Psychological Thought
psyct.psychopen.eu | 2193-7281

PsychOpen
publishing psychology

Theoretical Analyses

The Physiological Processes Underpinning PET and fMRI Techniques With an Emphasis on the Temporal and Spatial Resolution of These Methods

George Varvatsoulias*[a]

[a] West London Mental Health NHS (National Health Service) Trust, London, United Kingdom.

Abstract

In this paper the scanning techniques of PET and fMRI are presented and discussed in technical terms. The main focus of this paper is the physiological processes underpinning these techniques and the ways they operate temporally and spatially. Physiological processes captured by these techniques refer generally to the volume of blood in the brain and the concentration of oxygen in the blood. Temporal and spatial resolution in the case of these methods refers to data collection when the brain is scanned. Temporal resolution records the exact time when a cognitive process takes place; spatial resolution demonstrates in what part of the brain such activity takes place. A comparison between these two techniques shows that one needs the other in terms of measuring the blood and oxygen in the brain so clear pictures of cognitive processes and their locations to be obtained. Both PET and fMRI are in use from cognitive neuroscience, for through the measures that they take from the brain, cognitive processes and their locations can be clearly identified and read.

Keywords: PET, fMRI, ASL, MR Spectroscopy, blood, oxygen, temporal resolution, spatial resolution

Psychological Thought, 2013, Vol. 6(2), 173–195, doi:10.5964/psyct.v6i2.75

Received: 2013-05-11. Accepted: 2013-05-25. Published (VoR): 2013-10-25.

*Corresponding author at: 15 Ludlow Road, London, United Kingdom, W5 1NX. E-mail: George.Varvatsoulias@wlmht.nhs.uk

This is an open access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/3.0), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Introduction

Cognitive neuroscience explores the mind's cognitive processes by studying the brain's neural activities. Neural activities are located in specific regions of the brain and are investigated through imaging techniques such as PET and fMRI (Otte & Halsband, 2006).

PET (Positron Emission Tomography) and fMRI (functional Magnetic Resonance Imaging) are non-invasive scanning techniques[i] (Shibasaki, 2008). They both make use of cutting-edge technology in order to systematically study and diagnostically examine the structural and functional complexities of human brain (McKeefry, Gouws, Burton, & Morland, 2009). PET and fMRI are computerised methods aiming to explore cerebral functions and disorders.

PET is a scanning technique allowing for the recording of changes in the brain after injury with or without cognitive activation (Tate, Shenton, & Bigler, 2012). It is also a method that studies higher-order cognitive abilities, such as language, memory, and perception (Kitson, Cuccurullo, Ciarmiello, Salvo, & Mansi, 2009; Matthews, Johansen-Berg, Reddy, 2004). Functional MRI is an imaging technique that detects which brain areas are involved in partic-

ular neural actions, cognitive processes, or emotional responses. It is also a widely used method to investigate diseased parts of the brain (Billings, Churchill, & Payne, 2010). PET and fMRI explore the brain's physiological constraints through spatiotemporal dynamics.

In this paper, it will be discussed how physiological processes have an impact on temporal and spatial resolution with regards to cognitive operations occurring in various parts of the brain. To this aim, specific examples will be provided so that the reader to understand how cognitive processes taking place depend on spatiotemporal dynamics and their physiological stipulations. PET and fMRI make use of physiological processes of the brain so to record temporal and spatial resolution measurements.

In particular:

