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Neuro IS: The Potential of Cognitive Neuroscience for Information Systems Research

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NEURO-IS:

THE POTENTIAL OF COGNITIVE NEUROSCIENCE FOR INFORMATION SYSTEMS RESEARCH

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Abstract

This paper proposes the idea of applying cognitive neuroscience theories, methods, and tools in Information Systems (IS) research (termed "Neuro-IS"), and introduces a research agenda for exploring the potential of cognitive neuroscience for IS research. Recent cognitive neuroscience discoveries have clarified the neural bases of human psychological processes and behavior and provided insights that may advance progress on core IS research questions on designing and deploying IT tools, technology adoption and use, e-commerce, virtual teams, human-computer interaction, decision making, and information sharing in organizational and market environments, among others. Functional neuroimaging techniques (fMRI, PET, EEG, MEG) have led to a better understanding of the brain areas and structures involved when people make decisions, deal with risk, uncertainty, and ambiguity, respond to rewards and social influences, trust and distrust, cooperate and compete, and acquire and process information. Similar to economics, marketing, and psychology, IS research may also benefit from integrating some of these new discoveries in cognitive neuroscience into IS theories about how IT supports human processes. Moreover, the use of neuroimaging techniques in IS research could complement traditional methods and data, such as self-report surveys, interviews, lab and field experiments, and archival data to integrate new objective sources of brain data for IS theory development and testing. This paper provides several examples of potentially fertile intersections of cognitive neuroscience and IS research on such areas as technology adoption and use, e-commerce, and group support systems. The paper also overviews today's functional neuroimaging tools and gives guidelines on how IS researchers can utilize these tools to obtain additional new insights into IS phenomena. Finally, it discusses the implications of incorporating cognitive neuroscience theories and functional neuroimaging tools in neuro-IS research, aiming to enhance the diversity of theories, methods, tools, and data in the portfolio of IS researchers.

Keywords: Cognitive Neuroscience, Functional Neuroimaging, Brain Imaging, Neuroeconomics

Track: Breakthrough Ideas in Information Technology

Introduction

Academics and practitioners alike suggest that the study of the human brain can revolutionize the social sciences (The Economist 2005). This is because many social scientists have teamed up with cognitive neuroscientists to examine a variety of social phenomena with functional neuroimaging tools, and many interesting insights are emerging through the direct and objective measurement of brain activity. Cognitive neuroscience examines the brain mechanisms underlying mental processes using functional neuroimaging tools that measure brain activation in response to mental processes. The human brain is the most complex organ in the human body, containing around one hundred billion neurons that can communicate with electrochemical signals through quadrillion (10^{15}) synapses.

However, despite many advances of cognitive neuroscience in the social sciences, such as neuroeconomics, neuromarketing, and psychology, IS research is still largely unaware of these advances. While economics, marketing, and psychology have already begun to exploit the potential of cognitive neuroscience and functional neuroimaging to enrich their theories, IS researchers are yet to consider how these can be used to inform IS theories. This paper argues that IS researchers can benefit by becoming intelligent users of the new discoveries, theories, and techniques generated from understanding the brain mechanisms underlying human behavior. This paper aims to answer two questions: How can cognitive neuroscience, and the new theories it has spawned, inform IS theories? How can IS researchers leverage functional neuroimaging tools to complement existing data collection techniques?

The purpose of this paper is to propose a research agenda to help advance our understanding of IS phenomena and theories by: (1) integrating the cognitive neuroscience literature, and (2) utilizing today's functional neuroimaging tools that allow temporal and spatial observation of brain activity to complement existing data collection techniques.

First, IS researchers have much to gain from recent advances of cognitive neuroscience in the social sciences (economics, marketing, and psychology) that examine brain activity in response to various stimuli. Understanding the underlying brain functions involved in a certain behavior substantially enhances our understanding of the neural bases of the behavior. As reviewed later, there is considerable progress in the underlying brain mechanisms that guide decision making under conditions of risk, uncertainty, and ambiguity, cooperative and trusting behaviors, understanding the future behavior of others, responding to rewards and social influences, and consumer behaviors. IS researchers can become intelligent users of this emerging literature to strengthen the theorizing of IS phenomena. The cognitive neuroscience literature may challenge existing theoretical constructs and may call for new ones that more closely correspond to the brain's underlying functioning. Thus, recognizing that distinct brain mechanisms are responsible for different human behaviors can shed light on theories on the complex interaction of people with IT.

Second, IS researchers typically collect data with surveys, field and lab experiments, interviews, secondary data, and analytical models. While these techniques have certainly advanced the IS discipline, recent discoveries in functional neuroimaging tools enable researchers to determine the location, frequency, and timing of brain activity with a high degree of accuracy. By directly asking the brain, not the person, neuroimaging techniques allow an objective, reliable and unbiased measurement of thoughts, beliefs, and feelings and link them to specific human processes (e.g., decisions, choices, and behavior). Given that functional neuroimaging tools are becoming more sophisticated, accessible, and also affordable, IS researchers can complement their existing data collection techniques with neuroimaging tools. While self-reported data are susceptible to common method bias, integrating primary data with secondary brain imaging data gives the opportunity to triangulate multiple measurement methods and strengthen the validity of research results (Mingers, 2001). Functional neuroimaging techniques can identify the localization of existing IS constructs, examine whether IS constructs actually correspond to the brain's functioning, identify the dimensionality of IS constructs and which brain areas they span, whether IS behaviors are driven by the same underlying brain mechanism, and whether various stimuli cause their intended activation in appropriate brain areas.

Our proposition for IS researchers is to first become familiar with the cognitive neuroscience literature and utilize its findings to enhance our understanding of IS phenomena, and then consider the use of functional neuroimaging tools to analyze brain processes that are relevant to IS. We propose that many of the discoveries in cognitive neuroscience can have direct implications for IS theories. This can open up directions for research that could accelerate progress toward understanding the complex and elusive issues concerning the interplay of information, technology, and human behavior, and could allow the establishment of another rigorous method for studying IS phenomena.

Applying cognitive neuroscience theories, methods, and tools in IS research ("Neuro-IS") can create opportunities for IS research in at least four areas: (1) identifying the neural bases involved in IS phenomena to complement existing data sources and help better understand, predict, and shape human behavior; (2) better understand the nature, localization, dimensionality, antecedents, and consequences of existing and new IS constructs, and (3) identifying potential differences between existing IS theories and constructs and their underlying brain mechanisms that would call for strengthening or even questioning existing IS theories, assumptions, and constructs, and (4) help building superior IS theories with assumptions and constructs that better correspond to the brain's functionality.

The paper offers a research agenda with many examples of potentially fertile intersections of cognitive neuroscience and neuro-IS on such areas as technology adoption and use, e-commerce, and group decision support systems (GDSS). An illustrative example for each of these areas is discussed below, while a more detailed research agenda is provided in the paper after the cognitive neuroscience literature in the social sciences has been reviewed.

First, the frontiers of technology adoption and use about belief formation and change, behavior self-regulation, social influences, automatic processes, and affect may be advanced by cognitive neuroscience. For example, as technology adoption research increasingly focuses on the automatic and habitual behaviors that characterize the post-adoption and use of IT tools, neuro-IS can expand the domain of applicability for technology adoption theories beyond controlled conscious processes to encompass the fundamental role of automatic unconscious processes. Also, Bagozzi (2007) stresses the need to include the role of emotions in technology adoption. As the complex interplay between emotion and cognition becomes better understood in the cognitive neuroscience literature, neuro-IS can help integrate the role of emotions in technology adoption and use.

