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Applying Functional Near Infrared (fNIR) Spectroscopy to Enhance MIS Research

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Research Commentary

Applying Functional Near Infrared (fNIR) Spectroscopy to Enhance MIS Research

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Abstract

This review paper introduces the emerging technology of optical brain imaging, also known as functional near infrared (fNIR) spectroscopy, and discusses its potential role in enhancing theory and methodology used in MIS research. We discuss basic fNIR principles including the technique's safe and portable nature, which allows ambulatory brain activity assessment in real world environments. We then touch on the neural correlates that fNIR measures, and the cortical oxygenation changes in the dorsal and anterior regions of the prefrontal cortex. We compare fNIR with traditional neuroimaging methods such as fMRI and PET. We also list case studies, future directions, and potential approaches relevant to MIS. fNIR may be used to inform theory and improve assessments in MIS-based studies, including informing theory, by identifying neural correlates, studying constructs that could not easily if at all be measured with traditional methods, applying objective constructs that subjects are unaware of, and designing better surveys.

Keywords: Functional Near Infrared (fNIR) Spectroscopy, Brodmann Area 9, Brodmann Area 10, Dorsolateral Prefrontal Cortex, Anterior Prefrontal Cortex.

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1. Introduction

The importance of neuroscience and its potential is recognized in management information systems (MIS) research (e.g., Dimoka et al., 2012; Riedl et al., 2010a). Recent studies utilizing neuroimaging techniques such as functional magnetic resonance imaging (fMRI) have provided invaluable insight into key topics of interest to the MIS community. Dimoka et al. (2012), for example, show that trust and distrust are distinctly different constructs because each is apparently processed mainly in different brain regions. Those neural correlates imply that trust is associated with brain regions related to rational thought, while distrust is associated more with brain regions known to be related to emotional fear reaction. Likewise, Riedl, Hubert, and Kenning (2010b) provide a neural mechanisms-based explanation of why men and women are different in their trust processing. In both cases, neuroscience provided answers that haunted survey-based MIS research for quite some time and could not be convincingly answered by survey and ethnographic research alone. Studies employing neuroscience are, however, still quite rare, possibly because of the high cost involved and the extraordinary training needed to conduct fMRI and PET studies. This paper introduces a more affordable and versatile neuroimaging tool, optical brain imaging, that, despite its lesser resolution and limited application only to the prefrontal cortex (PFC), can provide an alternative that more social scientists can apply and that, because of its versatility, can address research contexts where fMRI would be less applicable.

Adding fNIR into the MIS toolbox is important for several reasons. First, revealing neural mechanisms and their relation to behavior can enhance our understanding of MIS in general. This could be crucial in developing theory because already certain brain areas can be associated, even if only on a broad level, with certain types of emotion and other constructs of interest to social sciences (Dimoka, 2011). fNIR can also be beneficial in the creation of better IT interfaces and research questionnaires. Second, because fNIR instrumentation can be portable, wearable, and even battery-operated and wireless (Ayaz et al., 2013), it provides the ability to measure objective brain-based assessment metrics in natural working environments. Such environments typically place many restrictions on the subject that make other types of neuroimaging impractical. These metrics can supplement the behavioral measures and subjective self-reported measures. Technology is already moving toward that direction with other kinds of wearable imaging.

2. What is fNIR

2.1. An Overview

fNIR is an emerging neuroimaging technique that has recently been added to the neuroscience toolbox. The ability to monitor the brain in real world settings without or with minimal restrictions to the participants can shed light on unknown cognitive processes, lead to a better understanding of the brain, and potentially optimize MIS approaches. fNIR enables such neuroimaging by monitoring the oxy-hemoglobin and deoxy-hemoglobin concentration changes in the cortical tissue in the brain via a non-invasive, affordable, and relatively non-limiting manner (Chance, 1991, 1998; Chance, Chuang, UnAh, Alter, & Lipton, 1993; Hoshi & Tamura, 1997; Villringer & Chance, 1997; Villringer, Planck, Hock, Schleinkofer, & Dirnagl, 1993). fNIR sensors utilize near-infrared light that is sensitive to the hemoglobin molecule that carry oxygen that is vital for nerve cells. By tracking the changes of the hemoglobin molecule over time and at different brain areas, activations of respective areas can be monitored.

Figure 1 (left side) shows a light emitting diode (LED) based incarnation of near-infrared spectroscopy that was manufactured by a Drexel University start-up and is based on the work of the biomedical optics pioneer Professor Britton Chance. As the figure shows, this device is relatively small, portable, and field deployable with minimal limitations on the subject. It is also easy to use and safe. The combination of the four LEDs and 10 detectors results in 16 measurement locations, known as optodes, that cover the full forehead of the participant for assessing the anterior prefrontal cortex. Figure 1 (right side) shows these LEDs and detectors together with the corresponding brain areas in the PFC. The fNIR headset is placed on the forehead so that the bottom of the device is just above the eyebrows and its middle line is in line with the nose. This means that the center of the device approximately corresponds to the separation of the left from the right cortex hemispheres in the PFC. Figure 1 (right side) shows this separation as the dark area between sensors 9 and 10 on the one side and 7 and 8 on the other. The positioning of fNIR in this location means that fNIR measures the left and right dorsal and inferior anterior prefrontal cortex areas (Ayaz et al., 2006; Ayaz et al., 2012; Bunce, Izzetoglu, Izzetoglu, Onaral, & Pourrazaei, 2006;

Izzetoglu, Izzetoglu, Bunce, Onaral, & Pourrezaei, 2005).