1. PET and fMRI investigate the activity of neurons in terms of metabolic changes taking place in blood and oxygen flow (Ward, 2010, p. 53).[ii] PET and fMRI look at the volume of blood in the brain and the concentration of oxygen in the blood (Ito, Ibaraki, Kanno, Fukuda, & Miura, 2005). Both methods measure physiological processes and record changes when participants are asked to perform cognitive tasks (Whelan, 2007).
2. PET and fMRI temporal and spatial resolution are determined by physiological and cognitive processes (Chen, Wieckowska, Meyer, & Pike, 2008). PET and fMRI, by recording physiological processes, investigate mental activities of the brain while at the same time temporal and spatial resolutions generate data - deriving from neurotransmitter and receptor molecules to large network brain cells - regarding the structure and function of the brain at all levels (Cavanna & Trimble, 2006; Ganis & Kosslyn, 2002, p. 493).
3. PET and fMRI modalities are considered to be limited not in terms of utility and functionality, but in terms of accuracy as to the recording of cognitive activities, such as changes taking place on inhibitory and/or excitatory synapses[iii] the distance between which is just a few millimetres as to the physiologic properties[iv] they depend on (Buckner & Logan, 2001, p. 29; Chen & Li, 2012).
4. In comparing the two techniques what we find is that cognitive processes which are detected through PET can also be detected from fMRI scanners as well (Berlin, 2011). fMRI scanners can detect more cognitive activations compared to cognitive activations detected by PET. fMRI scanners prove more powerful from PET ones for they have been found to be more clinically useful in the detection of hemispheric mapping of cognitive processes (Sternberg, 2011).

The Human Brain

The human brain is an organ of complicated physiology which consumes 20% of the body's oxygen available in the blood (Berker, 1996; Dunn, Ellegala, Fox, & Kim, 2006). It consists of 100.000.000.000 neurons of which 85.000 are lost per day between the ages 20-90 years. For someone who lives up to 90 years of age, the number of neurons who he/she may lose may increase up to 2.171.750.000 (Gazzaniga, 2009). PET investigates the brain through radiation, whereas fMRI through magnetic fields of 1.5 to 3 Tesla (T). Images obtained from both are analysed through voxels (Myers, 2002; Leite, 2009). Voxels are separated to small volumes of thousands, each of which represents data structures consisted of elements, such as colour and opacity, in a 3-D space (Crassin, 2011; Goldwasser & Reynolds, 1987). Through PET and fMRI, cognitive neuroscience is able to study in vivo physiological processes of particular brain regions (Lane et al., 2009; Volkow, Rosen, & Farde, 1997). Physiological processes are associated to neuronal activation of brain regions involved in task implementation. Responses collected from performance on tasks explain issues of greater or lower stimulation at specific areas of the brain (Kelly & Garavan, 2005; Tancredi & Brodie, 2007).

PsychOpen
publishing psychology

Physiological Processes Underpinning PET

PET employs radioactivity to quantitatively analyse metabolism and /or neurotransmitter receptors. (Sattler, Lee, Lonsdale, & Coche, 2010). Radioactivity is contained in naturally occurring elements, such as carbon, oxygen and nitrogen, which signal out data ready to be analysed (Leopold, 2007; Prichard & Brass, 1992). In PET the signal is provided by radio-labeled water which, after injection, circulates into the tissue surrounding the blood vessels (de Barros, Tsourkas, Saboury, Cardoso, & Alavi, 2012; Raichle, Grubb, Gato, Eichling, & Ter-Pogossian, 1976).

Radioactivity is the main method for measuring neural activity through PET (Aine, 1995; Schei, 2011). Radiotracers, such as oxygen-15 ($H_2{}^{15}O$) and fluorine-18 (^{18}F)[v] are injected into the participant's bloodstream in order changes in blood flow in particular brain regions to be directly measured (Kitson et al., 2009). Oxygen-15 can be injected in the form of water, whereas fluorine-18 is usually injected as glucose sugar (Burger & Townsend, 2007; Wagner, 1985). The distribution of tracers in the brain is the work of local blood supply, whereas variations of signals received from these tracers are the outcome of blood flow changes (Bammer et al., 2005; Brown, Clark & Liu, 2007). Radiotracers can provide information associated to the circulation of blood flow in a brain area, so emission of signals to be recorded (Lane et al., 2009). However, other tracers, such as radio-labelled neurotransmitters can also be used. Radio-labelled neurotransmitters can assist the understanding of substance-induced agents, such as the effect of drugs in the chemistry of the brain, based on the coupling between neuronal activity, metabolism and hemodynamics (Jenkins, 2012; Turner & Jones, 2003).

