Journal of Neuroscience, Psychology, and Economics
2011, Vol. 4, No. 2, 85–94

1937-321X/11/$12.00 DOI: 10.1037/a0023525

Integrating fMRI With Psychophysiological Measurements in the Study of Decision Making

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Neuroimaging techniques have recently been used to examine the neural mechanism of decision making. Nevertheless, most of the neuroimaging studies overlook the importance of emotion and autonomic response in modulating the process of decision making. In this article, the authors discuss how to integrating functional magnetic resonance imaging (fMRI) with psychophysiological measurements in studying decision making. They suggest that psychophysiological data would complement with fMRI findings in providing a more comprehensive understanding about the physiological and neural mechanisms of decision making. Also, this technique would yield valuable information in examining the interplay among emotions, autonomic response, and decision making. The discussion is presented in a tutorial format with concrete technical recommendations for researchers who may consider adopting the technique in their study of decision making.

Keywords: decision making, fMRI, psychophysiology

Decision making has been a popular research topic across a wide range of disciplines, such as economics, psychology, computer science, and neuroscience. One of the major goals in decision research is to understand the mechanism of how humans make decisions. The traditional economic research has assumed that humans make decisions based on rationality, and the ultimate goal of decisions is to maximize utility (Kahneman, 1997; Kahneman & Thaler, 2006; Stigler, 1950). On the basis of these assumptions, various computational models have been proposed to simulate the decision-making process of humans (McClure, Berns, & Montague, 2003; Montague, Dayan, & Sejnowski, 1996; O'Doherty et al., 2004; Schultz, Dayan, & Montague, 1997; Wunderlich, Rangel, & O'Doherty, 2009). With the rapid development of noninvasive neuroimaging techniques in the past decade, neuroscientists are now able to test the validity of these decision-making models in healthy individuals and to study how these computational models may be implemented in the human brain. This line of model-based neuroimaging study has gained widespread popularity in neuroeconomics research and advanced our understanding of the neural mechanism of decision making (O'Doherty, Hampton, & Kim, 2007). Nevertheless, most of the computational models assumed absolute rationality in the decision-making process and paid very limited attention to the influence of irrationality and emotion on humans' decision. In this review, we discuss why it is important to examine the role of emotion in decision making and how researchers can integrate functional magnetic resonance imaging (fMRI) with psychophysiological measurements to examine the body-brain interaction in decision making and the interplay between emotion and decision making.

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We thank J.-B. Pochon for comments and suggestions for improving this article. This work is supported by Program Project Grant P01 NS019632 from the National Institute of Neurological Disordersand Strokes.

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The Reasons for Integrating fMRI With Psychophysiology

Traditionally, emotion has been thought to have negative impact on decision making. However, studies in lesion patients revealed that emotion is indispensible from adaptive decision making. Patients with lesions at the ventral me-

dial prefrontal cortex (vMPFC) or amygdala showed deficits in making advantageous decisions and in experiencing emotions (Bechara, Damasio, Damasio, & Anderson, 1994; Bechara, Damasio, Damasio, & Lee, 1999; Bechara, Tranel, & Damasio, 2000; Fellows, 2004; Fellows & Farah, 2005). Using the Iowa gambling task (IGT) and the measure of skin conductance response (SCR), researchers revealed that the decision deficits in these patients were associated with the absence of a distinct autonomic nervous system response preceding a risky decision (Bechara, Damasio, Tranel, & Damasio, 1997; Bechara et al., 2000; Bechara, Tranel, Damasio, & Damasio, 1996; Crone, Somsen, Van Beek, & Van Der Molen, 2004). In particular, patients with lesion in vMPFC failed in generating anticipatory SCR when they were about to make risky decisions (Bechara et al., 1997). They preferred options with high reward even when these options are accompanied with chance of much severer punishment leading to an overall loss in long term (Bechara et al., 2000). These patients also demonstrated maladaptive decision making in their daily lives, such as having trouble in maintaining relationships and making improper financial and job decisions (Bechara et al., 1994; Damasio, 1994; Damasio, Tranel, & Damasio, 1991). These findings provide compelling evidence in support of the "somatic marker" hypothesis proposed by Damasio (1994), who argued that emotion (as indexed by changes in the autonomic nervous system responses) is critical to optimal decision making. Accordingly, anticipatory SCR and other autonomic responses serve as warning signals from the body for unfavorable decision (Damasio, 1994). Although the participants may not have conscious awareness of such warning signals from their body, the success in generating the anticipatory autonomic response has been demonstrated to reduce the selection of risky unfavorable options (Bechara, 2003). Therefore, emotion and autonomic responses have an indispensable role in the process of decision making.