Figure 1. The fNIR Sensor (left) and Measurement Locations (right)[1][2]

2.2. The Measures

The biological process fNIR records is the change in levels of oxyhemoglobin (*HbO*) and deoxyhemoglobin (*HbR*) concentrations in the red blood cells as their hemoglobin binds to and releases oxygen, respectively. Blood oxygenation, specifically oxygen supply in the brain, is tightly regulated, and slight fluctuations in the blood oxygenation are connected to neural activation of the immediate surrounding cortical tissue through a well-known paradigm called neurovascular coupling. The increase in oxygen-rich blood after increased activity is called hemodynamic response. Hemodynamic response is delayed by at least 2-3 seconds, and up to 6-8 seconds. fNIR tracks these relative changes in brain activity through changes in the concentration changes of HbR and *HbO*. fMRI also tracks the hemodynamic response, through blood oxygen level dependent (BOLD) signals, but only with one time-series for each brain region as opposed to four time-series in fNIR. The four time-series measures in fNIR are oxy-hemoglobin, deoxy-hemoglobin, total-hemoglobin (estimate of blood volume), and oxygenation (difference in hemoglobin).

The temporal resolution of the fNIR sensor depicted in Figure 1 (left side) is 500 milliseconds, which means a complete scan of all 16 optodes with 3 channels in each is completed twice a second. Light absorption is dominated by *HbO* and *HbR* in the 700 nm to 900 nm wavelength. The LEDs emit light at two wavelengths: one above and one below the isosbestic point of *HbO* and *HbR* (i.e. where light is absorbed more or less equally by *HbO* and by *HbR*—at 805 nm) (Cope et al., 1988; Jobsis, 1977; Villringer & Chance, 1997). Hence, one of thewavelengths, 730 nm, is more sensitive to HbR, and the other wavelength, 850 nm, is more sensitive to HbO. The measurement location is a volumetric area in the middle of light source and detector. The depth of measurement volume from the surface is a function of the light source and detector distance. It is approximately half of the distance between the light source and the detector. The sensor pad shown in Figure 1 (left side) has a 2.5 cm source-detector separation,

[1] Adapted from Ayaz et al. (2012). Also appears at http://drexel.edu/conquer/research/presentations/
[2] Source http://www.biomed.drexel.edu/fNIR/CONQUER/Optical_Brain_Imaging.html

which forms a tight grid of 2 by 8 covering the forehead.

The LEDs are activated one at a time in sequence. Each time an LED is activated, the four detectors surrounding it are sampled. The sensors measure the light that is reflected back from the red blood cells through the scalp and skull. Using reflectance mode near-infrared spectroscopy for cortical tissue assessment was first reported by Jobsis (1977). The arrangement of the four LEDs and 10 sensors, shown at the top of Figure 1 (right side), results in the data being collected in 16 channels. For each of the 16 channels, fNIR shows the level of *HbO* in red and of *HbR* in blue. The combined value of the two, measuring blood volume, is shown in green. A sample of this output is shown in Figure 2 as these levels change over time for a single subject in a single treatment condition. All the analyses are done for each subject in each session individually. Typically, a single trial measurement interval can be around 30 seconds long and multiple trial/repetitions with multiple experiment conditions can yield experiment times anywhere between 5-10 minutes to a couple of hours. fNIR shows the changes in *HbO* and *HbR* compared to the resting time level that is measured prior to the actual experiment (Ayaz et al., 2012).