PET images are received by tracing the blood flow with water, or by glucose metabolism containing a hydrogen atom (Rex et al., 2008).[vi] Research has shown that blood flow provides better readings of brain function compared to glucose consumption. This is because blood flow is more sensitive to neural activation than glucose (Kurzban, 2010; Raichle, 1994). Also, blood flow imaging can be repeated more times per session, so changes in cerebral functions to be recorded for different tasks. The outcome of this are adequately imaged neural activities from different parts of the brain (Frackowiak & Friston, 1994; Mukamel & Fried, 2012).

PET is a sensitive method in that it employs the use of radiotracers labelled with short-lived positron-emitting isotopes so that chemical reactions in the brain can be read (Ganguly, Mondal, Nandy, & Roesch, 2009; Posner & Raichle, 1994). Tracers in the blood flow are lacking radioactive stability. In order to come to a normal and balanced form a positron needs to be emitted for spatial images of the brain to be recorded (Leenders, Gibbs, Frackowiak, Lammertsma, & Jones, 1984; Velikyan, 2011). A positron during PET consumes lower energy in that it travels a shorter distance – between 2-3mm - to collide with an electron (Phelps, 2000; Roß & Ametamey, 2011). An electron frees two photons that are spotted by detectors placed around the head and in this way the accuracy of readings can be monitored (Cherry, 2006; Khalil, 2011).

Biochemical selectivity is another significant feature of PET. Through biochemical selectivity, specific radiotracers are designed to be selectively bound with molecular targets (Pike, 2009)[vii]. Molecular targets, such as receptors, transporters and enzymes influence the metabolism or synthesis of neurotransmitters (Diamanti-Kandarakis et al., 2009; Weng, Ding, & Volkow, 1999)[viii]. In this way, PET is also widely used in the study of biochemical and pharmacological imaging of the brain, together with the identification of anatomical aspects related to cognitive processes (Drevets, Price, & Furey, 2008; Volkow et al., 1997).

The identification of anatomical aspects through PET refer to the localisation of cognitive processes in certain areas of the brain. Identification of location helps neuroscientists research interactions between cognitive processes

PsychOpen
publishing psychology

via relevant physiological precipitants, such as cerebral blood flow. PET in studying the physiological processes taking place in the brain greatly contributes to questions of localisation and interaction (Stam & van Straaten, 2012). The biochemical imaging of brain identifies through PET the mechanisms involved in the study of compounds of composite cognitive activities, whereas the pharmacological imaging through this imaging technique is a combination of diagnostic mapping of neuronal activation and drug development in terms of clinical monitoring of the factors triggering cognitive processes in the brain (Lawrence & Heinz, 2011).

The PET technique explains cognitive processes mediated by respective neural activity (Drevets et al., 2008; Pinel, 2003). It also helps to diagnose cerebral disorders as well as in the investigation and understanding of the causes of brain diseases, so that to offer relevant treatments (Linden, 2006).

Physiological Processes Underpinning fMRI

Functional MRI is a non-invasive technique and does not use ionised radiation as it is the case for PET (Kwan-Hoong, Ahmad, Nizam, & Abdullah, 2003; Sutton, Ouyang, Karampinos, & Miller 2009). Investigation in the scanner can last up to 60 minutes. Functional MRI depends on blood flow increase in vessels and tissues associated to the brain's neuronal activity (Belliveau et al., 1991; Moridani, 2009). The outcome of such increase is a reduced level of deoxyhemoglobin in oxygen extraction (Huppert et al., 2009)[ix].

Functional MRI studies neural activity in relation to oxygen levels fluctuated in the blood. Heightened demand for oxygen in the blood increases neural activity (Laureys, Peigneux, & Goldman 2002; Vazquez, Masamoto, Fukuda, & Kim, 2010). Increased neural activity means that brain regions are in need for more oxygen. Demands in oxygen are obtained via increased blood flow to meet neural metabolic activation (Jespersen & Østergaard, 2012; Mintun et al., 2001).