On the other hand, a number of psychophysiological studies in healthy populations have also demonstrated the importance of the autonomic nervous system in modulating decision making. Researchers reported that the level of autonomic arousal as indicated by skin conductivity and heart rate correlated closely with the decisions made by healthy individuals (Batson, Engel, & Fridell, 1999; Campbell, Stout, & Finn, 2004; Crone et al., 2004; Kleeberg et al., 2004; Lo & Repin, 2002; Sugita & Suzuki, 2003; Tomb, Hauser, Deldin, & Caramazza, 2002). Furthermore, psychopharmacological study demonstrated that the process of decision making can be altered by a drug, which acts on the autonomic nervous system (Rogers, Lancaster, Wakeley, & Bhagwagar, 2004). In particular, healthy individuals who received a mild dose of propranolol, a beta-adrenoceptor blocker that suppresses the sympathetic nerve activity, were less able to discriminate different punishment signals in making risky decisions than the control group that received a placebo (Rogers et al., 2004).

Findings from the fMRI community on decision research align with the observations from early animal and lesion studies that the medial prefrontal cortex (MPFC) together with the striatum, insular cortex, and amygdala play important roles in the human decision process (Breiter, Aharon, Kahneman, Dale, & Shizgal, 2001; De Martino, Kumaran, Seymour, & Dolan, 2006; Hampton, Adolphs, Tyszka, & O'Doherty, 2007; Hare, Camerer, Knoepfle, & Rangel, 2010; Kable & Glimcher, 2007; Knutson, Taylor, Kaufman, Peterson, & Glover, 2005; McClure et al., 2003; O'Doherty et al., 2004; Tom, Fox, Trepel, & Poldrack, 2007; Wunderlich et al., 2009; Xue et al., 2009). Among the various neural substrates associated with decision making, the vMPFC received a lot of attention as neuroimaging data illustrated that this region is involved in the process of valuation, and its response fits well with the prediction of various computational models (Hampton et al., 2007; Hare et al., 2010; Xue et al., 2009). It is interesting to note that this region of the brain has also been associated with generating autonomic responses (Bechara et al., 1997; Wong, Massé, Kimmerly, Menon, & Shoemaker, 2007). In addition, the insular cortex, which has been associated with modulating decision making, especially in addiction-related decisions (Naqvi & Bechara, 2009; Naqvi, Rudrauf, Damasio, & Bechara, 2007), has long been regarded as an important region in representing autonomic responses (Saper, 1982; Saper, 2002; Yasui, Breder, Saper, & Cechetto, 1991). Indeed, the neural network for decision

making (i.e., vMPFC, insular cortex, amygdala, and striatum) highly overlaps with the cortical autonomic network (CAN), which is involved in modulating the activity of the brainstem autonomic centers, and hence the arousal level of the sympathetic and parasympathetic nervous systems (Cechetto & Shoemaker, 2009; Critchley, Corfield, Chandler, Mathias, & Dolan, 2000; Ongur & Price, 2000; Wong et al., 2007). Neuroimaging findings revealed that vMPFC and the insular cortex (IC) respond not only to decision-making tasks, but also to a number of cognitive and physical tasks that elicited autonomic responses without the involvement of any explicit decision making (Kimmerly, Wong, Menon, & Shoemaker, 2007; Wong et al., 2007). Specifically, convergent evidence from electrophysiology, neuroanatomy, and clinical studies has ascribed a role for the insula in providing interoceptive signals, including those related to pain, temperature, taste, and visceral sensation (Craig, 2002, 2009), which can be used to guide decisions (Naqvi & Bechara, 2009; Xue, Lu, Levin, & Bechara, 2010).

Putting together, there is a close relationship among decision-making, emotion, and autonomic responses. Nevertheless, the majority of the recent fMRI studies, mostly guided by economic models, have largely overlooked the important role of emotion and autonomic responses in decision making and, thus, neglected the need of integrating psychophysiological measurements in fMRI studies. Psychophysiological measurements can be used not only to quantify the emotional response associated with decision making but are also important tools for researchers to examine the body–brain interaction in the process of decision making. The missing psychophysiological assessments in the fMRI studies of decision making limited the interpretation of the data. For instance, it is difficult to determine whether the vMPFC response reflects only the evaluation process itself or also the autonomic responses accompanied with the decision. Therefore, integrating fMRI with psychophysiological measurements in the study of decision making will provide researchers a more comprehensive understanding about the neural mechanism that underlies decision making.

Challenges in Integrating fMRI With Psychophysiological Measurements

Despite the obvious benefits and necessities in integrating fMRI with psychophysiological measurements in the study of decision making, there are a number of technical and experimental challenges that have restrained the development in this field. The most common problem would be the availability of MRI-compatible psychophysiology equipment. Nowadays, the most typical psychophysiological measurements are SCR, heart rate (HR), and respiration. There are also some more sophisticated but more noise sensitive measurements, such as electroencephalogram (EEG), electromyogram (EMG), and muscle sympathetic nerve activity (MSNA), which pose further technical challenges in the MRI environment, and we do not discuss them in detail here. SCR is an indirect measure of the activity of the sympathetic nervous system, which innervates the eccrine sweat gland and controls the secretion of sweat. The conductivity of skin changes according to the amount of sweat secretion. Through applying a small constant current between two surface electrodes attached to participants' fingers, the skin conductivity and hence the sympathetic nerve activity can be estimated (Boucsein, 1992). Inside the MRI environment, however, electrophysiological signals like SCR are often contaminated by the artifacts introduced by (a) the magnetic induction, which is due to the movement of the conductive cables and electrodes attached to the participant's body; (b) the rapid switching of the MR gradient during the scanning; and (c) the radio frequency (RF) emitted by the RF coil (Abacherli et al., 2005).