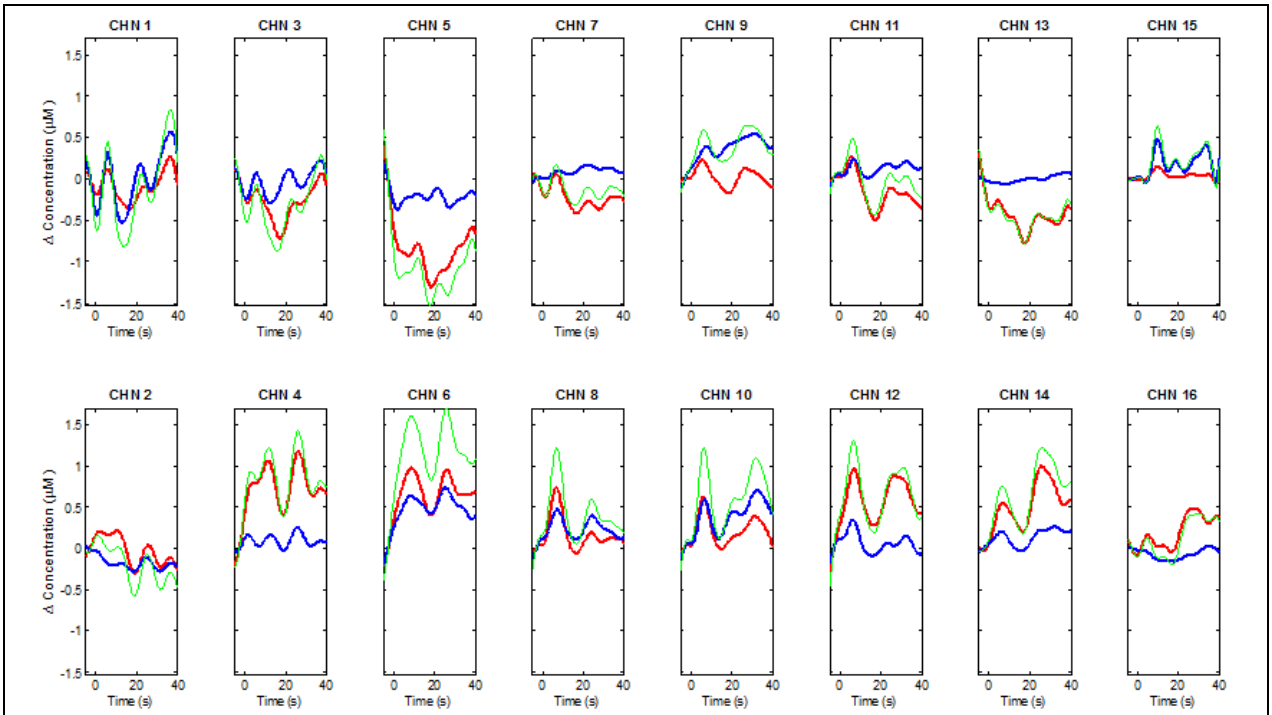

Figure 2. Sample Output of fNIR by Optodes

2.3. Signal Analysis in Brief

The combined changes in the received light intensities at 730 nm and 850 nm enable absorption assessment and can be used to calculate the relative changes in *HbO* and *HbR* over time by applying a modified Beer-Lambert law based on a method proposed by Cope et al. (1988). Infrared light is partially absorbed (due to light absorbing molecules like hemoglobin and water) and scattered (due to inhomogeneous layered structure) as it travels through the body. The light-absorbing molecules, chromophores, that interact mainly within the 700-900 nm wavelength range are *HbO* and *HbR* (Ayaz et al., 2012). By comparing the logarithmic ratio of the emitted light and the detected light of these two wavelengths, considering the absorption level of each in tissue and the distance between the LED and the sensor, the relative change in the optical density can be calculated. The algorithm for doing this applying the Beer-Lambert law is detailed in Cope et al. (1988), and its application in fNIR in Ayaz et al. (2012). Data are passed through a low-pass frequency filter before the Beer-Lambert analysis to filter out physiological and high frequency noise in signals, such as the signal component related to the cardiac cycle (changes in blood pressure from one heartbeat to the next) and respiration rate (Izzetoglu et al., 2005). Other automatic noise reduction algorithms include independent component analysis, principal component analysis, and optimal filtering (Ayaz, Shewokis, Curtin, Izzetoglu, & Onaral, 2011).

Typically, oxygenation levels are used to assess brain activation due to experimental conditions. Oxygenation changes are calculated as *HbO – HbR.* Also, time averaging can be used to get mean activation in a given time period. The output of this signal processing analysis is a set of 16 data points, one for each optode, as these change in time for each individual in each treatment. The signals must be adjusted individually for each subject because of variations in skin color, complexity, perspiration, and so on. These adjustments involve setting the strength of the LED lights, detector sensitivity, and default adjustments in the COBI Studio software (Ayaz et al., 2011). These adjustments need to be done prior to the actual data collection in the experiment for each subject individually. Once the device has been adjusted to the subject, a baseline measure is taken. This baseline value will be used to test changes in subsequent cortical hemodynamic response values as the subject is exposed to the treatments in the experimental design. Setting individual baselines is important because fNIR readings vary substantially across subjects, as does the biology it measures (Blood, Zatorre, Bermudez, & Evans, 1999).

Current convention in fNIR is to report activity in all of the optodes (Ayaz et al., 2012). Some researchers, such as Katayose, Nagata, and Kazai (2006), Ayaz et al. (2011), and Moghimi, Kushki, Guerguerian, and Chau (2012), report an overall average over the entire PFC. Others, such as Matsuda and Hiraki (2006), report activity averaged out in four regions created by grouping the optodes in to a 2-by-2 set of boxes representing anterior left, anterior right, posterior left, and posterior right.

2.4. Within-Subject Design

The fNIR data after the filtering and Beer-Lambert analysis can then analyzed in the same way that survey or archival data are analyzed with regression or analysis of variance methods. Also, other advanced methods such as linear mixed models have been applied for statistical comparison (Baayen, Davidson, & Bates, 2008; Langers, Jansen, & Backes, 2007; McKendrick, Ayaz, Olmstead, & Parasuraman, 2014; Singh & Dan, 2006). The CONQUER CollabOrative group recommends applying within-subject statistical design analyses because of possible inter-subject variation such as metabolic differences (Ayaz et al., 2011). For example, Matsuda and Hiraki (2006) report that, among the 13 children they examined, there was high variability in recorded activity in the PFC during video games. Katayose et al. (2006) also report that not all subjects responded the same. In their case, only four of the five subjects showed increase in *HbO* as they heard music.

3. Potential Neural Correlates Identified by fNIR

Understanding the cortical hemodynamic response activity in the regions of the PFC recorded by fNIR can be advised by previous fMRI research. fNIR records data from the PFC, and specifically regions that overlap partly with the outer regions of Brodmann Areas 9 and 10. Brodmann Area 9, BA9, is located in the dorsolateral PFC. Brodmann area 10, BA10, is the anterior prefrontal cortex. BA9 and BA10 are associated with executive functions such as assessment and short-term memory (Marley, 2011). Research using fNIR has not discussed at depth what meaning to assign to the left and right regions of BA9 and BA10. In some cases (e.g., Ayaz et al., 2012), fNIR results were discussed as indictors of overall cognitive activity in the executive functions of the brain.

3.1. The Right Dorsal Region of the PFC

The dorsolateral PFC has been associated in previous fMRI research to trust created through reciprocal exchanges in trust games (Baumgartner, Heinrichs, Vonlanthen, Fischbacher, & Fehr, 2008; Delgado, Frank, & Phelps, 2005; King-Casas et al., 2005; Krueger et al., 2007; McCabe, Houser, Ryan, Smith, & Trouard, 2001). Related neural correlates associated with this region are suggested by fMRI research by Pliszka et al. (2006). Pliszka et al. showed that activity in the right dorsal region of the PFC is associated with conscious inhibition of elective behavior. Pliszka et al. requested subjects while inside an fMRI machine to press a button when they saw one card, what they called the “go condition”, or to refrain from doing so if after seeing the first card they were exposed to another card, what they called the “no go condition”. They reported that the right dorsal region of the PFC was more active in the no go condition. In other words, it may be that increased activity in this region indicates conscious inhibition of behavior. Maybe because this region is associated with response suppression, it is also associated with attention deficit hyperactivity disorder (ADHD) (Rubia et al., 1999). Perhaps also supporting this association, Shulman et al. (1997) suggest, based on a review of positron emission tomography (PET) studies, that

reduced activity in this region is associated also with reduced spontaneous thought unrelated to the task subjects are currently doing. Interestingly, BA9 seems to be related to psychiatric disorders too (for more details read Marley (2011)).