Functional MRI measures the intensity of radio-waves received by the brain (Devonshire et al., 2012; Price, Allison, Massoth, Clarke, & Drost, 2002). Magnetic resonance signals are sensitive to the sum of deoxyhemoglobin levels in the blood (Kim & Ogawa, 2012; Toronov et al., 2003). Deoxyhemoglobin sometimes functions as an internal contrast-enhancing agent which serves as a source for signals received from fMRI (Bandettini, Wong, Hinks, Tikofsky, & Hyde, 1992; Kim & Bandettini, 2010). The investigation of neuronal activity via fMRI depends on three main physiological processes:

1. Blood volume, where cerebral blood flow is measured regionally.
2. Blood flow, where water molecules in blood are magnetically monitored in order for signal changes to be detected.
3. Blood oxygenation, where blood vessels display falling levels of baseline oxygenation. In this way, neuronal stimulation increases blood flow, whilst oxygen consumption does not (Bandettini, 2006).

Functional MRI is sensitive to blood oxygen level-dependent signal changes (BOLD)[x], and hence highly popular for "taking" brain mapping images to be taken (Feng, Caprihan, Blagoev, & Calhoun, 2009; Ogawa, Lee, Kay, & Tank, 1990). Due to venous blood flowing from a region - during neural activity - the production of BOLD signal changes affects the degree of deoxygenation (Christen, Bolar, & Zaharchuk, 2013; Gore, 2003). This may result in a displacement of the position of signal change from the location of neural activity to the draining veins (Olman, Inati, & Heeger 2007). The popularity of the BOLD fMRI methodology relates to the fact that it can be performed on many clinical scanners, for no external agents, such as tracers or contrast, are required (Chiou & Hillary, 2011; Kwong et al., 1992).

PsychOpen
publishing psychology

Functional MRI can also measure blood flow and blood volume through a method called *arterial spin labelling* (ASL). Through this method it is succeeded repetitive measurement of cerebral blood flow (CBF). If we compare arterial spin labelling to contrast-based methods, such as BOLD, ASL techniques provide a more biologically-based correlate to the activation of neurons aiming at adequate estimations regarding the location and extent of neural function (Liu & Brown, 2007). ASL is a rich method for the measure of cerebral blood flow by the help of fMRI. Another method for measuring perfusion[xi] with fMRI is dynamic susceptibility contrast (DSC) where quantification of blood vessels fluid is taken (Zaharchuk et al., 2010). Cognitive neuroscience research is concerned with the activity of neurons in the brain and has been greatly benefited by the use of perfusion methods such as ASL and DSC through the technical applications of fMRI.

Neural activity fluctuations influence the BOLD signal. The BOLD signal depends on the hemodynamic response function (HRF)[xii], which follows three stages (Arichi et al., 2012; Hoge & Pike, 2001; Logothetis, Pauls, Augath, Trinath, & Oeltermann 2001). The *initial dip* where the amount of oxygen consumed from neurons increases levels of deoxyhemoglobin, whilst it decreases the BOLD signal (Li & Freeman, 2007). The initial dip provides a good spatial localiser in regard to early neural activity and cerebral blood flow (CBF) increases (Ances, 2004; Wager, Hernandez, Jonides, & Lindquist, 2007). Next is *overcompensation* where consumption of increased oxygen relates to blood flow increase in a particular brain area. Blood flow increase is higher compared to the oxygen consumption increase (Hoshi & Tamura, 1993; Schleim & Roiser, 2009). That means that the BOLD signal increases too. The increase in BOLD signal is what fMRI records. Finally, comes *undershooting* where blood flow and oxygen consumption levels dip prior to coming back to initial stages (Lu, Golay, Pekar, & van Zijl, 2004; Poser, van Mierlo, & Norris, 2011). This could lead the venous system into relaxation, whilst deoxyhemoglobin levels to a further increase (Aquino, Schira, Robinson, Drysdale, & Breakspear, 2012; McIntyre, Richter, Morden, Wennerberg, & Frankenstein, 2003).