Similar artifacts have been observed in electrocardiogram (ECG), a common technique in clinical HR monitoring. ECG traces the potential change over the heart generated at the sinoarterial (SA) and atrioventricular (AV) nodes. In addition to the artifacts introduced by magnetic induction and RF pulses, the cardioballistic effects caused by the mechanical movement of the heart and the flow of blood inside the magnetic field further contaminated the ECG signal. It is more important to note that in both SCR and ECG measurements, the induced current at the conductive cables and electrodes may build up significant amount of heat and pose

potential hazards to the participants (Kugel et al., 2003).

Recently, MRI-compatible psychophysiological equipment is available commercially from different manufacturers. These MRI-compatible systems usually include a built-in real-time filter to suppress MRI-related artifacts, and they are made of MRI-compatible materials to minimize the potential hazards to the participants when they are used according to the instructions. Still, it is common to find artifacts in the acquired data from these systems, which required further preprocessing before statistical analysis. In the following section, we discuss the use of these MRI-compatible systems and the postacquisition "de-noising." We aim to provide some practical guidelines for researchers who are new to the field and are interested in integrating fMRI with physiological measurements. After that, we discuss the compromises and recommendation in the experimental design and data-analysis approaches for decision studies. At the end, the safety issue and other logistic considerations in integrating fMRI with psychophysiological measurements will be discussed.

Measuring SCR During fMRI Experiment

Among various psychophysiological measurements, SCR and HR are the most common measurements used in decision-making experiments outside of the scanner. SCR and HR responses are usually observed during the decision and feedback stages. The setup and analyses of these measurements are relatively straightforward, which partly explains their popularity in decision research. Inside the MRI scanner, although both SCR and ECG were subject to MRI-induced artifacts, the denoising process of SCR signals is much simpler than ECG. Indeed, SCR signals have relatively long latencies whereas MRI-induced artifacts are usually within a much higher frequency range. Therefore, a low-pass filter is sufficient to separate the SCR signals from the MRI artifacts. SCR can be recorded from a pair of nonmagnetic electrodes applied to the fingers or foot of the participants. The key to getting clean SCR data is to minimize the movement artifacts introduced by body movement, which may move the measurement electrodes and cables. After removing the MRI artifacts with a low-pass filter, SCR signals can be analyzed with the same approach as regular SCR studies outside of the scanner. The details of SCR analysis have been documented in detail by Boucsein (1992). Bach, Flandin, Friston, and Dolan (2009) have recently proposed use of a linear convolution model to separate the overlapping SCR in experiments with rapid event-related design. As we discuss in the later section that the event-related design is more suitable and frequently adopted in decision research, the linear convolution model-analysis approach would hence greatly improve the flexibility in the experimental design of future decision studies with SCR measurements.

Measuring HR During fMRI Experiments

In this section, we focus the discussion on the acquisition and analysis of HR data as they pose unique challenges in fMRI studies. However the same rationale and similar approaches should be applicable to other psychophysiological measurements inside of the MRI scanner.

One of the major advantages of HR measurement is that HR is modulated by both the sympathetic and parasympathetic nervous systems. In the contrary, SCR reflects only the response of the sympathetic nervous system as there is no parasympathetic innervation at the sweat gland. Although the sympathetic and parasympathetic nervous systems often work in antagonistic fashion, there are occasions that parasympathetic nerve activity is altered while sympathetic nerve activity remains unchanged (Mark, Victor, Nerhed, & Wallin, 1985; Wong et al., 2007). Therefore, obtaining SCR and HR measurements at the same time will provide empirical information about the differential responses and interaction between the sympathetic and parasympathetic nervous systems during decision making. The two common approaches in obtaining HR information are through ECG and pulse oximetry. Each of them has unique advantages over the other. We describe and compare the two techniques in the following paragraphs.

ECG is a widely used technique in acquiring HR information in both clinical and research settings. Because of its exceptional high temporal resolution, ECG provides very precise beat-by-beat HR information, which is particularly important in the analysis of heart rate variability (HRV). The common configuration of research