3.2. The Left Dorsal Region of the PFC, BA9

The left anterior regions of BA9 and BA10 are more active when subjects read a passage and need to predict how the story they just read will develop (Chow, Kaup, Raabe, & Greenlee, 2008). Also, fMRI research shows that subjects asked to evaluate whether a picture matches a sentence they had just read had a more active left superior medial frontal gyrus (partly overlapping the left region of BA9) when that sentence was idiomatic compared to a literal sentence (Lauro, Tettamanti, Cappa, & Papagno, 2008). Likewise, Hugdahl et al. (1999) report increased activation in the left middle frontal gyrus (partially overlapping BA9) when subjects performed a semantic categorization of proposing words that match a given category, such as U.K. soccer clubs.

Left BA9 is active not only in verbal contexts. The left dorsolateral PFC is also more active when subjects are involved in multiple relational integration problems. Relational integration problems involve choosing what figure to add into a 3-by-3 set of figures in which one figure is left out. Multiple relational integration problems involve matching the missing figure based on the patterns in both the rows and the columns. In multiple relational integration problems, but apparently not so when choosing a figure to match the pattern of only the rows or only the columns or just choosing a figure that is the same as all the other 8 figures in a 3-by-3 block when all the 8 figures are the same, BOLD signals indicated increased activity in the left dorsolateral PFC and in BA10 (Christoff et al., 2001)[3]. Additionally, when subjects assessed in a questionnaire how easy it was to use a website, their left dorsolateral PFC was more active (Dimoka et al., 2011).

The left dorsal region of the PFC, just as the right region, may also be involved in conscious elective behavioral inhibition, but regarding verbal activity. Elliot, Dolan, & Frith (2000) asked subjects to complete a sentence by adding the missing word. They reported that the left dorsolateral prefrontal cortex was more active when the subjects were asked to add a word that did not fit the context of the sentence as compared to when they were asked to complete it with a word that did fit into the overall context of the sentence. In other words, the dorsolateral prefrontal cortex seems to be more active when there is response suppression (Elliot et al., 2000).

3.3 Anterior Region of the PFC, BA10

The functionality of BA10, the anterior prefrontal cortex, also known as the rostral PFC and the front polar cortex, is not well understood. It may be involved in moral judgment (Borg, Hynes, Van Horn, Grafton, & Sinnott-Armstrong, 2006). It also seems to be associated with executive functions related to how to carry out an activity in many kinds of cognitive tasks including awareness of activities, remembering what to do, multitasking, consciously concentrating on a task, and conscious switching from one activity to another (Burgess, Simons, Dumontheil, & Gilbert, 2005). BA10 is the largest region in the frontal lobes (Christoff et al., 2001) and is about twice as large in humans than in great apes (Semendeferi, Armstrong, Schleicher, Zilles, & Van Hoesen, 2001). BA10 shows increased BOLD activity—among other things—in verbal retrieval (Rugg, Fletcher, Frith, Frackowiak, & Dolan, 1996), color memory retrieval (Martin, Haxby, Lalonde, Wigges, & Ungerleider, 1995), language (Klein, Milner, Zatorre, Meyer, & Evans, 1995), auditory perception (Kosslyn, Alpert, & Thompson, 1995), prospective memory (Burgess, Scott, & Frith, 2003), and visual reasoning (Christoff et al., 2001). It would seem that the common thread in many previous studies of BA10 is that it is involved in episodic memory of many kinds (though not exclusively) (Burgess et al., 2005).

In a rare lesion study of BA10 of a man in his early 20s whose almost entire rostral PFC was removed after a car accident, the man showed resulting problems with multitasking but not with memory, perception, or other executive functions (Metzler & Parkin, 2000). The lack of an apparent effect on executive functions of a lesion in this area was also apparent in other case studies (e.g., Bird, Castelli, Malik, Frith, and Husain (2004); Goel and Grafman (2000)). Comparable results were also obtained in a

[3] BOLD is blood-oxygen-level-dependent contrast. It is used in fMRI to measure changes in neuron activity based on the increased paramagnetic properties of deoxygenated hemoglobin compared to oxygenated.

comprehensive experiment involving 60 acute neurological patients, many of whom had brain tumors, who were matched with equivalent IQ level healthy subjects: learning, planning, and remembering were not significantly different, but multitasking ability was reduced among those with left rostral lesions (Burgess, 2000).

BA10 seems to be involves in meta-cognition, too; that is, in self-reflection (Johnson et al., 2002). It may also be involved in assessing the mental states of other people (Frith & Frith, 2003). BA10 may be involved in these activities also as a coordinator of activities in other brain regions (Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999). Another hypothesis, the default hypothesis, is that, because BOLD activity in this region is decreased when people encounter new or demanding cognitive tasks (Christoff, Ream, & Gabrieli, 2004), BA10 as a default is active in coordinating and evaluating information but that resources are drawn away from it when new or complex cognitive tasks need to be performed. An alternative view proposed by Burgess et al. (2005) is that BA10 may serve as a gateway. It may be involved in the coordination of information towards solving desired objectives, perhaps with the medial region directing more attention toward sensory input, and the lateral toward internally created thoughts.

To summarize, BA9 is associated with cognitive effort (Owen, McMillan, Laird, & Bullmore, 2005), calculation (Ernst & Paulus, 2005), and working memory (Braver et al., 1997); and, overall, BA9 and BA10 are associated with executive functions of assessment and using short-term memory, including verbal and non-verbal memory, judgment, problem solving, and sematic memory (Burgess et al., 2005).