Second, neuro-IS can help strengthen e-commerce theories by drawing upon knowledge of the brain mechanisms underlying online consumer decision-making, trust, uncertainty, and risk, rewards and pricing, rationality and emotions, personalization and privacy, and human-computer interaction. For example, since online transactions are inherently uncertain (Pavlou, et al., 2007), drawing upon the neuroimaging literature that has localized brain activity when people face risk (nucleus accumbens) (Knutson, et al., 2001), uncertainty (prefrontal and parietal cortex) (Huettel, et al., 2005), and ambiguity (insular cortex) (Hsu and Camerer, 2004), neuro-IS can help assess the degree of risk, uncertainty, and ambiguity of different websites, link them to specific IS constructs, and predict whether consumers will transact with these websites.

Third, the cognitive neuroscience literature on decision making and cooperation can potentially help advance the GDSS literature in terms of designing systems that facilitate group decisions and facilitate collaborative group work. For example, since the cognitive neuroscience literature (e.g., Decety, et al., 2004) distinguishes between cooperation (orbitofrontal cortex) and competition (medial prefrontal and inferior parietal cortices), GDSS tools can be designed to spawn activation in the "cooperative" brain areas and prevent activation in the "competitive" areas.

Besides these three exemplar areas, other IS research areas can benefit from neuro-IS. For example, the literature on IT labor can draw upon the cognitive neuroscience literature on rewards that has identified the brain areas activated in response to the magnitude (Hsu, et al., 2005), predictability (Knutson, et al., 2001), and timing of rewards (McClure, et al., 2004c) to devise favorable compensation schemes for IT employees. The IS strategy literature can also benefit by drawing upon the knowledge of how people evaluate the magnitude and probability of gains and losses to strengthen theories on how IT executives make IT investments and select IS projects.

The paper proceeds as follows: The next Section briefly reviews some neuroimaging studies in the social sciences, showing how neuroeconomics and neuromarketing have informed economics and marketing, respectively. The following section briefly reviews the literature on brain anatomy and functionality and refers interested readers to detailed Appendices. The next Section selectively identifies psychological processes that are related to IS research, reviews the key brain areas associated with them, and suggests several areas of IS research that could potentially benefit by cognitive neuroscience and functional neuroimaging studies (TAM, e-commerce, GDSS). The final Section discusses the potential of integrating cognitive neuroscience and functional neuroimaging in IS research.

Exemplar Cognitive Neuroscience Studies in the Social Sciences

The ability to link brain activity to human decisions and behavior has attested the feasibility of cognitive neuroscience to the social sciences, and it spawned great interest among social scientists. Neuroeconomists and psychologists have pioneered this trend, followed by neuromarketers. Notably, Glimcher and Rustichini (2004) argue that the diverse cognitive neuroscience, neuroeconomics, psychology, and neuromarketing literatures converge into a new discipline with the ultimate goal to provide a unified theory of human behavior. Below we review the scope and objectives of neuroeconomics and neuromarketing, along with some representative examples of research studies in these areas.

Examples from Neuroeconomics

Neuroeconomics is the application of cognitive neuroscience to analyzing and understanding economic-related behavior using functional neuroimaging techniques (Zak, 2004). Neuroeconomics help develop realistic models of economic behavior that are based on brain activities that underlie human behavior and decisions (Camerer, 2003). The neuroeconomics literature mainly uses experimental games to examine behavior and strategic decision making when subjects are presented with different scenarios and payoffs (e.g., Rustichini 2005), as briefly reviewed below:

Neuroeconomics studies of decision making under uncertainty have shown that different neural mechanisms govern the anticipation of gains and losses. Kuhnen and Knutson (2005) showed that the prospect of a $5 gain activated a different part of the brain compared to the prospect of a $5 loss. These findings are consistent with prospect theory (Kahneman and Tversky, 1979) that proposes that people weigh gains and losses differently. Neuroimaging techniques thus validated that our brain indeed processes information about gains and losses in different areas.

Bhatt and Camerer (2005) showed that decision making has both a cognitive (thinking) and an emotional (feeling) component, and subjects whose brain activity displays good cooperation between the limbic area of the brain (emotional area) and the prefrontal cortex (thinking area) were the most successful in experimental games.

Hsu and Camerer (2004) showed that an area of the brain (termed insular cortex) that is activated in response to adverse bodily states, such as pain, is activated when subjects are asked to choose among ambiguous gambles. However, this area is not activated when the subjects choose between certain or uncertain gambles. These findings suggest that ambiguous (versus uncertain) gambles activate a brain area that triggers negative emotions, explaining why people loathe ambiguous situations and prefer certain gains or at least uncertain gambles.

Smith et al. (2002) showed that attitudes about payoffs and beliefs on expected outcomes interacted behaviorally and neurally, challenging a well-known economic assumption that evaluating payoffs and outcomes is independent. For a detailed review of the neuroeconomics literature, see Kenning and Plassmann (2005) and Braeutigam (2005).

Examples from Neuromarketing

Neuromarketing is the application of cognitive neuroscience theories and techniques to the field of marketing. By understanding how the human brain activates in response to marketing and advertising stimuli (Zaltman, 2003), neuromarketing aims to build better models to understand consumer behavior and market products (Lee et al., 2006). For example, McClure et al. (2004b) tried to explain the consumers' preference for Coke over Pepsi. Using functional neuroimaging techniques, the authors showed activation of the dorsolateral prefrontal cortex (a brain area implicated in modifying behavior based on emotion and affect) when notifying subjects that they are drinking Coke. However, no such activation was observed when subjects were notified that they are drinking Pepsi, implying that the Coke's preference was due to cultural information biasing preference choice in the dorsolateral prefrontal cortex.

One area of neuromarketing is purchase choice. Braeutigam and his colleagues (Braeutigam, et al., 2004; Braeutigam, et al., 2001) used magneto-encephalogram brain imaging technique (MEG) to identify differences in brain activation between predictable and unpredictable choices. This research suggests that different brain regions are activated in response to choice predictability, with unpredictable choices eliciting brain activations in regions associated with silent vocalization and the judgment of immediate versus delayed rewards.

Another area of neuromarketing focuses on eliciting brain activation from brand advertising. Ioannides et al. (2000) examined MEG brain activations spawned by brand advertising stimuli. With similar techniques, Young (2002) examined the impact of advertisements on brand development, awareness, and attention, while Rossiter et al. (2001) showed that visual images that created faster activation in the prefrontal cortex created stronger brand recognition. For a comprehensive review of the neuromarketing literature, please see Lee et al. (2006).

Basics of Cognitive Neuroscience

The field of cognitive neuroscience focuses on understanding the interaction between 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 human processes, thoughts, and behaviors using functional neuroimaging techniques. For more details on brain basics, please see Appendix 1.

Cognitive neuroscience is a cross-disciplinary field that spans neuroscience, cognitive psychology, and engineering, among others. It covers individual and social perception, cognition, attention, memory, emotion, consciousness, executive functioning, and decision making. Most studies focus on identifying the functionality specific brain areas that are activated by a specific task.

There are two major brain systems - the *prefrontal cortex* (higher cognitive processing), and the *limbic system*.

The major key areas of the prefrontal cortex are the dorsolateral (upper outer), vetromedial (lower middle), medial (middle), and orbitofrontal (above the eyes) cortices (Figure 1). This brain area 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.

The limbic system consists of the most interior margins of the brain. The major regions of the limbic system are the amygdala, cingulate cortex, nucleus accumbens, and the hippocampus (Figure 1). The limbic system is primarily concerned with behaviors governed by emotional responses (Lautin, 2001). It also influences the formation of memory by integrating emotional states with stored memories of physical sensations. A description of the anatomy and functionality of the prefrontal cortex and the limbic system is given in Appendix 2.