Functional MRI can also measure metabolic changes through methods called MR spectroscopy and/or fMRI spectroscopy. MR spectroscopy[xiii] refers to a non-invasive test of diagnosis which measures metabolic changes in the form of biochemical alterations in the brain. In this way, what is compared is normal brain activity as to the chemical composition of brain tissue to brain abnormal activity. MR spectroscopy is very useful tool in the detection of tissue changes from normal to abnormal brain activity and vice versa (Kirov, Tal, Babb, Herbert, & Cohen, 2013).

The use of fMRI spectroscopy is a combination of magnetic resonance spectroscopy (MRS), fMRI, and diffusion-tensor imaging (DTI)[xiv]. Through this combination what is measured are metabolic, functional and connectivity correlates of brain structures via the activation of neuron-based cognitions. What is obtained is the assessment of physiological function of observable metabolites and concentration changes of cerebral blood flow and their correlation to cognitive performance participants are subjected to during tasks (Mangia et al., 2006; Minati, Grisoli, & Bruzzone, 2007).

In testing a participant across the same brain area, hemodynamic response function does not exhibit important fluctuations with regards to neural activity. However, when a participant's brain is scanned across different areas, hemodynamic response function appears with changes having to do with cerebrovascular (cognitive functions related to blood vessels supplying the brain) and oscillary brain dynamics (alpha, beta gamma, delta and theta oscillations activating neural assemblies in different cortical locations) as well as time-frequency distribution (the study of a signal both in time and frequency domains at the same time) (Akgül, Sankur, & Akin, 2005; Başar,

PsychOpen
publishing psychology

Güntekin, & Öniz, 2006; Cohen, 1989); something, which is also the case when different participants take part in the same study (Schwartz, Maquet, & Frith, 2002). The amount of deoxygenated hemoglobin found within a voxel may decrease local hemodynamic responses in the order of seconds (Buckner et al., 1996; Eggebrecht et al., 2012).

Before concluding this part of the discussion, it is argued that PET, fMRI, and MR Spectroscopy are not always found in concert as to which one could be the process of choice when certain questions about brain functions involving cognitive activations are targeted. That implies that there are researchers who consider that to identifying particular brain functions, PET, fMRI, MR spectroscopy imaging techniques should better be individually used and not in combination (Crosson et al., 2010; Pillai, 2010).

To use an example, in studying the dopamine system in the brain[xv]. The reason I show specific interest to dopamine is because it's a metabolite which can positively correlate PET and fMRI (Moeller, Tomasi, Honorio, Volkow, & Goldstein, 2012). Neuroscientists argue that the positive correlation between PET and fMRI, in reference to dopamine, has to do with the fact that neuronal activation that is elicited in various areas in the brain, such as the amygdala and the dorsal anterior cingulate cortex can be measured both in terms of 6-[^{18}F]fluoro-L-DOPA positron emission tomography[xvi] as well as functional magnetic resonance imaging BOLD signal changes (Barrio et al., 1990). A correlation between PET and fMRI, the above areas refer to, is when dopamine is released under conditions of stress so that regulation between aversive stimuli to be processed (Kienast et al., 2008). PET and fMRI prove useful techniques for such processing to be recorded and fully measured.

Other example of having PET and fMRI working in unison for the generation of data is the study of serotonin via a combination of functional and molecular measurements regarding the imaging of its activity in the brain (Gerstl et al., 2008). Another example could be the study of neurotransmitter systems of noradrenaline and acetylcholine in view to obtain mapping information as to the regulation of prefrontal cortical function. A combination of PET and fMRI can again prove useful in respect to the scanning of cognitive activities related to that part of the brain (Robbins, 2005).

it is suggested that through PET imaging dopaminergic activity can be indirectly mapped by the use of particular tracers - as from page 3ff of the present article - so that functional consequences of this neurotransmitter to be observed with regards to the neuronal activation of specific pathways (Slagter et al., 2012).