3.4. A List of Some Constructs fNIR Neural Correlates can Address

Note that, while fMRI scans the entire brain, fNIR scans only the prefrontal cortex. Accordingly, neural correlates associated with brain areas other than the prefrontal cortex are outside the scope of fNIR research. Table 1 summarizes some of the neural correlates available to research through fNIR and their potentially related constructs and many others that are not. This is only a partial list and intended only to demonstrate some areas of interest. Some of these additional areas are discussed in Dimoka et al. (2012) and Riedl et al. (2010a).

Table 1. Some Neural Correlates fNIR Can Study and Their Related MIS Constructs (On Left) and Neural Correlates of Potential Interest to MIS that Cannot Be Studied with fNIR (On Right)

MIS constructs related to neural correlates accessible with fNIR	MIS constructs related to neural correlates outside fNIR accessibility
Prefrontal cortex - Attention - Task novelty - Familiarity - Habit - Cognitive effort and ease of use - Moral judgment and justice theory - Conscious choice and behavior - Sematic memory retrieval - Learning - Multitasking - Conscious inhibition - Judgment, such as trustworthiness assessments - Confusion	**Broca's area, Wernicke's area, and auditory cortex** - Verbal activity including: hearing, talking, listening, language processing, meaning of words
	Premotor cortex - Planning behavior, including planning to say words - Learning motor skills
	Motor cortex - Saying words - Eye motion
	Visual cortex and the occipital lobe - Identifying and Responding to visual cues
	Insula - Pain, empathy, and social emotions
	Limbic system and the amygdala - Emotional Fear - Distrust
	Olfactory bulb - Identifying and remembering smells and odors

Additionally, fNIR can augment current studies of trust and distrust as done in the context of fMRI (e.g., Dimoka, 2010; Riedl et al., 2010b; Riedl & Javor, 2012; Riedl, 2013) where it could serve to study in real-

world settings (e.g., Gefen, Sela, Ayaz, & Izzetoglu, 2012) the evolving and context dependent relationships among trust, risk, and behavior (Gefen & Pavlou, 2012; Pavlou & Gefen, 2004, 2005). fNIR could also provide insight on the crucial relationship between familiarity and trust as they occur in real world settings, as opposed to sitting in the movement and social limiting environment of an fMRI. To date, studying the relationship between familiarity and trust has been limited to ethnographic, panel, and survey research (Gefen & Carmel, 2008; Gefen, Wyss, & Lichtenstein, 2008; Gulati, 1995; Palmer, 2005) without resort to brain imaging.

4. Advantages and Disadvantages of fNIR

The relative advantages of fNIR over fMRI and PET can be summarized as a matter of considerable cost savings, versatility, portability, ease of deployment, size, and nonintrusiveness. Training to use fNIR is easier and faster than fMRI and PET. Moreover, it is safer than PET because it does not require radioactive tracers, and safer than fMRI because it does not expose the subject to strong magnetic fields[4]. All this means that obtaining review board permission for fNIR is typically easier than for fMRI and PET studies. Most importantly, fNIR is applicable to daily activities in natural settings. A main disadvantage of fNIR is that measurements are limited to the outer cortex area. fNIR can only measure areas close to the surface/skin, in contrast to fMRI that can measure all brain areas. Additionally, spatial resolution is limited (i.e. fMRI has a resolution of millimetres whereas fNIR has a resolution of centimeters) (Ayaz et al., 2013). All in all, fNIR is not a replacement for other imaging systems, but has its own advantages and disadvantages that make it useful for a range of applications.

4.1. Lower Cost

Cost is always a factor in neuroscience research, and it can be prohibitive. The Neurocognition Laboratory at Temple University, for example, estimates the cost of an fMRI experiment at $1000 per subject[5]. New fMRI machines operating at 3 tesla cost in excess of 2 million dollars[6], and even older second hand 3 tesla models can cost in the range of $600,000-$900,000[7]. Add to those numbers that the suite that houses it costs another $500,000, not including the maintenance and care, all this amounts to what in many cases could be a prohibitive expense[8]. Operating such a machine is also expensive and requires a team of several technicians to oversee the operation. This puts fMRI research totally out of range for most behavioral scientists. fNIR, in contrast, while not exactly cheap, cost as low as $30,000[9], which puts it in the affordable range of business, psychology, and other non-medical schools. fNIR also does not require expensive dedicated labs and the support of technicians. Once the hardware is purchased, the cost of administering an experiment is negligible and is measured only in researcher time and data analysis. To place price and spectroscopy in context, another tool available to MIS research is electroencephalography (EEG), available for as low as around $650 from Emotiv http://www.emotiv.com/[10]. A discussion about the suitability of EEG to MIS research is available in Dimoka et al. (2012).

4.2. Increased Versatilability

While cost is a crucial advantage of fNIR, it would be a mistake to think of fNIR only as a cheap and downgraded alternative to fMRI. fNIR has the distinct advantage of being versatile. It is portable, easy to deploy, and small. fNIR consists of no more than a headgear the size of a bandana, a control box the size of a small laptop, and a laptop computer or PC. All these can easily be deployed anywhere for field studies in natural settings. There is also a battery operated miniaturized version available (Ayaz et al., 2013). Moreover, fNIR, in contrast to fMRI, does not require large stationary labs with heavy protective

[4] These magnetic fields can add considerable cost and risk to the operating team. See http://www.med.nyu.edu/cbi/facilities/7tesla.html

[5] http://www.temple.edu/tunl/WhatisfMRI.htm

[6] http://news.sciencemag.org/sciencenow/2005/12/12-01.html and http://www.sevencounties.org/poc/view_doc.php?type=doc&id=8947

[7] Informed by Zetta Medical Technologies, LLC, 1313 Ensell Road, Lake Zurich, IL 60047, March 2013.