Figure 1 selectively identifies the major brain areas that are of interest to the social sciences and could relate to IS.[1]

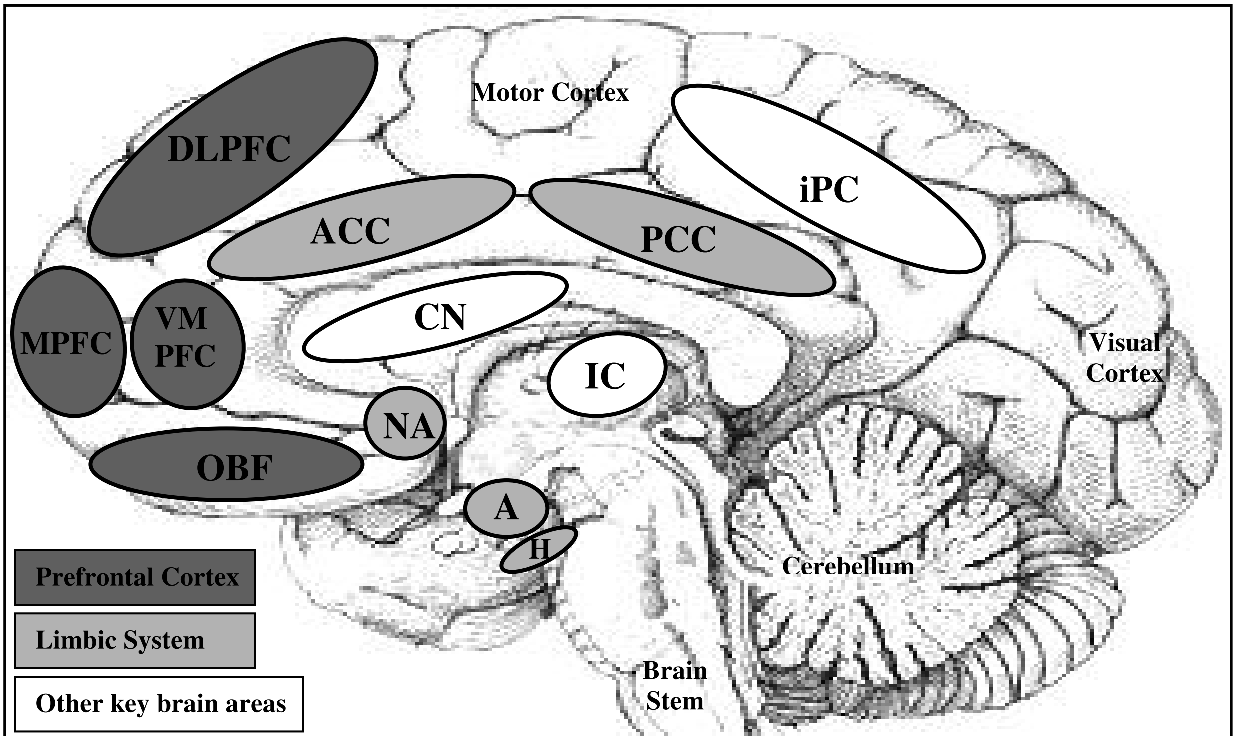

Figure 1. The Major Areas of the Brain

DLPFC: Dorsolateral Prefrontal Cortex, VMPFC: Ventromedial Prefrontal Cortex, OBF: Orbitofrontal Cortex MPFC: Medial Prefrontal Cortex, ACC/PCC: Anterior/ Posterior Cingulate Cortex, NA: Nucleus Accumbens; A: Amygdala, H: Hippocampus, CN: Caudate Nucleus, IC: Insular Cortex, iPC: Inferior Parietal Cortex

[1] While it is possible to map various processes into specific brain areas, the property of modularity must be viewed with caution. Many complex processes are simultaneously driven by several distinct brain areas that communicate with each other. Therefore, besides specific (modular) brain areas that are responsible for relatively simple processes, it is also important to acknowledge that more complex processes are driven by inter-related brain "circuits" that communicate with each other, as we will describe later.

Mapping the Cognitive Neuroscience Literature to Information Systems Research

While there is a diverse literature on cognitive neuroscience applied to the social sciences (Walter, et al., 2005), such as neuroeconomics and neuromarketing, we selectively reviewed the literature on research areas that closely relate to phenomena of interest to IS researchers. Our objective to show how the cognitive neuroscience literature can inform IS research, and also to provide a basis for IS researchers to use functional neuroimaging techniques to better understand IS phenomena and build superior IS theories.

Decision Making

The cognitive neuroscience literature in the social sciences focused on inferring the brain bases of decision making, aiming to provide accurate models of decision making (Sanfey, et al., 2006). The literature has identified the prefrontal cortex (mostly the orbitofrontal and dorsolateral 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 and calculation) aspects of decision-making, while the limbic system is responsible for the emotional (feeling) aspects of decision-making (Sharot, et al., 2004).

The literature has examined the cognitive and emotional aspects of decision-making using neuroimaging techniques in which subjects were asked to engage in decision-making activities. For example, using the Iowa gambling task,[2] Bechara et al. (1994) showed that the orbitofrontal cortex is responsible for decision making associated with calculating reward and punishment. While healthy subjects learned to choose only the "good" decks, patients with lesions in the orbitofrontal cortex continued to choose the "bad" decks as well. Hsu et al. (2005) showed that the level of effort required in decision making correlates with activation in the orbitofrontal cortex and the amygdala. Recognizing that decision making has a cognitive and an emotional component, Bhatt and Camerer (2005) showed that subjects whose brain activations exhibited good cooperation between the limbic system and the prefrontal cortex were the most successful in experimental games of decision-making.

Risk, Uncertainty, Ambiguity, and Loss

Decision making under certainty, risk, uncertainty (known probabilities), ambiguity (unknown probabilities), and probability of loss is another major area explored in the cognitive neuroscience with neuroimaging tools.

<u>Risk:</u> Matthews et al. (2004) showed a correlation between an individual's risk avoidance and brain activation in the nucleus accumbens. Knutson et al. (2001) also showed nucleus accumbens activation in games of risky prediction.

<u>Uncertainty:</u> In a meta-analysis of 27 brain imaging studies of uncertain decision-making, Krain et al. (2006) showed that brain activity mainly occurred in the orbitofrontal and inferior parietal cortices (emotional information processing). Similar findings were reported by Bechara et al. (2000) and Volz et al. (2004). Huettel et al. (2005) even showed that activations in the orbitofrontal and inferior parietal cortices increased with higher uncertainty, and Hsu et al. (2005) showed the orbitofrontal cortex to play a key role in distinguishing among levels of uncertainty.

<u>Ambiguity:</u> In a meta-analysis of 14 brain imaging studies of ambiguous decision-making, activity was shown in the dorsolateral prefrontal, anterior cingulate, the parietal, and the insular cortex (Krain, et al., 2006).

<u>Loss:</u> The insular cortex is activated in risky games with loss prediction (Paulus and Frank, 2003). Activation in the insular cortex implies negative feelings due to the probability or expectation for loss.

The literature also studied the differences in decision-making in certain, risky, uncertain, and ambiguous conditions. Gonzalez et al. (2005) used fMRI to study subjects who were asked to choose among certain and uncertain choices. The results showed a higher activation in the orbitofrontal, dorsolateral, and parietal cortices when choosing among uncertain versus certain choices. Gonzalez et al. (2005) also showed that while both uncertain and ambiguous decisions activate the orbitofrontal and parietal cortices, there are significant differences between uncertain and ambiguous decision making in the orbitofrontal and dorsolateral prefrontal cortex and the anterior cingulate cortex. Hsu and Camerer (2004) found that the insular cortex was differentially activated when people chose certain money amounts rather than ambiguous gambles. Since the insular cortex processes information about adverse bodily states (e.g., pain), ambiguous gambles activate the insular cortex that is associated with negative emotions.