setting ECG is a standard three leads measurement following the Einthoven's triangle. However, inside the MRI scanner, the length of conductive cables should be minimized to avoid magnetic induction. The three ECG electrodes therefore should be placed in proximity to the heart on the left side of the chest. Two common electrode configurations for fMRI ECG are (a) placing two electrodes diagonally across the left nipple (i.e., one on the sternum and the other on the lower left of the ribcage) and the ground electrode on the low end of the sternum and (b) placing two electrodes at about 5 cm vertically above and below the left nipple and the ground electrode at the middle of the sternum (Gray, Rylander, Harrison, Wallin, & Critchley, 2009). Carbon fiber electrodes and cables are recommended because of its nonmagnetic nature. Beat-by-beat HR can be determined from the interval of successive peaks of the R-wave. Nevertheless, artifacts introduced by magnetic induction and RF pulses can severely obstruct the detection the R-peak from the ECG trace. Shielded ECG sensor and built-in adaptive real-time filter may suppress some of the artifacts (Abacherli et al., 2005). To minimize the induction caused by motion inside the magnetic field, participants should be encouraged to keep not only their head still but also their whole body as still as possible throughout the scanning. The conductive cables should be minimized in length, fastened with tape, and should never go in loops. Postacquisition denoising may be required if R-peaks are indistinguishable in the ECG trace. Fast Fourier transform (FFT) can be performed to identify the recurring artifact frequencies that can then be attenuated with band-stop filters. To have a precise estimation of the frequency spectrum and filtering of the artifacts, data should be sampled at a much higher sampling rate (i.e., 4,000 Hz) than regular psychophysiological studies. More complex denoising approaches have been proposed and discussed in more details in previous reports (Abacherli et al., 2005; Gray, Minati, et al., 2009; Odille et al., 2007). The denoised ECG trace can then be analyzed with peak detection algorithm to determine the beat-by-beat HR. Visual inspection of proper peak detection is highly recommended to identify any misclassification of peaks due to residual artifacts or signal distortion introduced in the denoising process.

An alternative approach for measuring HR inside the MRI environment is through pulse oximetry. Pulse oximeter applies a beam of red and infrared light on one side of a finger and measures the amount of light penetrated and received on the other side. The amount of light that can penetrate the finger varies according to the blood oxygenation and blood volume in the arteries. The pulsation of the arteries inside the finger generates a pulsatile waveform on the pulse oximetry, which can be used to determine the beat-by-beat HR. Because the acquisition and transmission of the pulse oximetry signal can be conducted by optical fiber, the pulse oximetry signal does not suffer from any interference from the MRI scanning. Pulse oximetry is therefore a safe and convenient alternative to ECG. Relative to ECG, however, HR determined from pulse oximetry is less precise because of the sluggishness of the pulse waveform and the latency of the blood pressure waveform that travels from the heart to the finger. Indistinguishable waveform may be obtained under the circumstance of hypoperfusion caused by vasoconstriction. Extensive movement can also distort the light signal obtained from the receiver. To improve the quality of the measurement, it is important to ensure that participants have good blood supply to their fingers. Especially inside the chilly scanner room, experimenters may consider to cover the participants with a blanket to minimize heat loss and reduce vasoconstriction. Other than the finger, pulse oximetry can be obtained from the toe or earlobe so that participants can spare their fingers for button pressing while performing decision tasks. Previous studies have demonstrated that HRV determined from pulse oximetry and ECG is highly correlated (Giardino, Lehrer, & Edelberg, 2002; Selvaraj, Jaryal, Santhosh, Deepak, & Anand, 2008). Thus, pulse oximetry is regarded as an acceptable alternative when clean ECG trace could not be obtained.

Measuring Respiration During fMRI Experiments

Besides SCR and HR, we suggest that respiration should be monitored with MRI-compatible respitrace, which measures the respiratory pattern of the participants throughout

the experiment. Respiratory patterns change when individuals are engaging in emotional and cognitive processes, which are key components that influence the overall process of decision making. Furthermore, beat-by-beat HR is modulated by respiratory patterns through the respiratory sinus arrhythmia. The outflow of parasympathetic nerve activity to the heart is blocked during inspiration. Because parasympathetic nerve activity suppresses HR, blocking parasympathetic outflow to the heart would result in tachycardia. Respiratory patterns can be easily monitored with MRI-compatible respitrace, which is basically an elastic band placed around the chest. The change of the chest cavity size reflects the pattern of inspiration and expiration. Although more sophisticated and precise approaches, like spirometer with a facemask, can be used to record airflow and gas exchange volume, the apparatus may cause discomfort to the participants and increase their anxiety levels. At the beginning of data collection, respitrace reading can be calibrated to a relative percentage scale based on the maximum inhale and exhale magnitude of a particular participant. Previous reports have suggested that respiratory patterns may cause task independent BOLD signal change (Birn et al., 2010; Chang, Cunningham, & Glover, 2009; Glover, Li, & Ress, 2000). The measured respiration patterns can be used not only to examine the task-dependent physiological change but also to improve the accuracy in separating task-related BOLD signal change from the BOLD response due to nonneuronal physiological noise (Birn, Murphy, Handwerker, & Bandettini, 2009). A more detailed analysis approach will be discussed in the next section.

