in TAM2 Venkatesh and Davis (2000) deals with a user's perceptions of the beliefs that referent others have about the focal behavior. The neuroscience literature has identified the major brain area associated with capturing others' beliefs and intentions (medial prefrontal cortex). Future research could incorporate additional constructs that relate to the classic TAM constructs, identify their neural correlations, and examine whether and how they have an effect on users' intentions to use a system.

Finally, Bagozzi (2007) emphasizes the value of deepening how TAM represents goal-directed self-regulatory aspects of system use to bridge both the gap between intention and use and the gap between use and goal attainment. Neuroimaging studies modeled the brain area that mediates regulation of goal-directed actions intended to achieve delayed rewards (e.g., Hasselmo, 2005). The literature has insights on the brain structures involved in regulating tasks, intentions, goals, and outcomes (Borg, et al., 2006; Chadderdon and Sporns, 2006; Kable, et al., 2005), which can help build theories on the relationships among intentions, use, and goal attainment in the context of system use.

Implications for Practice

Functional neuroimaging tools can help practitioners design better IT tools, such as useful and user-friendly systems that facilitate user adoption, use, and enhanced productivity. Rather than relying on users' perceptual evaluations, the brain areas associated with the desired effects can be used as the objective dependent variable in which the IT systems will be evaluated. For example, the areas associated with perceived usefulness and perceived ease of use can be used by IS practitioners as a basis for designing superior IT tools that would facilitate technology adoption and use by enhancing the magnitude and probability of the utility gained and reducing the users' cognitive overload.

Conclusion

This study is a first attempt to explore the potential of cognitive neuroscience in IS research by showing how it can inform the literature on technology adoption and use. We hope the interesting findings, insights, and implications from this study will entice IS researchers to employ functional neuroimaging to build superior IS theories.

Appendix 1

Anatomy and Functionality of the Major Brain Systems and Areas

Higher Cognitive Processing (Prefrontal Cortex)

The prefrontal cortex is activated in the planning of complex cognitive behaviors, such as problem solving, short-term memory, moderating acceptable behavior, deciding between right and wrong, and orchestrating thoughts and actions in accordance with one's goals. It consists primarily of the following areas:

The *dorsolateral prefrontal cortex* is a very unique part of the frontal cortex specific to humans. It is one of the more highly evolved areas of the human brain, and it is involved in higher functions, such as conscious behavioral control, executive functioning, planning, working memory, cognitive performance, intelligence levels, memory retrieval, and problem-solving skills (Cumplings, 1993; Duke and Kaszniak, 2000; Stuss et al., 2000).

The *ventromedial prefrontal cortex* is activated in response to emotional states that influence decision-making and preference judgments, and it plays a role in anxiety disorder and depression. Patients with injury in the ventromedial prefrontal cortex are unable to properly respond to social cues and obey conventional social rules (Damasio, 1996).

The *orbitofrontal cortex* is involved in decision making. It also regulates planning and behavior associated with uncertainty, rewards and punishments, changing reinforcements, and social behavior (Kringelbach and Rolls, 2004).

The *medial prefrontal cortex* is related to executive control and understanding the intentions of others.

The Limbic System

The limbic system is governs emotional responses and influences the formation of memory by integrating emotional states with stored memories of physical sensations. It consists primarily of the following areas:

The *amygdala* is an almond-shaped area located deep in the medial temporal lobe in both hemispheres. It plays a key role in emotional information processing, such as anger, jealousy, distrust, negative emotions, pleasure, and fear (LeDoux, 2003). It is also involved in regulating both positive and also negative emotions (Hamann and Mao, 2002).

The *cingulate cortex* is part of the brain situated roughly in the middle of the cortex. The anterior cingulate cortex is the frontal part of the cingulate cortex, and it can be divided into the executive (anterior), evaluative (posterior), cognitive (dorsal), and emotional (ventral) components (Bush, et al., 2000b). The anterior cingulate cortex is vital in cognitive functions, such as decision-making and reward anticipation (Mayberg, et al., 1999), and the frontal portion of the anterior paracingulate cortex is related to social inferences and predicting how others will behave.

The *nucleus accumbens* provides a liaison between the limbic system (which regulates emotions) and the central gray nuclei (which helps in reasoning and planning). The nucleus accumbens constitutes the central link of the reward circuit, and it is involved in motivation. It is activated in the presence of stimuli associated with rewards, pleasure, and addiction, but it is also activated in the presence of aversive, novel, unexpected, or intense stimuli.

The *hippocampus* is located under the temporal lobe, and it processes information to be stored in long-term memory (Dimoka, et al., 2007).

Other important brain areas for human emotions are the caudate nucleus and the insular cortex. The literature has typically differentiated these two areas from the limbic system because they are considered more primitive.

The *caudate nucleus* is located in the center of the brain on both hemispheres. It is highly innervated by dopamine neurons, which are activated when one receives an unexpected reward. The caudate nucleus also affects a person's motivation level, and it is activated with social cooperation, trusting intentions, and trust-building tasks.

The *insular cortex* is a structure of the human brain that is located within the cerebral cortex, beneath the frontal, parietal and temporal lobes. The insular cortex processes information to produce an emotional sensory experience, such as disgust, unease, and unfairness. It is also responsible for the integration of information about affective and reactive components of pain, and it belongs to the circuitry related to fear, loss, and anxiety (Bornhövd, et al., 2002).

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