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[2] In the Iowa gambling task (http://en.wikipedia.org/wiki/Iowa_gambling_task), the participants are presented with 4 virtual decks of cards. They are told that each time they choose a card they might win or lose some money, and the goal of the game is to win as much money as possible. Two of the decks are "bad decks", which means that, over a long enough time, they will make a net loss, while the other two are "good decks" that over time will make a net gain.

In the Ultimatum game[3] using fMRI, Sanfey et al. (2003) found that unfair offers activated the dorsolateral prefrontal, the anterior cingulate, and the anterior insular cortices. The dorsolateral prefrontal cortex is linked to the cognitive processes of executive control, while the anterior cingulate cortex was activated due to the negative emotions associated with the unfair offer. The activation of the anterior insular cortex is a reflection of the receiver's negative emotional response to the unfair offer (an area associated with feelings of disgust). Interestingly, the level of activity in the anterior insular cortex could reliably predict whether a person would reject an unfair offer.

Rewards and Utility

The cognitive neuroscience literature offers insights into how people react to rewards by uncovering the mechanisms involved when people receive rewards, increase their utility, and shape their behavior (Walter, et al., 2005).[4] Knutson and Cooper (2005) and McClure et al. (2004c) described the brain's reward circuitry as the limbic system (mainly the nucleus accumbens and the amygdala), the orbitofrontal cortex, and the caudate nucleus. Specifically, the orbitofrontal cortex is activated when a person processes relative rather than absolute rewards (Elliott, 2003), perhaps due to the need for calculating relative rewards. Caudate nucleus activation is correlated with the magnitude of the reward (Hsu, et al., 2005), while the predictability of the reward specifically activates the nucleus accumbens (Knutson, et al., 2001). The amygdala (that is activated by intense emotions) is activated in response to a prediction of a large positive reward (Hommer et al., 2003) and the devaluation of a higher reward (Gottfried et al., 2003).

The literature also examined the anticipation versus the actual experience of rewards (O'Doherty, et al., 2002). Knutson et al. (2005) showed that the magnitude of an anticipated reward activated the caudate nucleus and the nucleus accumbens, while the anticipated probability of a reward proportionately activated the orbitofrontal cortex. Erk et al. (2002) also showed higher activations in the nucleus accumbens and the orbitofrontal cortex in response to looking at products of high social value (sports cars) versus ones with lower social value (regular cars). The authors explained that the anticipation of social stimuli of high social rank, dominance, and wealth were responsible for these brain activations. In a similar study, McClure et al. (2004c), the nucleus accumbens was shown to be activated in anticipation of increased utility, while the medial prefrontal cortex was activated in response to the actual experience of increased utility. These findings closely correspond to the behavioral decision making literature (Kahneman, 2000) that also distinguishes between anticipated and experienced utility.

Finally, the literature also examined the anticipation of positive versus negative rewards, showing that different brain mechanisms evoke the anticipation of positive and negative rewards (Knutson and Peterson, 2005). The nucleus accumbens is activated by the anticipation of positive rewards (Breiter, et al., 2001; Knutson, et al., 2001). Kuhnen and Knutson (2005) showed that the prospect of a \$5 gain activated the nucleus accumbens, while the anticipation of a \$5 loss did not. Also, the caudate nucleus was activated when people contrasted monetary gains and losses (Delgado, et al., 2005). Interestingly, activation in the caudate nucleus predicted a person's future behavior. The caudate nucleus is responsible for processing diverse information to influence behavior (Tricomi, et al., 2004). The potential for a negative reward produces a greater overall brain activation and slower response times than the potential for a positive reward (Camerer, 2003; Smith, et al., 2002). This finding is consistent with prospect theory (Kahneman and Tversky, 1979) that suggests that people weigh losses more heavily than gains.

Consumer Behavior

The areas of the brain activated during consumer purchasing tasks are mainly the ventromedial prefrontal cortex (that plays a role in preference judgments and social decision making) and the limbic system (McClure et al., 2004b; Paulus and Frank, 2003). Deppe et al. (2005b) showed that a consumer's first brand choice was associated with an increased activation of the ventromedial prefrontal cortex and lower activation of the dorsolateral prefrontal cortex (which is associated with higher cognitive functions). These results suggest that a consumer's first choice brand is associated with social rather than rational decision making, pointing out to impulse versus planned purchasing.

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[3] In the ultimatum game (http://en.wikipedia.org/wiki/Ultimatum_game), two subjects are paired, and the first player (proposer) is provisionally allotted a divisible "pie" (usually money). The proposer then offers a portion of the pie to a second person (responder). The responder, knowing both the offer and the total amount of the pie, then has the opportunity to either accept or reject the proposer's offer. If the responder accepts, she receives the amount offered and the proposer receives the remainder of the pie. However, if the responder rejects the offer, then neither player receives anything. In either case, the game ends, and the two subjects receive their winnings and depart. The Ultimatum game can be repeated several times.

[4] Utility reflects the subjective value of a reward (Erk et al., 2002).

McClure et al. (2004b) also found that immediate rewards (gift certificates) primarily activate the limbic system (posterior cingulate cortex, nucleus accumbens), while delayed rewards differentially activated the lateral prefrontal and inferior parietal cortices. The authors argued that choosing between immediate and delayed rewards constitutes a battle between the limbic system that activates in response to immediate rewards (impulse purchases) versus the lateral prefrontal and inferior parietal cortices that cognitively evaluate inter-temporal trade-offs (planned spending).

Finally, neuroimaging techniques have recently questioned existing consumer behavior theories. While traditional theories suggest that a person's utility is solely based on consumption levels, Cohen, Laibson, and McClure (2005) showed that a consumer's utility is severely damaged by unexpected reductions in consumption levels. These findings are consistent with the cognitive neuroscience literature on rewards in which people react more negatively to losses than rewards, as reflected by their increased activation in the caudate nucleus (Delgado, et al., 2005).

Theory of Mind

Inferring what other people think and predicting how other people will behave is known as the "theory of mind". The literature has identified a brain area that is responsible for the theory of mind (Fletcher, et al., 1995), including the medial prefrontal cortex (McCabe, et al., 2001; Siegal and Varley, 2002) and the anterior paracingulate cortex (Gallagher, et al., 2002; McCabe, et al., 2001). These areas are consistently activated in neuroimaging studies that require subjects to infer the beliefs, thoughts, and intentions of others (Frith and Frith, 2003), and patients with lesions in the medial prefrontal cortex could not make any predictions about how others think (Stuss, et al., 2001). This is because the medial prefrontal cortex enables executive control about understanding other people's intentions (Cole and Mitchell, 2000). The anterior paracingulate cortex is responsible for social inferences (Rilling et al., 2004) because people who make mental state attributions engage in a social interaction with the person whose behavior they predict (Walter, et al., 2005). Summarizing the literature, Bhatt and Camerer (2005) integrated the "social" and "calculative" components of the theory of mind by showing that the anterior paracingulate cortex is activated when people express beliefs about the social reasoning of others, while the medial prefrontal cortex is activated when making decisions and choices based on calculative expectations of what others will do.

Trust/Distrust and Cooperation/Competition

Cognitive neuroscience has also focused on trust and distrust, showing that trust is associated with the caudate nucleus and the medial prefrontal cortex, while distrust is associated with the amygdala and the right insular cortex.