Relative to general psychophysiological experiments, participants may have a higher level of anxiety during an fMRI experiment due to the unusual environment and the tight space inside the MRI bore. The real-time resting HR may serve as an index of anxiety level. Participants may have an elevated baseline HR at the beginning of the experiment due to a higher anxiety level. When it is close to the end of the experiment, participants may become more familiar with the environment and the experimental task, their anxiety level and baseline HR may be significantly lower than at the beginning of the experiment. These task independent changes of anxiety and physiological arousal levels present challenges in the interpretation of data. So we recommend having the participants to walk around the scanner room and get familiar with the environment before the experiment. At the beginning of the experiment, first-time fMRI participants may be given a short practice scan (e.g., $>$5 min) so that they can get familiar with the experimental task and the scanner noise. Experimenters may also advise the participants to pace their breathing for a few minutes or put on some soothing music to ease the anxiety level of the participants as long as these manipulations are done consistently across participants and do not have direct influence on the experimental task. At the same time, there should be sufficient time ($\sim$10 min) for the electrodes and electrolytes to be stabilized on the skin. A 5-min baseline resting measurement before the actual scan would provide an index of the intrinsic arousal level of the participants. Experimenters may also consider having the anatomical scan prior to the functional scans and increasing the number of dummy scans at the beginning of each session. The participants would then have sufficient time to settle down and prepare for the functional scans. As mentioned earlier, it is important to maintain a steady body temperature of the participants as it can also minimize the effect of changes in body temperature on the autonomic arousal level.

Experimental Design and Data Analysis

The two major experimental designs for fMRI studies are the block and event-related design. The block design groups trials of the same conditions into blocks and alternates blocks of different conditions throughout the experiment. For event-related design, experiment trials of different conditions are mixed together and presented in a pseudorandomized or balanced fashion (Dale & Buckner, 1997; Friston et al., 1998; Josephs, Turner, & Friston, 1997). In general, event-related design is more suitable for decision research as it has the flexibility to categorize trials based on the decisions of the participants and the outcomes. However, the caveat for event-related design is that the measured BOLD response is not as robust as in block design. In traditional psychophysiological study, whatever it is a block or event-related design experiment, there is an extended inter-condition interval so that there would be

sufficient time to separate the physiological responses of the preceding and subsequent block or event. In fMRI studies, the early event-related design experiment had similar extended interstimulus interval (ISI), but it has been gradually replaced with rapid event-related design to improve the design efficiency. The rapid event-related design takes advantage of the linearity of BOLD signal so that trials can be presented with much shorter ISI (i.e., >1 s–2 s). Jittering is usually introduced to increase the estimation efficiency and to reduce anticipatory effect. The overlapping BOLD signal from different trials is separated with a general linear model. A similar approach has been proposed for analyzing SCR data based on the linearity assumption of SCR data (Bach, Flandin, Friston, & Dolan, 2009). We expect that the same approach can be applied to analyze other psychophysiological data as long as the assumption of linearity is satisfied. By adopting a rapid event-related design approach, we can further separate the neural and psychophysiological response involved in the decision stage and the feedback stage (Xue et al., 2010).

Psychophysiological responses have to be quantified before they can be integrated in the analysis of fMRI data. One of the common approaches to quantify the magnitude of physiological responses is to compute the difference between the peak and the baseline measurements. An alternative is to compute the area under curve, which considers both the height and width of the response. To address the issue of intrinsic arousal difference across participants, physiological response can be normalized to the overall mean or median and presented in terms of percentage of signal change. The estimated physiological responses can be then compared across conditions and provide empirical evidence for the distinct physiological mechanisms underlying different conditions. In addition, the magnitude of the physiological responses can be included in the fMRI analysis as parametric modulators to improve the goodness of fit and to minimize the residual error in the proposed model. On the other hand, the psychophysiological data can be used to categorize experiment trials into different conditions based on each participant's physiological responses. Whatever approach is adopted, it is important to synchronize the acquisition of the fMRI and psychophysiological data. Triggers (e.g., a TTL pulse) from both the scanner and the computer that present experimental stimuli can be logged simultaneously on the psychophysiology data. The recorded triggers can then be used to estimate the onset of each trial precisely. This is especially important in the decision studies that adopt the event-related design. Because each trial lasts for a very brief period of time (e.g., 5 s–10 s), thus a precise estimation of trial onset ensures accurate quantification of the response magnitude.

Some of the previous studies have pointed out that variation in HR and respiration pattern would cause task independent nonneuronal BOLD changes (Birn et al., 2009; Chang et al., 2009; Glover et al., 2000). It is not uncommon that psychophysiological data are included as covariates of no interest in the fMRI analysis and the contribution of task-related physiological change was disregarded. On the contrary, we suggest dividing the BOLD signal into two components: (a) BOLD signal change due to task-related physiological responses and (b) BOLD signal change due to task-independent nonneuronal physiological change. As mentioned before, task-related physiological change can be characterized by using a general linear model. The residual error in the physiological data can be included in the fMRI analysis as covariates of no interest while the magnitude of the physiological change can be included as parametric modulators.