In comparison to that, imaging dopaminergic activity with fMRI is a direct process. What is meant is that dopaminergic activity and/or release is recorded not only through reward consumption - as in note 15 - but also through reward prediction; in other words, after a task has been completed, as well as before that to be put into an implementation procedure (Knutson & Cooper, 2005).

Finally, in measuring dopaminergic activity through MR spectroscopy there have been discovered associations between neurotransmission of mental disorders. A dysfunctional state which relies on dopaminergic activity and has been explored via MR spectroscopy is the condition of schizophrenia, where associations between glutamate and dopamine have been recorded as to the onset of this disorder, i.e. dopamine was found being modulated by glutamate in the case of schizophrenia (Marsman et al., 2013).

In summing up, as to the role of dopamine being examined under differing imaging techniques, such as PET, fMRI, and MR spectroscopy, there are evidence-based studies proving the role of PET as a general mapping

PsychOpen
publishing psychology

technique to the outset of the identification of dopaminergic activity; fMRI as a direct process to signaling out dopamine in view to identifying issues of prediction and consumption of the reward activity of this neurotransmitter; and MR spectroscopy in terms of recording interactions of dopamine with other neurotransmitters, such as glutamate.

Another example could be the study of the cognitive ability of attention. In studying attention via PET imaging, what is recorded is the relationship of this cognitive ability to particular stimulus features, such as shape, movement, location, size and colour, when subjects undergo specific tasks (Awh, Vogel, & Oh, 2006). As to the study of attention via fMRI, what can be imaged is the neuronal association between this cognitive ability to decreased perceptions of pain, in a case such as distracting a subject's attention from harmful stimulants (Hammersley, 2010). As to the study of attention via MR spectroscopy, what can be imaged is the role of attention as intellectual functioning in terms of metabolite changes; in other words, what is imaged are differences in metabolite activity and how these influence attention during target implementations, such as subjects being prompted to a particular stimulus regarding visual attention during increase or decrease of amino acids (Yeo et al., 2011).

In summing up, as to the second example I have used regarding the cognitive ability of attention and how that could be imaged during PET, fMRI and MR spectroscopy techniques, it may be argued that the former of them studies attention in relation to object observation features so that the brain to be stimulated; fMRI studies how attention could be increased and/or decreased when neuronal activity is distracted from object observation; whilst, finally, MR spectroscopy studies attention via metabolic alteration.

What Determines the Temporal and Spatial Resolution of These Methods

Temporal and spatial resolution form an integral part of data collection for both techniques. Temporal resolution is based on the time needed for a cognitive process to occur, whereas spatial resolution on the location a cognitive activity is processed in the brain (Roche, Commins, & Dockree, 2009). By ‘location’ it is meant that a brain area may respond to a stimulus other areas could respond too (Chialvo, 1997; Grill-Spector, Henson, & Martin, 2006).

The spatiotemporal characteristics of PET and fMRI are determined by:

- The knowing-where of cognitive functions anatomy and processes
- The knowing-when of brain activity and human behaviour
- The knowing-what of physiological processes regarding the changes occurring in different brain regions (Pichler, Kolb, Nägele, & Schlemmer 2010; Weng et al., 1999).

PET and fMRI spatiotemporal resolution is also determined by hemodynamic responses and oxygenation changes as per the neural activity underpinning these physiological constraints (Detre & Wang, 2002). Temporal resolution refers to when a neural event takes place and how long it lasts, whereas spatial resolution focuses on where that neural event is situated (Nadal, Munar, Àngel-Capó, Roselló, & Cela-Conde, 2008; Shadlen & Newsome, 1996). Cognitive neuroscience does not simply observe where neuronal activity happens but to what extent can be accurately explained in relation to the spatiotemporal underpinnings of its occurrence (Stephan, 2004).