In the 'trust game'[5] using fMRI, King-Casas et al. (2005) showed activation in the caudate nucleus when a person showed benevolent reciprocity, while the activity subdued when the person showed malevolent reciprocity. The authors also showed that the level of activation in the caudate nucleus increased when the monetary amount at stake in the trust game increased. Activation levels in the caudate nucleus also predicted whether players would act cooperatively in the next round. In contrast, Winston et al. (2002) showed activation in the amygdala and right insular cortex (areas associated with intense negative emotions) when subjects judged other people as untrustworthy.

The literature distinguished between cooperation and competition based on activation in the orbitofrontal cortex, which is only activated by cooperation (Rilling, et al., 2002) and not by competition (Walter, et al., 2005), and the inferior parietal and medial prefrontal cortices, which are only activated by competition (Decety, et al., 2004).

Interacting with Humans versus Computers

The neuroimaging literature has identified differences when human beings interact with computers versus humans. Walter et al. (2005) identified activation in the medial prefrontal cortex when people play against humans but not against computers. Similarly, McCabe et al. (2001) showed a significant activation in the prefrontal cortex when subjects played a cooperative game with a human as opposed to a computer. When playing the Prisoner's dilemma and the Ultimatum game, Rilling et al. (2004) showed stronger brain activations when humans played against humans than computers, clearly distinguishing whether a subject played against a human versus a computer partner. Rilling et al. (2004) also showed that participants rejected unfair offers from human partners more frequently than those from computers, while they cooperated with human partners more often.

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[5] In the trust game (http://en.wikipedia.org/wiki/Trust_game), one of the subjects acts as a decision-maker and receives a monetary amount. The first subject is told that she can send *any* amount of the initial amount to the second subject. Every dollar sent by the first subject is tripled by the experimenter before it reaches the second subject, who then gets to decide how much of the tripled money to keep and how much to send back to the first subject. After the second subject decides how much money to return, the game ends. The trust game is repeated many times as the two subjects build a reputation for reciprocity.

Table 1 summarizes the key brain areas activated in response to the identified processes:

Table 1. Summary of Brain Areas Activated for Focal Processes

Brain Area / **Process**	Dorsolateral Prefrontal Cortex	Ventromedial Prefrontal Cortex	Orbitofrontal Cortex	Medial Prefrontal Cortex	Limbic System	Amygdala	Anterior Cingulate Cortex	Nucleus Accumbens	Caudate Nucleus	Insular Cortex	Inferior Parietal Cortices
Decision Making	X		X		X	X	X				
Risk								X			
Uncertainty			X								X
Ambiguity	X						X			X	X
Loss										X	
Rewards			X	X		X		X	X		
Consumer Behavior	X	X			X						X
Theory of Mind				X			X				
Trust									X		
Distrust						X				X	
Cooperation			X								
Competition				X							X

Application of Cognitive Neuroscience to Information Systems Research

Cognitive neuroscience can create opportunities for IS research in two areas: (1) identifying the neural bases involved in IS phenomena to complement existing sources of data and help better understand, predict, and influence human behavior; and (2) identifying potential differences between existing IS theories and constructs and the underlying brain mechanisms that would call for strengthening or even questioning existing IS theories and constructs and building superior ones that better fit the brain's mechanisms.

This section suggests how IS research can take advantage of the rapidly emerging cognitive neuroscience literature in the social sciences, and how to utilize functional neuroimaging techniques to better understand IS phenomena. Since neuroimaging studies have identified the role of several brain areas in different processes and behaviors, IS researchers can start identifying how existing IS constructs map into specific brain areas. The localization of brain activity in response to IS constructs can provide valuable information about the dimensionality of IS constructs, and what brain areas (e.g., prefrontal cortex, limbic system, emotions) may be involved in IS constructs. For example, perceived usefulness may have a cognitive and an emotional element associated with increased utility. A review of the literature can help determine whether IS constructs are unidimensional or whether they span multiple brain areas, helping the development of new IS constructs and even questioning the dimensionality of existing IS constructs.

Neuroimaging studies can be designed specifically for IS constructs by measuring brain activation in response to stimuli that specifically aim to trigger these constructs, such as systems with different degrees of functionality (usefulness) and user friendliness (ease of use). Brain activation can be correlated with survey measurement items, linking brain activations with responses on existing IS scales. Moreover, neuroimaging studies can help determine the temporal order of IS constructs in response to a stimulus, uncovering a causal ordering among IS constructs (e.g., whether a system's ease of use precedes its usefulness). Having identified the localization of IS constructs in the brain, IS studies can examine whether activation in a certain brain area can predict a behavior. For example, activations in the caudate nucleus predict whether a person will act cooperatively in the future (Delgado et al. 2005), while activation in the insular cortex predicts whether a person will reject an offer (Sanfey, et al., 2003).

Neuroimaging studies can also help identify whether different stimuli spawn brain activation, thus testing potential antecedents of IS constructs. Studies can examine whether IT tools and designs spawn brain activation in the area a certain IS construct is supposed to be located. For example, whether new IT tools increase a system's usefulness, could be tested by showing activation in the brain's reward areas (nucleus accumbens, amygdala, caudate nucleus).

Finally, neuroimaging studies may question existing IS theories and assumptions. For example, Smith et al. (2002) questioned a well-known assumption in economics about the independence of payoffs and outcomes using a PET study. Future IS research can examine whether behavioral processes correspond to neurological findings.

Summarizing these possibilities, the cognitive neuroscience literature and functional neuroimaging techniques can help IS researchers (1) better understand the nature, localization, dimensionality, antecedents, and consequences of existing and new IS constructs, (2) challenge IS theories and assumptions, and (3) help build superior IS theories.

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, it would be beneficial to identify the neural correlates of the core TAM constructs (perceived usefulness and ease of use) to provide a basis for deeper theorizing about the causal processes that govern these constructs. TAM theorizes the role of several different cognitive appraisals of the IT artifact, such as judgments of relevance, quality and compatibility. Martin (2007) showed that humans have a dedicated brain circuitry for perceiving and knowing about tools. Perceptions of IT attributes may rely on the cortical areas that mediate uncertain object classification based on perceived attributes (Aron, et al., 2004; Grinband, et al., 2006). A better understanding of the brain mechanisms underlying perceptual processes could lead to superior IS theories of technology adoption and use and also belief formation in general.

Insights surrounding the "theory of mind" may enable IS researchers to better understand the nature and role of social influence on behavior. For example, the subjective norm construct in TAM2 (Venkatesh and Davis, 2000) is concerned with a user's perceptions of the beliefs that important others have about the focal behavior. The neuroimaging literature has identified the brain areas associated with representing others' beliefs and intentions (medial prefrontal and anterior cingulate cortex). It may be useful for IS research to theorize the brain mechanisms as users reason about the beliefs and intentions of others who have an effect on their motivation to adopt a system.

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 and the theory of planned behavior, 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. 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.

The cognitive neuroscience literature has made many advances in understanding how automatic processes, such as reinforcement learning processes, occur in the brain. These studies shed light on the brain areas associated with automatic adaptive decision making (Frank and Claus, 2006) and reinforcement learning with different probabilities, magnitudes, and delays of reinforcement (Fu and Anderson, 2006). As IS research increasingly focuses on the automatic and habitual behaviors that characterize post-adoption and use, it calls for better theories on the learning processes that govern habitual behavior. These reinforcement learning studies may thus contribute to a better foundation for the analysis of continuance behavior compared to reasoned action or planned behavior frameworks.