Other Considerations

When psychophysiological measurements are included in fMRI studies, the safety of using the psychophysiological equipment inside the MRI environment should be put in the highest priority. Improper use of physiological measurement equipment inside the scanner may cause severe consequences to the participants (Kugel et al., 2003). The major potential hazards are the force induced on the metallic components of the measuring devices and the voltage induced on the measuring cables and electrodes under the strong magnetic field of the scanner. Gray, Minati, and colleagues (2009) have discussed extensively the safety issue in integrating psychophysiological measurements inside the MRI environment for general fMRI studies, which is also applicable to decision-making fMRI experiments. If MRI compatible

equipment could not be obtained, researchers can consider having a parallel psychophysiological recording session outside the scanner.

Besides, there are some logistic considerations for having psychophysiological measurement during fMRI studies. For instance, the setup and calibration of psychophysiological measurements require additional time and manpower in running the experiments. Depending on the number of measurements and the hardware configuration at specific location, the setup time for psychophysiological measurements can range from an extra 15–30 min. Ideally, experimenters should schedule the experiments at the same time of the day for each subject because the level of autonomic arousal changes according to the circadian rhythm. If possible, experimenters should also control the alcohol and caffeine intake of the subjects before the experiment as these stimulants would affect the autonomic arousal of the subjects.

In summary, this article discussed the rationale and some technical and experimental challenges in integrating fMRI with psychophysiological measurements in decision research. Autonomic responses have an indispensible role in decision making. Psychophysiological data supplement fMRI findings in providing a more comprehensive understanding about the physiological and neural mechanisms of decision process. The interference of the MR environment on the psychophysiological measurement is the major technical challenge in the field. Also, there is safety concern in having additional psychophysiological measurements equipment inside the MR environment. Some remedies are available and discussed in this article. The availability of more efficient denoizing algorithms and commercialized MRI-compatible systems would accelerate the future development in integrating the two techniques in the study of decision making.

References

Abacherli, R., Pasquier, C., Odille, F., Kraemer, M., Schmid, J. J., & Felblinger, J. (2005). Suppression of MR gradient artefacts on electrophysiological signals based on an adaptive real-time filter with LMS coefficient updates. *MAGMA, 18,* 41–50.

Bach, D. R., Flandin, G., Friston, K. J., & Dolan, R. J. (2009). Time-series analysis for rapid event-related skin conductance responses. *Journal of Neuroscience Methods, 184,* 224–234.

Batson, C. D., Engel, C. L., & Fridell, S. R. (1999). Value judgments: Testing the somatic-marker hypothesis using false physiological feedback. *Personality and Social Psychology Bulletin, 25,* 1021–1032.

Bechara, A. (2003). Risky business: Emotion, decision-making, and addiction. *Journal of Gambling Studies, 19,* 23–51.

Bechara, A., Damasio, A. R., Damasio, H., & Anderson, S. W. (1994). Insensitivity to future consequences following damage to human prefrontal cortex. *Cognition, 50,* 7–15.

Bechara, A., Damasio, H., Damasio, A. R., & Lee, G. P. (1999). Different contributions of the human amygdala and ventromedial prefrontal cortex to decision-making. *Journal of Neuroscience, 19,* 5473–5481.

Bechara, A., Damasio, H., Tranel, D., & Damasio, A. R. (1997, February 28). Deciding advantageously before knowing the advantageous strategy. *Science, 275,* 1293–1295.

Bechara, A., Tranel, D., & Damasio, H. (2000). Characterization of the decision-making deficit of patients with ventromedial prefrontal cortex lesions. *Brain, 123,* 2189–2202.

Bechara, A., Tranel, D., Damasio, H., & Damasio, A. R. (1996). Failure to respond autonomically to anticipated future outcomes following damage to prefrontal cortex. *Cerebral Cortex, 6,* 215–225.

Birn, R. M., Kenworthy, L., Case, L., Caravella, R., Jones, T. B., Bandettini, P. A., & Martin, A. (2010). Neural systems supporting lexical search guided by letter and semantic category cues: A self-paced overt response fMRI study of verbal fluency. *NeuroImage, 49,* 1099–1107.

Birn, R. M., Murphy, K., Handwerker, D. A., & Bandettini, P. A. (2009). fMRI in the presence of task-correlated breathing variations. *NeuroImage, 47,* 1092–1104.

Boucsein, W. (1992). *Electrodermal activity.* New York, NY: Plenum Press.

Breiter, H. C., Aharon, I., Kahneman, D., Dale, A., & Shizgal, P. (2001). Functional imaging of neural responses to expectancy and experience of monetary gains and losses. *Neuron, 30,* 619–639.

Campbell, M. C., Stout, J. C., & Finn, P. R. (2004). Reduced autonomic responsiveness to gambling task losses in Huntington's disease. *Journal of the International Neuropsychological Society, 10,* 239–245.

Cechetto, D. F., & Shoemaker, J. K. (2009). Functional neuroanatomy of autonomic regulation. *NeuroImage, 47,* 795–803.

Chang, C., Cunningham, J. P., & Glover, G. H. (2009). Influence of heart rate on the BOLD signal:

The cardiac response function. *NeuroImage, 44,* 857–869.

Craig, A. D. B. (2002). How do you feel? Interoception: The sense of the physiological condition of the body. *Nature Reviews Neuroscience, 3,* 655–666.