Spatiotemporal dynamics depend on duration (time), frequency (rate of occurrence) and the brain areas cognitive processes take place (Démonet, Thierry, & Cardebat, 2005; Michel, Seeck, & Landis, 1999). PET has poor temporal resolution (30sec), whereas it has good spatial resolution (10mm); 30sec in PET refers to the time a tracer needs to reach the brain, whereas another 30sec are needed for radiation to peak (Benaron et al., 2000). Longer times refer to slower speed, and slower speed in PET emphasises the problem of slow recordings of cognitive

PsychOpen
publishing psychology

processes (Massimini, Huber, Ferrarelli, Hill, & Tononi, 2004). Cognitive processes are normally recorded at a time closer to one second, which is why PET temporal resolution is poor (Bell, 2004).

Time determines a relatively poor temporal resolution in the order of seconds (1-4sec) for fMRI, but very good spatial resolution (1mm). For instance, hemodynamic responses may result in a decrease of temporal resolution from 2sec to 4sec. This is because hemodynamic responses determine time constraints during neural events (Kwong et al., 1992; Uludağ, 2008). Recording speed is better in fMRI, for it allows cognitive phenomena to be monitored more accurately, and also to be located more precisely (Detre & Wang, 2002; Marrelec, Ciuciu, Pélégrini-Issac, & Benali, 2004).

Temporal and spatial resolution measurements are important in the understanding of individual differences between participants undergoing the same or different cognitive tasks, as well as in the comprehension of cognitive processes between controls and brain-impaired patients (D'Esposito, 2008). Recordings of cognitive activities through fMRI provide a better understanding regarding their region and spatial location in the hemispheres (Stevens, Calhoun, & Kiehl, 2005).

Since spatiotemporal resolution differs between these two methods, PET and fMRI can be employed in association with event-related or blocked designs (Ward, 2010). Blocked designs are suggested for PET due to the poor temporal resolution of this method (Horwitz, Friston, & Taylor, 2000; Petersen & Dubis, 2012). Through blocked designs participants can perform repeated tasks in both PET and fMRI many times (Grabowski & Damasio, 1996). Event-related fMRI calculates selective averaging of individual tests in mixed tasks in order for brain functions to be studied more effectively (Jimura & Braver, 2010; Weng et al., 1999).

Comparison Between PET and fMRI

Spatiotemporal resolutions are determined by the study of basic units of activated networks at the time when and location where neural events occur (Logothetis, 2008). Variability of changes in a signal at the time it is received and the space it is situated in can also determine PET and fMRI spatiotemporal resolution (Kiebel & Friston, 2004). Table 1 below presents differences between PET and fMRI scanning techniques applicable to their temporal and spatial resolution.

In summary, there is an increasing interest both techniques to be used in combination, for PET is a more sensitive method compared to BOLD fMRI, the reason being the quantitative investigation of events at the molecular level through the use of radio-labeled tracer molecules and has proved to be the one of the most powerful methodologies *in vivo* (Bolus, George, Washington, & Newcomer, 2009; Zaidi & Del Guerra, 2011, p. 5667). As such, PET and fMRI alone are not accurate to deal with a wide area of questions in a research or diagnostic study. Nowadays, it is rather common for PET and fMRI readings to be obtained on separate scanners, and then spatially co-registered via advanced image-alignment algorithms (Hill, Batchelor, Holden, & Hawkes, 2001; Zaidi & Del Guerra, 2011)[xx]. In this way, physiological constraints and cognitive processes are able to determine spatiotemporal characteristics through better and more balanced resolutions (Crosson et al., 2010; Wager et al., 2007).

PsychOpen
publishing psychology

Table 1

In Comparing PET and fMRI Several Reasons Can Be Identified for why Spatiotemporal Determination Is an Important Issue for Both These Methods