Dual process (controlled vs. automatic) theorizing about modes of cognition have begun to play a role in IS research linking external information influences to internal TAM constructs. For example, Bhattacherjee and Sanford (2006) drew upon Petty and Cacioppo's (1986) influential elaboration-likelihood model (ELM) from social psychology. ELM posits two distinct paths through which external communication shapes beliefs and attitudes: a central route, characterized by thoughtful information processing and high involvement, and a peripheral route characterized by lower elaboration of the information and lower involvement. The relative influence of the relevance and quality of an informational message about a system's benefits (a central cue) versus source credibility (a peripheral cue) on belief and attitude change depends on individual and situational differences. Note that central versus peripheral processing closely parallels the controlled versus automatic distinction. Cognitive neuroscience research has been instrumental in clarifying the distinct neural circuits that underlie controlled versus automatic processing modes (e.g., Lieberman, 2007), and it has specifically analyzed the brain structures involved with forming relevance and credibility judgments in decision making (e.g., Deppe, et al., 2005a). Overall, the cognitive neuroscience literature promises to substantially expand the domain of applicability for TAM theories beyond controlled conscious processes to encompass the fundamental role of automatic unconscious processes.

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 (prefrontal cortex) that mediates regulation of goal-directed actions intended to achieve delayed rewards (e.g., Hasselmo, 2005). The literature has many 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). Ridderinkhof et al. (2004) describes the interrelated functioning of brain structures responsible for monitoring ongoing actions and performance outcomes relative to progress toward goal and reward attainment (the posterior medial frontal cortex), on the one hand, with structures responsible for enacting needed adjustments to behavioral strategies (the lateral prefrontal cortex), on the other hand. These findings can help IS researchers build theories to understand the relationships among intentions, use, and goal attainment in the context of system use.

IS 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. Cognitive neuroscience showed the brain specialization of emotion and cognition ("ventromedial and orbitofrontal areas subserve emotional function, whereas lateral and dorsal areas subserve cognitive function," (Gray and Braver 2002, p. 4116). Ochsner et al. (2002) studied the role of cognitive reappraisals (in the lateral and medial prefrontal cortices) on emotional activation (amygdala and medial orbitofrontal cortex). Kalish et al. (2005) located the site of expected anxiety modulation (medial prefrontal and anterior cingulate cortex). 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.

Overall, the frontiers of technology adoption and use about belief formation and change, behavior self-regulation, social influences, automatic processes, and affect may be advanced by cognitive neuroscience theory and methods.

Electronic Commerce

Electronic commerce has become a core research area in the IS literature. We argue that the cognitive neuroscience literature and functional neuroimaging studies can help further enhance the IS literature on e-commerce.

Since e-commerce transactions are inherently uncertain (Pavlou, et al., 2007), the neuroimaging literature has localized brain activity when subjects are faced with risk (nucleus accumbens) (Knutson, et al., 2001), uncertainty (prefrontal and parietal cortex) (Huettel, et al., 2005), and ambiguity (insular cortex) (Hsu and Camerer, 2004). Besides verifying that risk, uncertainty, and ambiguity are distinct constructs associated with different brain areas, IS researchers can assess the degree of risk, uncertainty, and ambiguity of different websites, link them to specific IS constructs, and predict whether consumers will transact with these websites. For example, risk can be linked to seller opportunism, uncertainty to fulfillment timing, and ambiguity to privacy and security concerns. IS researchers can also assess the effects of IT stimuli (e.g., third-party accreditation, consumer feedback, privacy and security seals) and website characteristics on brain activation to examine whether they reduce risk, uncertainty, and ambiguity.

The IS literature has also focused on building trust to reduce risk and uncertainty (Pavlou and Dimoka, 2006). Cognitive neuroscience has shown that trusting intentions activate the caudate nucleus, which predicts if the person will act cooperatively (King-Casas, et al., 2005). This helps IS researchers examine whether potential trust-building mechanisms spawn activation in the caudate nucleus. The neuroimaging literature also distinguished between trust and distrust (amygdala and insular cortex), supporting the trust literature that these two constructs are distinct. The literature also distinguished between the prefrontal cortex and the limbic system (Bhatt and Camerer, 2005) as the cognitive and emotional areas of the brain, respectively. This distinction supports the trust literature that argues that trust has a cognitive and an affective component, but it allows IS studies to examine whether credibility is associated with the cognitive part of the brain, and whether benevolence is associated with the emotional part of the brain.

A major e-commerce limitation is the delay in receiving products (Pavlou and Gefen, 2005). The neuroimaging literature on immediate rewards (limbic system) and delayed rewards (lateral prefrontal and inferior parietal cortex) can inform how consumers make decisions about purchasing online or in traditional stores. The instant gratification construct may relate to brain activation in the limbic system, while delayed gratification may relate to the rewards area of purchasing online at a lower price and higher convenience. IS researchers can examine whether brain activation in these areas can predict whether consumers will purchase online, what rewards and promotions sellers must offer to spawn brain activation in the prefrontal and parietal cortices, and whether such activations would persuade consumers to purchase online. IS researchers can also examine how much to price expedited shipping, how mail-in rebates enable planned spending, how instant promotions trigger and how cooling-off periods prevent impulse purchases by allowing more "rational" brain areas to take over, and how to prevent product returns.

The neuroimaging literature also showed that consumer decision-making involves the orbitofrontal (cognitive area) and the amygdala (emotional area) (Hsu, et al., 2005). Depending on which brain area is mostly activated during online purchasing, IS researchers can distinguish between utilitarian and hedonic consumers, identify whether consumers "need" or "like" certain products, and whether activation in the cognitive or emotional area better predicts whether consumers will purchase different types (utilitarian or hedonic) products.

The neuroimaging literature on rewards and utility can help understand the tradeoff between personalization and privacy. While personalization benefits are likely to spawn the consumer's utility areas (nucleus accumbens, orbitofrontal cortex, caudate nucleus), privacy concerns are likely to activate the areas associated with pain and loss (insular cortex). IS studies can determine how online sellers can provide personalization rewards by using private information without making consumers fear about their privacy and activating their brain's insular cortex.

E-commerce is an instance of human-computer interaction. The cognitive neuroscience literature showed that brain activation is usually more pronounced when subjects interact with humans than computers (McCabe, et al., 2001). Accordingly, the design of websites and online recommendation agents (Komiak and Benbasat, 2006) can have a human-like character to spawn greater activation in the orbitofrontal cortex that captures cooperative intentions.

In sum, the cognitive neuroscience literature can help IS researchers strengthen e-commerce theories by drawing upon knowledge of the brain mechanisms underlying online consumer decision-making, trust, uncertainty, and risk, rewards and pricing, rationality and emotions, personalization and privacy, and human-computer interaction.

Group Decision Support Systems (GDSS)

The neuroimaging literature on decision making and cooperation can potentially help advance the GDSS literature, particularly in terms of designing systems that enable better group decisions and facilitate collaborative group work.

Since the human brain has a cognitive and an emotional component, Bhatt and Camerer (2005) showed that subjects with brain activation in both areas were the most effective in experimental tasks. Drawing upon this information, GDSS can be designed and used to induce decision makers to engage both the cognitive (prefrontal cortex) and emotional (limbic system) parts of their brain, and examine their effects on superior decisions. Also, since activation in the anterior cingulate cortex is linked to superior cognitive control and performance (van Veen and Carter, 2005), IS researchers can design GDSS to induce activation in the anterior cingulate when subjects make decisions.

Cognitive neuroscience distinguishes between cooperation (orbitofrontal cortex) and competition (medial prefrontal and inferior parietal cortices) (Decety, et al., 2004). This can promote group cooperation by designing GDSS functionalities to spawn activation in the "cooperative" brain areas and prevent activation in the "competitive" areas.

IS researchers started investigating issues surrounding dual-task interference, multitasking, and task switching (Heninger, et al. 2006). Given a person's limited attention, cognitive neuroscience has shown that secondary tasks can be less disruptive to primary tasks if the former are mastered to the point of automaticity (Kunde et al. 2007). This information can be used to design GDSS that automate secondary tasks to prevent dual-task interference.