Craig, A. D. B. (2009). How do you feel–now? The anterior insula and human awareness. *Nature Reviews Neuroscience, 10,* 59–70.

Critchley, H. D., Corfield, D. R., Chandler, M. P., Mathias, C. J., & Dolan, R. J. (2000). Cerebral correlates of autonomic cardiovascular arousal: A functional neuroimaging investigation in humans. *Journal of Physiology, 523*(Pt. 1), 259–270.

Crone, E. A., Somsen, R. J. M., Van Beek, B., & Van Der Molen, M. W. (2004). Heart rate and skin conductance analysis of antecendents and consequences of decision making. *Psychophysiology, 41,* 531–540.

Dale, A. M., & Buckner, R. L. (1997). Selective averaging of rapidly presented individual trials using fMRI. *Human Brain Mapping, 5,* 329–340.

Damasio, A. R. (1994). *Descartes' error: Emotion, reason, and the human brain.* New York, NY: Putnam.

Damasio, A. R., Tranel, D., & Damasio, H. (1991). Somatic markers and the guidance of behavior. In H. Levin, H. Eisenberg, & A. Benton (Eds.), *Frontal lobe function and dysfunction* (pp. 217–228). New York, NY: Oxford University Press.

De Martino, B., Kumaran, D., Seymour, B., & Dolan, R. J. (2006, August 4). Frames, biases, and rational decision-making in the human brain. *Science, 313,* 684–687.

Fellows, L. K. (2004). The cognitive neuroscience of human decision making: A review and conceptual framework. *Behavioral and Cognitive Neuroscience Reviews, 3,* 159–172.

Fellows, L. K., & Farah, M. J. (2005). Different underlying impairments in decision-making following ventromedial and dorsolateral frontal lobe damage in humans. *Cerebral Cortex, 15,* 58–63.

Friston, K. J., Fletcher, P., Josephs, O., Holmes, A., Rugg, M. D., & Turner, R. (1998). Event-related fMRI: Characterizing differential responses. *NeuroImage, 7,* 30–40.

Giardino, N. D., Lehrer, P. M., & Edelberg, R. (2002). Comparison of finger plethysmograph to ECG in the measurement of heart rate variability. *Psychophysiology, 39,* 246–253.

Glover, G. H., Li, T. Q., & Ress, D. (2000). Image-based method for retrospective correction of physiological motion effects in fMRI: RETROICOR. *Magnetic Resonance in Medicine, 44,* 162–167.

Gray, M. A., Minati, L., Harrison, N. A., Gianaros, P. J., Napadow, V., & Critchley, H. D. (2009). Physiological recordings: Basic concepts and implementation during functional magnetic resonance imaging. *NeuroImage, 47,* 1105–1115.

Gray, M. A., Rylander, K., Harrison, N. A., Wallin, B. G., & Critchley, H. D. (2009). Following one's heart: Cardiac rhythms gate central initiation of sympathetic reflexes. *Journal of Neuroscience, 29,* 1817–1825.

Hampton, A. N., Adolphs, R., Tyszka, M. J., & O'Doherty, J. P. (2007). Contributions of the amygdala to reward expectancy and choice signals in human prefrontal cortex. *Neuron, 55,* 545–555.

Hare, T. A., Camerer, C. F., Knoepfle, D. T., & Rangel, A. (2010). Value computations in ventral medial prefrontal cortex during charitable decision making incorporate input from regions involved in social cognition. *Journal of Neuroscience, 30,* 583–590.

Josephs, O., Turner, R., & Friston, K. (1997). Event-related fMRI. *Human Brain Mapping, 5,* 243–248.

Kable, J. W., & Glimcher, P. W. (2007). The neural correlates of subjective value during intertemporal choice. *Nature Neuroscience, 10,* 1625–1633.

Kahneman, D. (1997). New challenges to the rationality assumption. *Legal Theory, 3,* 105–124.

Kahneman, D., & Thaler, R. H. (2006). Anomalies: Utility maximization and experienced utility. *Journal of Economic Perspectives, 20,* 221–234.

Kimmerly, D. S., Wong, S., Menon, R., & Shoemaker, J. K. (2007). Forebrain neural patterns associated with sex differences in autonomic and cardiovascular function during baroreceptor unloading. *American Journal of Physiology: Regulatory, Integrative and Comparative Physiology, 292,* R715–722.

Kleeberg, J., Bruggimann, L., Annoni, J. M., Van Melle, G., Bogousslavsky, J., & Schluep, M. (2004). Altered decision-making in multiple sclerosis: A sign of impaired emotional reactivity? *Annals of Neurology, 56,* 787–795.

Knutson, B., Taylor, J., Kaufman, M., Peterson, R., & Glover, G. (2005). Distributed neural representation of expected value. *Journal of Neuroscience, 25,* 4806–4812.

Kugel, H., Bremer, C., Puschel, M., Fischbach, R., Lenzen, H., Tombach, B., & Heindel, W. (2003). Hazardous situation in the MR bore: Induction in ECG leads causes fire. *European Radiology, 13,* 690–694.