[8] http://www.sevencounties.org/poc/view_doc.php?type=doc&id=8947

[9] There's a wide spectrum of price range, some optical brain imaging devices can go as high as $500,000 depending on the configuration, number of optodes, and hardware options.

[10] More heavy duty EEG can cost in the range of $60,000 to $70,000.

shielding to hold very large machinery weighing in the tens of tons and emitting strong radiation that make current fMRI machines only suitable to stationary dedicated labs. fNIR also does not limit data collection only to subjects who must lie down in a noisy MRI tube. This is a theoretically important issue as noise is a potential distracting experimental artefact.

Noise in itself can affect behavior and perception, such as performance among children with ADHD (Abikoff, Courtney, Szeibel, & Koplewicz, 1996) and solving math problems also among people who do not suffer from ADHD (Usher & Feingold, 2000).

fNIR also allows data collections while subjects move about naturally—a significant advantage over fMRI where subjects are instructed to lie motionless. Moreover, conceivably, lying down in a motion-restricted environment could also in itself affect behavior, perceptions, and emotions, and not all subjects feel comfortable being exposed to such an environment. fNIR, because it only involves a small headgear, avoids introducing such artefacts into the experimental design. fNIR is also less intrusive than fMRI and PET by far. The headgear of fNIR is mostly not noticeable by the subjects after a few seconds of wearing it.

Consequently, when neuroimaging needs to be done in natural settings, or anywhere else outside a fMRI tube and not requiring the injection of radioactive isotopes as in PET, there is no other current alternative to fNIR for measuring cortical hemodynamic response. If social science research wants to apply neuroimaging to study human behavior and thought in natural settings such as offices, meeting and training sessions, or even in online settings where people sit in front of a computer screen, then optical brain imaging such as fNIR poses the least constraints on the study design. Moreover, fNIR studies can be conducted by one person: the experimenter. In contrast, PET and fMRI require the attendance of several skilled and certified technicians apart from the researcher. Additionally, fNIR only requires that the subject have an exposed and clean forehead onto which the headgear can be attached. This is a minimal requirement compared to PET and fMRI that pose potential danger to subjects and are therefore limited in their usage and time of exposure. Moreover, all fNIR does is to expose the subjects to near infrared light in ambient wavelengths and intensity to which they are already exposed daily from the sun. In contrast to fMRI, fNIR can be applied to subjects who are pregnant, to infants, and to those who have artificial implants/limbs or pacemakers. Importantly, many typical subjects are not required to remove their glasses when wearing optical brain imaging headgear.

4.3. Faster Training

Social scientists looking into adding optical brain imaging to their research can expect to be training ready in hours with fNIR. This is orders of magnitude shorter than fMRI. Administering PET is mostly out of the question because it requires medical training that social scientists do not typically have. As social scientists seldom collaborate with medical labs, it puts tools such as PET out of range.

4.4. Disadvantages and Limitations

The main disadvantage of optical brain imaging is that its penetration and resolution are limited to studying only broad areas in the PFC. fNIR has a resolution in the range of 2-3 cm^2, and the system we describe in Section 2 can only measure the PFC, not other cortical areas due to hair interference. fMRI, in contrast, has a resolution of 2-3 mm^3, and, in more recent studies, even 1 mm^3, and can record BOLD activity anywhere in the brain. These are critical limitations of fNIR, which make it an alternative only for some types of PFC research. fNIR is also only suited for the study of neural correlates as they apply to brain regions 2-3 cm^2 wide. Put into perspective, however, the relatively low resolution problem of fNIR is of lesser concern considering social science research discusses neural correlates as they apply to entire brain regions such as the entire amygdala, insula, and PFC (e.g., Dimoka, 2010), rather than the subdivisions in those regions. This does not mean that comparing subdivisions in those regions is not important, such as comparing the central subdivision of the amygdala with its medial subsection (Yalch & Spangenberg, 2000). Lastly, optical brain imaging, as is the case with fMRI, records neural activity. Setting the statistical thresholds for false positive and false negatives is crucial, as in any statistical analysis comparing means. Optical brain imaging, or indeed any other data collection method, should not

be treated as a false-proof black box[11].

5. Wearable Optical Brain Imaging Informing MIS Research

Optical brain imaging allows researchers to identify changes in brain activity through cortical hemodynamic response signals. This is true of other methods of neuroimaging too, such as fMRI, but the affordability, versatilability, and non-intrusiveness of fNIR place it in an arguably unique position to inform MIS. This section discusses some of those aspects with examples. While many of these suggestions can apply to other neuroimaging technologies, their application with fNIR has the unique advantage that it can be applied without introducing intrusive experimental artifacts such as lying in a solitary manner in a confined tube with limited movement as is the case with fMRI. Moreover, fNIR allows the application of these suggestions even when measuring activity done in teams in almost natural settings.

5.1. Informing Theory by Identifying Neural Correlates

fNIR can inform MIS, as do other optical brain imaging methods, by identifying neural correlates of behaviors, emotions, perceptions, and other important constructs. In other words, optical brain imaging can show association between changes in behaviors, emotions, perceptions, and other constructs on the one hand, and changes in cortical hemodynamic response activity in various brain regions on the other. Knowing from previous research to some extent what those brain regions do can result in new insight into research questions of interest. This has been applied already with fMRI to identify the neural correlates of trust and distrust, and thus to show how the two are distinctly different with trust being centered in regions such as the PFC and the insula, which suggests cooperation, while distrust in the amygdala, which suggests fear (Dimoka, 2010). Likewise, neural correlates may provide new insight on why men and women differ in their trusting behavior (Riedl et al., 2010b). Data collected through surveys, observations, and other methods used by social scientists do not provide such a peek into changes in brain activity. Neural correlates may also advise on the development of new theory by showing how social phenomena are related to otherwise immeasurable brain activity. This allowed Dimoka (2010), for example, to suggest that distrust was not the opposite of trust but a totally unrelated construct dealing with fear, which has been suggested in the past (McKnight, Kacmar, & Choudhury, 2004) but never convincingly shown because survey data alone cannot show this beyond doubt.