Outlining a "Neuro-IS" Study

IS researchers may believe that neuroimaging techniques are inaccessible or costly. However, these misconceptions are far from reality. Similar to how IS research largely draws from other disciplines for theories and tools, IS researchers can also learn the basic neuroscience concepts and neuroimaging techniques (as outlined in this paper). Research in neuroeconomics and neuromarketing offers guidance about the level of familiarity with the cognitive neuroscience literature required by IS researchers to employ functional neuroimaging techniques in their studies.

Formulating the Research Question

Similar to all research projects, neuroIS projects must start with a meaningful problem, especially one that cannot be fully examined with other research methods. Having developed the hypotheses, it is important to assess whether they can be tested with a neuroimaging study or a combination of other techniques. For example, an fMRI study can be combined with survey questions before and/or after the fMRI session to match fMRI data with survey responses.

Selecting the Neuroimaging Technique and Accessing Neuroimaging Facilities

The next step is to select a functional neuroimaging technique (fMRI, PET, EEG, MEG). Each technique has its advantages and disadvantages. If the study requires a high spatial resolution, fMRI and PET must be used. If the study requires high temporal resolution, EEG or MEG should be used. A study that requires both a high temporal and spatial resolution could use a combination of these techniques (such as fMRI or PET with EEG/MEG). Appendix 3 reviews the four functional neuroimaging techniques and compares their advantages and disadvantages.

In terms of getting access to functional neuroimaging facilities, most metropolitan areas have neuroimaging centers (either in hospitals or Universities) that usually offer their facilities for a modest fee. For example, using an fMRI machine (which is the most expensive functional neuroimaging technique) usually costs about $200 per hour to rent, which allows to conduct experiments with 2 subjects. Considering that most neuroimaging studies only require 5-15 subjects, a neuroimaging study can be completed with less than the cost of a typical survey or lab experiment.

Designing the Experimental Protocol

The next stage is to translate the hypotheses into an experimental protocol to guide the neuroimaging studies. Similar to all controlled experiments, it is important to design an experimental protocol with the appropriate tasks, manipulations, and controls to assure that no biases are created by the experimental design. The literature should serve as guide in designing appropriate experimental protocols. Neuroimaging techniques require a comparison of people performing different tasks – an "experimental" task and a "control" task. Ideally, the control task must activate exactly the same brain areas as the experimental task, except the brain area under investigation. The difference between the images taken while the subject is performing the two tasks shows what part of the brain is differentially activated by the experimental task. For example, fMRI and PET use a 'subtraction' method to statistically identify regional brain activation during a task by measuring brain activity during the task of interest and then removing all activations spawned in the control task. Therefore, choosing an appropriate control task is a major feature of functional neuroimaging studies.

Data Analysis and Reporting

To compare activations across subjects, the brains must be spatially normalized to a template brain, i.e. they are transformed so that they are similar in size and spatial orientation. There are two popular packages used to analyze brain images - Statistical Parametric Mapping (SPM) (http://www.fil.ion.ucl.ac.uk/spm/) and Brain Voyager (http://www.brainvoyager.com/). Both packages use statistical (generalized linear) models to identify the significant differences above background brain activity and highlight the brain areas of activity linked specifically to the process under investigation. Learning to use SPM and Brain Voyager is comparable to learning LISREL and PLS.

Similar to common statistical data analysis techniques, the analysis of brain imaging data is conducted at the aggregate level by combining the normalized brain activations of all subjects in the sample. Since the analysis uses correlation-based methods to link brain activations with decisions and behaviors at the aggregate level, a sample of about 10-15 subjects is often required. However, the analysis is *not* conducted individually for each subject, and it is necessary to aggregate all subjects to account for individual variations and noise in the data.

Summary

In sum, performing a "neuro-IS" study is similar in principle to designing an experimental or survey study that entail some basic principles for assuring that the responses are due to the experimental or survey manipulations and not due to confounding or spurious effects. However, given the need to use advanced neuroimaging tools, IS researchers are encouraged to initially team up with researchers who are familiar with functional neuroimaging techniques, such as neuroscientists, neuroeconomists, or neuromarketers, at least in their first studies. Collaborations between IS and other researchers can help familiarize IS researchers about experimental techniques, designs, and procedures.

Discussion

Advances in neuroimaging techniques now make the direct and objective measurement of human thoughts, beliefs, and feelings possible for the first time, opening the "black box" of the human brain. IS researchers stand to gain by becoming intelligent users of the cognitive neuroscience literature that delineates the brain mechanisms that underlie human behavior and processes. This paper aims to promote the use of the cognitive neuroscience literature and facilitate the employment of functional neuroimaging techniques in IS research to strengthen existing IS theories, offer new perspectives on emerging IS theories, and develop new IS theories that more closely correspond to the brain's circuitry functionality. In sum, this paper aims to enhance the diversity of theories, methods, and techniques available in the 'toolkit' of IS researchers needed to attack complex IS phenomena.

Implications for Theory

In terms of theory development, cognitive neuroscience can shed light on whether IS constructs are consistent with the brain's circuitry, or whether we need to redefine IS constructs to more closely correspond to the brain's circuitry. It can also shed light on the nature of existing and new IS constructs by identifying whether a construct spans different brain areas, and whether these areas correspond to cognitive (prefrontal cortex) areas, evolved emotional areas (limbic system), more primitive emotions, or other specific processes identified in the literature (Table 1). It can also inform if IS constructs (which may be considered distinct in the literature) also have a distinct brain circuitry, potentially challenging prevalent assumptions in the IS literature, similar to how Smith et al. (2002) and Hsu et al. (2005) challenged economic theories on the independence of payoffs and decisions. Finally, constructs that are deemed unidimensional in theory and measurement may in fact span multiple distinct brain areas, challenging the dimensionality of existing IS constructs and calling for their potential reconceptualization.

Implications for Research

In terms of measurement, functional neuroimaging techniques can offer data on brain functionality to complement existing sources of data. Brain data are valuable complements because they are direct, objective, and reliable, and they do not suffer from subjectivity biases, such as social desirability, common methods, and demand effects. Notably, Mast and Zaltman (2005) stated: "But if questionnaires, verbal reports and interviews all fail to predict behavior, what other methods are there we could use instead?" Neuroimaging data can complement human language and verbal reports that ignore the underlying brain processes that drive a human behavior, helping IS researchers get a more complete and accurate picture of human behavior. In terms of diversity of methods and tools, functional neuroimaging data can give yet another promising tool in the repository of IS researchers.

Future Research

Besides the exemplar suggestions for future IS research in technology adoption and use, e-commerce, and GDSS, other IS areas can potentially benefit from the cognitive neuroscience literature and functional neuroimaging tools. For example, the literature on IT labor can draw upon the neuroimaging literature on rewards that has identified the brain areas activated in response to the magnitude (Hsu, et al., 2005), predictability (Knutson, et al., 2001), and timing of rewards (McClure, et al., 2004c). This information can be used to devise favorable compensation schemes for IT employees. Also, the IS strategy literature can benefit by drawing upon the knowledge of how people evaluate the magnitude and probability of gains and losses to strengthen theories on how IT executives make IT investments.