Lo, A. W., & Repin, D. V. (2002). The psychophysiology of real-time financial risk processing. *Journal of Cognitive Neuroscience, 14,* 323–339.

Mark, A. L., Victor, R. G., Nerhed, C., & Wallin, B. G. (1985). Microneurographic studies of the mechanisms of sympathetic nerve responses to static exercise in humans. *Circulation Research, 57,* 461–469.

McClure, S. M., Berns, G. S., & Montague, P. R. (2003). Temporal prediction errors in a passive

learning task activate human striatum. *Neuron, 38,* 339–346.

Montague, P. R., Dayan, P., & Sejnowski, T. J. (1996). A framework for mesencephalic dopamine systems based on predictive Hebbian learning. *The Journal of Neuroscience, 16,* 1936–1947.

Naqvi, N. H., & Bechara, A. (2009). The hidden island of addiction: The insula. *Trends in Neurosciences, 32,* 56–67.

Naqvi, N. H., Rudrauf, D., Damasio, H., & Bechara, A. (2007, July 20). Damage to the insula disrupts addiction to cigarette smoking. *Science, 315,* 531–534.

Odille, F., Pasquier, C., Abacherli, R., Vuissoz, P. A., Zientara, G. P., & Felblinger, J. (2007). Noise cancellation signal processing method and computer system for improved real-time electrocardiogram artifact correction during MRI data acquisition. *IEEE Transactions on Bio-medical Engineering, 54,* 630–640.

O'Doherty, J., Dayan, P., Schultz, J., Deichmann, R., Friston, K., & Dolan, R. J. (2004, April 16). Dissociable roles of ventral and dorsal striatum in instrumental conditioning. *Science, 304,* 452–454.

O'Doherty, J. P., Hampton, A., & Kim, H. (2007). Model-based fMRI and its application to reward learning and decision making. *Annals of the New York Academy of Sciences, 1104,* 35–53.

Ongur, D., & Price, J. L. (2000). The organization of networks within the orbital and medial prefrontal cortex of rats, monkeys and humans. *Cerebral Cortex, 10,* 206–219.

Rogers, R. D., Lancaster, M., Wakeley, J., & Bhagwagar, Z. (2004). Effects of beta-adrenoceptor blockade on components of human decision-making. *Psychopharmacology, 172,* 157–164.

Saper, C. B. (1982). Convergence of autonomic and limbic connections in the insular cortex of the rat. *Journal of Comparative Neurology, 210,* 163–173.

Saper, C. B. (2002). The central autonomic nervous system: Conscious visceral perception and autonomic pattern generation. *Annual Review of Neuroscience, 25,* 433–469.

Schultz, W., Dayan, P., & Montague, P. R. (1997, March 14). A neural substrate of prediction and reward. *Science, 275,* 1593–1599.

Selvaraj, N., Jaryal, A., Santhosh, J., Deepak, K. K., & Anand, S. (2008). Assessment of heart rate variability derived from finger-tip photoplethysmography as compared to electrocardiography. *Journal of Medical Engineering and Technology, 32,* 479–484.

Stigler, G. J. (1950). The development of utility theory. I. *The Journal of Political Economy, 58,* 307–327.

Sugita, Y., & Suzuki, Y. (2003). Audiovisual perception: Implicit estimation of sound-arrival time. *Nature, 421,* 911.

Tom, S. M., Fox, C. R., Trepel, C., & Poldrack, R. A. (2007, January 26). The neural basis of loss aversion in decision-making under risk. *Science, 315,* 515–518.

Tomb, I., Hauser, M., Deldin, P., & Caramazza, A. (2002). Do somatic markers mediate decisions on the gambling task? *Nature Neuroscience, 5,* 1103–1104; author reply 1104.

Wong, S. W., Massé, N., Kimmerly, D. S., Menon, R. S., & Shoemaker, J. K. (2007). Ventral medial prefrontal cortex and cardiovagal control in conscious humans. *NeuroImage, 35,* 698–708.

Wunderlich, K., Rangel, A., & O'Doherty, J. P. (2009). Neural computations underlying action-based decision making in the human brain. *Proceedings of the National Academy of Sciences of the United States of America, 106,* 17199–17204.

Xue, G., Lu, Z., Levin, I. P., & Bechara, A. (2010). The impact of prior risk experiences on subsequent risky decision-making: The role of the insula. *NeuroImage, 50,* 709–716.

Xue, G., Lu, Z., Levin, I. P., Weller, J. A., Li, X., & Bechara, A. (2009). Functional dissociations of risk and reward processing in the medial prefrontal cortex. *Cerebral Cortex, 19,* 1019–1027.

Yasui, Y., Breder, C. D., Saper, C. B., & Cechetto, D. F. (1991). Autonomic responses and efferent pathways from the insular cortex in the rat. *Journal of Comparative Neurology, 303,* 355–374.

Received March 12, 2010
Revision received March 8, 2011
Accepted March 8, 2011 ■