Moreover, in many realms of social sciences, such as in MIS, researchers often expect a rational theory base connecting cause and effect. To a large extent, this may be based on the enormous impact the theory of reasoned action (Ajzen, 1985) and the technology acceptance model (Davis, 1989) have had. But, people do not always behave rationally, certainly not when it concerns trust theory (Blau, 1964). Connecting cause and effect through an irrational theoretical basis, or a basis that currently lacks a rational explanation, is not easy. Even significant correlations may seem to sceptical reviewers as superfluous, random correlations. Making the case for such a connection when there is no theory base could be made easier if a clear neural correlate exists. If the biology is there, then the relationship exists whether or not there is a current rational social science theory explaining it. A prime example of this as it relates to fMRI is that women adopt IT differently than men do. This has been shown empirically (e.g., Venkatesh & Morris, 2000; Gefen & Straub, 1997) and may be related to socio-linguistics (Tannen, 1995), but, without biological evidence, many reviewers are still reluctant to accept it. Fortunately, thanks to neural correlates, the biology is there to support this hypothesis and not only with survey data. As Riedl et al. (2010b) showed with fMRI, men in an eBay context show increased activity in the dorsal anterior cingulate and BA10 in the PFC, while women show increased activity in the insula cortex and caudate nucleus. These neural correlate may possibly indirectly support the hypothesis that women invest more in understanding other people.

The previous MIS fMRI research cited above resulted in important insights to theory thanks to fMRI's ability to identify neural correlates. Not all MIS research, however, can be conducted in the limiting context of an fMRI with the many repeated measurements it needs to ensure a reliable signal reading. That is where fNIR comes in. fNIR can identify neural correlates by restricting the subjects only to the

[11] Setting the thresholds wrongly in fMRI with very small samples can result in nonsensical results such as showing that a dead salmon has BOLD activity indicating it is responding to picture of people in social settings: http://www.wired.com/wiredscience/2009/09/fmrisalmon/

extent that they need to wear a headband, which thus allow them to engage in regular, complex activities. This could allow MIS researchers to study complex activities such as how people interact in an online marketplace (e.g., Gefen & Carmel, 2012), what IT and IT-enabled cues they subconsciously pay more attention to in an human computer interface (HCI), and what in the IT interface may moderate their attention. All these could add new perspectives to the much applied theory of reasoned action (Ajzen, 1985) and its technology acceptance model (Davis, 1989) derivative. Moreover, not all researchers have access to fMRI, can afford to use it, or are licensed to do so.

5.2. Studying New Kinds of Constructs to Inform Theory

Optical brain imaging can also allow researchers to study a host of new constructs that cannot easily or convincingly be studied with other methods and methodologies. Ayaz et al. (2012), for example, studied cognitive workload among air traffic controllers with fNIR spectroscopy of the PFC, and Ayaz et al. (2011), also using fNIR spectroscopy, showed a pattern of decreased PFC activity with learning. Neither of these constructs (cognitive workload and cognitive learning) can be convincingly studied with traditional social science methods. And yet, adding such constructs could inform theory in many new ways. This, too, demonstrates the unique advantages that fNIR has over other kinds of neuroimaging. Air traffic controllers can be expected to function normally while directing aircraft if all the experiment requires of them is wearing a headband. It would be rather impossible to do so while confined individually and motionless in an fMRI machine.

5.2.1. Examples Relating to Trust Theory

Cognitive workload and learning may clarify, for example, how habit combines with perceived usefulness to predict IT usage. Results may possibly show a reduction in cognitive effort with experience. Such a result might imply a shift from assessing perceived usefulness towards using IT out of habit without any special additional thought. Being able to measure cognitive effort directly could also empirically support the crucial theoretical basis in trust theory of why people need to trust at all. Luhmann (1979) suggest that people trust because trust allows people to set aside concerns about others' possible behavior, and, in doing so, to simplify the overwhelmingly complex social world to cognitively manageable levels. This hypothesis is widely accepted, as is the hypothesis that trust is built through feedback and experience (Mayer, Davis, & Schoorman, 1995; Zucker, 1986), but it is hard to test reduced cognitive complexity or learning as a real-time cognitive process with current social science methods. Optical brain imaging such as fNIR could be used to test these hypotheses. fNIR could be used to show that when people refrain from action all together with strangers that there is little change in their PFC cortical hemodynamic response activity. That may imply that people are overwhelmed into inaction in such cases, indirectly supporting Luhmann's social complexity reduction hypothesis. Optical brain imaging could also be applied to show the measurable neural correlates of cognitive learning. Applying optical brain imaging in this manner could show high levels of PFC cortical hemodynamic response activity when people first encounter strangers, implying that people invest more cognitive effort into studying whether strangers are trustworthy. Again, fNIR has a unique advantage over other optical brain imaging techniques in that all it requires of subjects is to wear a headband.

5.2.2. Examples Relating to Human Computer Interface Design

Taking Ayaz et al.'s (2013) observations about cognitive workload and neuroergonomics to the realm of designing HCI could help improve these designs through objective complexity measures. HCI could be evaluated as having a better design when using it involves less cognitive effort. Applying this kind of fNIR construct could also provide a better theoretical basis for why perceived ease of use is so important in IT design and why it affects perceived usefulness and use intentions (Davis, 1989). Currently, this is explained as an exemplar of the theory of reasoned action (Ajzen, 1985) and its derivatives, but there may be a cognitive complexity aspect to it, too. This kind of investigation would be especially beneficial considering that, at least in some contexts of eBay-type activity, there are several different brain regions involved in assessing ease of use and usefulness (Dimoka et al., 2011). fNIR could reveal at least some PFC neural correlates in more natural and diverse settings, and hence allow for better HCI design and a better understanding of the process of reducing HCI's cognitive complexity.