Neuroimaging studies are not restricted to the individual as the unit of analysis. For example, Lo and Repin (2002) examined the brain responses of 10 professional foreign exchange traders in an fMRI study during a simulated market volatility while managing actual currency contracts of over $1,000,000. While obviously brain activations need to come from individual subjects, research can extend to multiple units of analysis. At the group level, GDSS research can examine group-level effects by examining several members of a group. For instance, King-Casas et al. (2005) examined two individuals in two separate fMRI scanner who simultaneously engaged in a cooperative game. At the organizational level, it is possible to obtain brain data from key organizational members (key respondents), such as IT executives or managers. At the cultural level, studies are performed by examining individuals from different cultures. For example, a comparison of Chinese and American preschoolers found that the underlying processes related to the theory of mind are consistent across the two cultures, although significant differences in executive functioning were found across the two cultures (Sabbagh, et al., 2006). Similar to cross-cultural research that identifies differences across people from different cultures, neuro-IS studies can study whether brain activations differ across individuals from different cultures. In fact, there are calls for future research to examine the brain areas involved in culturally-shaped moral values and norms (Moll, et al., 2005). Finally, the literature has extended to social processes by emphasizing the theory of mind (Amodio & Frith, 2006; Lieberman, 2007; Saxe, et al. 2004). Taken together, neuro-IS is not limited to the individual as the level of analysis but can extend to multiple levels as long as it is possible to obtain brain activations from key respondents from the various levels of analysis.

Conclusion

Despite the demonstrated potential of cognitive neuroscience for the social sciences, IS researchers could continue to ignore its potential for IS research. However, to ignore emerging theories about brain functionality and a major new source of objective brain data may be a huge disservice to the IS field. This paper's basic premise is that cognitive neuroscience can open up new research directions that could accelerate our progress toward understanding the complex issues on the interplay of IT tools and human behavior by integrating a rigorous scientific foundation for IS research that integrates objective data on brain activity. We hope that cognitive neuroscience and the use of neuroimaging techniques triggers a revolution in IS research that fundamentally strengthens the IS discipline. Overall, it is just hard to believe that a better understanding of brain functioning will not lead to better IS theories.

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Appendix 1

Brain Basics

The human brain is divided into two hemispheres and four lobes: *frontal*, *parietal*, *occipital* and *temporal* (Figure 2). Each lobe plays distinct roles that help subserve specific functions, as explained below:

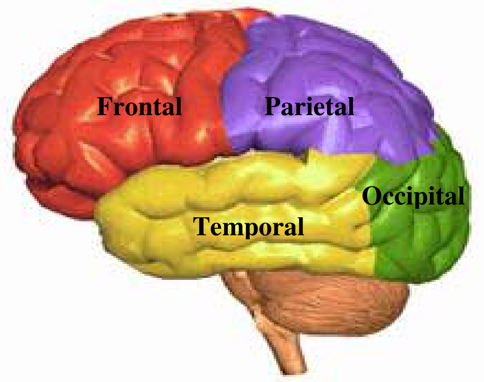

Figure 2. The Brain's Four Lobes

Frontal Lobe: The frontal lobe is located just behind the forehead. Being the most highly evolved lobe of the brain, it distinguishes humans from other primates, and it is responsible for purposeful acts such as creativity, reasoning, judgment, problem solving and socialization. The frontal lobes assist in planning, coordinating, controlling, and executing behavior. It is also involved in language, memory, impulse control, and motor function and skills. The frontal portion of the frontal lobe is called the prefrontal cortex that is responsible for "higher cognitive functions" and human personality. The back portion of the frontal lobe consists of the premotor and motor areas.

Parietal Lobe: The parietal lobe is situated behind the frontal lobe. The parietal lobe is the least understood brain lobe, but is the principal integrator of sensory and emotional information, such as touch, taste, pain, and temperature.

Occipital Lobe: The occipital lobe is located at the back of the brain, and it is responsible for interpreting visual stimuli, processing visual information, and recognizing objects. An injury to an occipital lobe could cause blindness.

Temporal Lobe: The temporal lobe is found under the parietal lobe, and it is responsible for hearing, memory, and meaning by interpreting and processing auditory stimuli. It also plays a role in emotion, perception, recognition and learning. The right temporal lobe is mainly involved in visual memory (i.e., memory for pictures or faces), while the left temporal lobe is mainly involved in verbal memory (i.e., memory for words and names).

While the frontal lobe is primarily engaged in controlled (planned) activities that require thought, the occipital, parietal, and temporal lobes are responsible for automatic activities. Despite their distinction, these four lobes are interconnected with neurons that allow humans to act by receiving, processing, and integrating multiple stimuli. For example, while controlled processes occur primarily in the prefrontal area of the frontal lobe ("executive" region), this brain area receives inputs from all other lobes and integrates them to form goals and plan actions.

Appendix 2

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, cognitive performance, intelligence levels, memory retrieval, and problem-solving skills.

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., 2000). 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).

To describe the various areas of the brain, the literature uses a set of standard terms, as shown in Table 2.

Table 2. Description of Standard Terms for Representing Brain Areas

Term	Anterior	Posterior	Dorsal	Ventral	Superior	Inferior	Medial	Lateral	Orbital
Explanation	Front	Back	Top	Bottom	Toward Top	Toward Bottom	Middle	Away from Middle	Above Eyes

Appendix 3

Overview of Functional Neuroimaging Techniques

Four functional neuroimaging techniques are commonly used to observe brain activation, two that measure changes in cerebral blood flow (fMRI and PET), and two that measure electromagnetic brain activity (EEG and MEG).

Functional Magnetic Resonance Imaging (fMRI)

fMRI is able to localize and track changes in blood oxygenation (a proxy for neural activity) during cognitive tasks. Due to its excellent spatial resolution, fMRI is currently the most commonly used functional neuroimaging tool. Magnetic resonance scanners produce sets of cross sections of the brain, exploiting resonance signals that are emitted by tissue water in a very strong magnetic field after excitation with a high frequency electromagnetic pulse. These resonance signals can be attributed to their respective spatial origin, and cross sectional images are calculated. Signal intensity depends on water content and certain magnetic properties of the local tissue.

The ability to visualize brain activity with fMRI depends on the fact that increased neural activity of a brain region is followed by a hemodynamic response. The resulting color-coded statistical parametric activation maps (SPMs) are generated from elaborate statistical analyses of fMRI time series comparing signal intensity during different activation states. With today's fMRI scanner technology, structural images are usually obtained with a resolution of about 1mm × 1mm × 1mm voxels (the equivalent of a pixel in a volume). As a rule, fMRI temporal resolution is about 1 second. For evaluation, however, one must also take into account that the cerebral blood flow response to the brain's activation is delayed by about 4–5 seconds.

Positron Emission Topography (PET)

PET also measures blood flow in the brain, which is a reasonable proxy for neural activity. PET imaging allows visualization of specific neurochemical changes in the brain. After injection of certain radioactive neurotransmitters, their spatial distribution can be detected by a PET scanner. PET scanners are sensitive to the radiation that results from the annihilation of emitted positrons when they collide with ubiquitously present electrons. From the detected distribution, information concerning metabolism or brain perfusion can be visualized. The spatial resolution of PET is quite high (about 3–6 mm), but its temporal resolution is very low (several minutes).

ElectroEncephaloGraphy (EEG)

EEG uses electrodes attached to the scalp to measure voltage fluctuations synchronized to behavioral responses. An electrode on the skin detects the summed potentials generated by a large number of neurons. While EEG has a temporal resolution in the order of milliseconds that can easily detect the time course of neural activity, its spatial resolution is mainly limited by the infinite number of source configurations that can generate identical potentials on the skull. Estimating solutions of source localization requires appropriate strict assumptions about sources and volume conduction to yield physiologically meaningful data. EEG is thus primarily used for its temporal resolution.

MagnetoEncephaloGraphy (MEG)

MEG is sensitive to changes of magnetic fields that are induced by electrical brain activity. The temporal resolution can be compared to EEG. However, in contrast to EEG, MEG can also depict activity in deeper brain structures. The limitation of spatial resolution also applies to MEG, and source localization also depends on a set of assumptions.