There are many constructs that could have become central to MIS but have been ignored because of the limitations imposed by traditional research methods. Among the new types of constructs that could be

studied are paying and losing attention and being distracted by features in the HCI. Oxygenation changes and hemodynamic responses as revealed through fNIR could provide an objective, even if indirect, measure of neural correlates, and through them perhaps suggest possible mental processes. Likewise, fNIR could identify what draws subjects' attention. In the case of HCI, this could include identifying the optimal location, shape, color, picture, and other attributes of a control, such as a button or picture. fNIR could also be used to gauge the ease of use of new interface designs by measuring PFC activity levels as people navigate through computer interfaces. Currently, this is done through subjective assessments. fNIR creates the possibility of making these assessments objective and adjustable in real-time to account for individual preferences and visual challenges. Moreover, blood volume, also measured objectively by fNIR, could indicate tension and arousal created by HCI aspects. These constructs cannot be easily measured with current methodologies, nor can the HCI design be adjusted immediately to a user's cognitive effort.

5.2.3. Objectively Measuring Constructs Subjects Are Not Aware of

Optical brain imaging such as fNIR can also be used to objectively measure the effects of events that subjects are not, or just barely, even aware of. Already, fMRI can be used as a lie detector (Harris, 2010). In more mundane circumstances, this may occur in an experiment where subjects are exposed to environmental changes, such as in an experiment that subtly changes the luminosity level of the computer screen. Understanding the nomological context of such effects is very hard with traditional social science research methods because the subjects are at most only barely aware of what is occurring. Recording neural correlates could provide one way of studying this, and, in doing so, provide theoretical insight. This could be true of any neuroimaging method, but is even more applicable in the case of optical brain imaging providing it is the executive function that is being studied (i.e., that it measures the PFC).

Additionally, it is often hard to obtain truthful answers in even anonymous questionnaires about sensitive topics because subjects self-censor their own answers so their answers are socially acceptable (Cook & Campbell, 1979). This is not a matter than can be easily overcome by research design because subjects may not even be aware that they are censoring themselves (Cook & Campbell, 1979). One example is initial trust. Initial trust is the product of many things, including whether the trusting party thinks the other party is form the same racial or social group (Zucker, 1986). Showing that this kind of initial trust is the consequence of racial, sexist, or any other kind of socially unaccepted bias may be harder to study because subjects may consciously lie, or even unconsciously reframe their thoughts so as not to be seen or perceived, even by themselves, as being unacceptably racist or sexist. Optical brain imaging could provide a way to measure this by showing that there is less cognitive effort, as recorded through neural correlates, in the PFC, and therefore presumably less reassessing when the trusted person is from the same racial or other social group as the trusting party.

5.2.4. Designing Better Surveys

A key concern in designing questionnaires is avoiding a case where questions may be phrased in a manner that will make the subjects realize, or think they realize, what the researcher is looking for, or just make the questions seem repetitive and so induce the subjects to answer accordingly in a manner that makes them seem internally consistent (Cook & Campbell, 1979). A common theme in these concerns is that the subjects invest extra time and thought to guess what is lying behind the question, and this possibly biases the answer. There is no rigorous objective way to measure these biases through statistics, only some indirect tell-tale effects that could be related to many other problems such as common method bias or low statistical reliability. Optical brain imaging, and in particular fNIR, because it measures actual changes in relative brain activity in the executive functions, may be able to provide some level of objective measure of this. Indeed, Ayaz et al. (2012) used such a technique with fNIR to study mental workload in training. By extension, mental overload should be evident and recorded by fNIR also when subjects think more extensively as they address a specific questionnaire item while considering how they answered previous items or what the researchers may be looking for in that item. Adding automatic markers to mark the beginning and ending of events in the process the subjects go through could allow for measuring PFC activity for each item. Moreover, such a mechanism could allow for measuring how these activities change over time for each item and over time as the subject progresses through the survey. This kind of fNIR application could also possibly identify when questionnaire items are too long or too boring, presumably by showing that subjects spend less time on those items than on

equivalent length items.

Along the same lines, such a mechanism of tracking PFC activity while subjects are completing a questionnaire could provide questionnaire designers with indications on the cognitive complexity of their questionnaire items. Currently, problematic questionnaire items can be identified by asking people in a pilot run to read and reflect about the items and indicate if any are misleading or otherwise problematic. This can also be done in a pretest by asking a small group of subjects to reflect on the items after completing the questionnaire (Cook & Campbell, 1979). These methods are good (Miles & Huberman, 1994), but they are subjective and subject to after-the-effect memory distortions. Problematic questionnaire items can also be identified indirectly through statistics with methods such as in a confirmatory factor analysis (Bollen, 1989). However, unwarranted or unexpected overlapping of variance can mean many things, not only that an item is misworded or requires longer and harder thinking to comprehend. With fNIR recordings of enhanced PFC activity, optical brain imaging can, in contrast, provide real-time objective indicators. PFC activity could indicate which questionnaire items are ambiguous or at least unclear to the extent that subjects need to reflect harder.

6. Conclusion

Wearable optical brain imaging has the potential to revolutionize some aspects of MIS research by opening new avenues of research into the neural correlates of behavior, cognition, perception, and emotions. It may also serve to improve current methodologies. This type of neuroimaging has lesser spatial resolution and penetration than fMRI, but it has unique advantages in that it is affordable, versatile, and non-intrusive. These advantages make it uniquely appropriate for studying the PFC in natural settings and without introducing considerable experimental artefacts.

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