Positron Emission Tomography (PET)	Functional Magnetic Resonance Imaging (fMRI)
PET technique images the brain's blood volume.	fMRI images the concentration of oxygen in the blood.
PET signals are generated by the use of radioactive tracers. PET imaging may take place only once.	In fMRI no radioactive exposure is involved, and signals depend on deoxyhemoglobin levels. Due to this fact, fMRI imaging can take place more than once.
PET makes use of positron-emitting radiopharmaceuticals.	fMRI makes no use of pharmacological agents.
Temporal resolution is 30sec in PET. It is regarded s slow, given the time needed for cognitive processes to be recorded (1sec).	Temporal resolution in fMRI between 1-4sec. Image acquisition rate is more accurate and images are recorded in more detail (Crosson et al., 2010; Kim, Richter, & Uğurbil, 1997).
Functional image resolution for PET is 10mm.	Functional image resolution for fMRI is 1mm. The more images are obtained, the higher the spatial resolution can be. In contrast, single signal measurements are usually not preferable for their decay is much lower than that of multiple images (Bandettini, 2002; Kim et al., 2004).
Multiple imaging acquisitions are required by PET, which means that participants need to remain in the scanner for extended times (Massoud & Gambhir, 2003; Poline et al., 2012).	Functional MRI scan time is very short, on an order of 1.5 to 2.0min per run, which means that faster functional brain imaging is provided and participants do not need extended times in the scanner (Amaro & Barker, 2006; Pruessmann, Weiger, & Boesiger, 2000).
PET produces much larger and slower resolutions.	fMRI produces smaller and quicker resolutions.
Only blocked designs are possible for PET (Ward, 2010). In PET blocked designs, stimuli that refer to the same condition can be categorised together (Schon, Tinaz, Somers, & Stern, 2008)[xvii].	Event-related or blocked designs are possible for fMRI. In efMRI dissimilar stimuli or conditions can intertwine with one another[xviii].
PET is more sensitive in the imaging of the brain, for it can scan the whole of it.	In fMRI some brain regions, such as those near sinuses[xix], are difficult to be imaged (Devlin et al., 2000; Shmueli et al., 2009).
Another issue not found the PET is that fMRI is very noisy. That means that when participants are asked to perform cognitive tasks, they may more easily be distracted. Noise, can be an issue for signal changes too (Ward, 2010)	Signals in fMRI can also be easily altered due to participants' head movement partly because of the noise they hear when the fMRI is operating. In PET, signals are not altered because of head movement (Goebel, 2007; Seto et al., 2001).
PET as a method of choice to study neuronal activity has been found to be more useful in the identification of object observation in terms of the neurotrans-mission involved, which by the help of MR spectroscopy can be outlined in the form of changes in metabolic activity.	fMRI as a method of choice to study neuronal activity has been found to be more direct compared to PET, for on the one hand neurotransmission can be identified not only during or after a particular task but also prior such task to take place. The conjunction of fMRI to MR spectroscopy in the study of neurotransmitters can as well be fruitful because the study of metabolic changes can be recorded in the increase and/or decrease of neurotransmission activity.

Conclusion

PET and fMRI are imaging techniques studying the human brain. They are non-invasive methods investigating neural pathways, allowing for cognitive processes to be explored. The physiological underpinnings of PET are that it researches brain activities via blood flow volume, whereas fMRI that it examines the amount of oxygen in the blood. PET employs ionised radiation to study the brain by means of injecting in the bloodstream tracers such

PsychOpen
publishing psychology

as oxygen-15 and fluorine-18, whilst fMRI studies deoxyhemoglobin levels in the blood, as well as changes in blood oxygen level-dependent signals (BOLD).

Brain activity and cognitive processes are recorded through corresponding spatiotemporal characteristics. PET and fMRI spatiotemporal resolution is determined by hemodynamic response measurements and neuronal activity oxygenation changes in relation to the aforementioned physiological constraints. When and where cognitive processes take place plays a significant role in the determination of spatiotemporal dynamics in terms of the time and space of their occurrence. However, there are differences in the spatiotemporal dynamics between these two methods: PET has poor spatiotemporal resolution, whereas fMRI has a better one.

Functional MRI, unlike PET, is more predominant nowadays (Pichler, Wehrl, & Judenhofer, 2008). One of the main reasons is that the former does not employ radiation and participants can be studied many times. Another is that both techniques measure cognitive processes in relation to different physiological constraints. However, PET and fMRI can both provide an accurate scanning of the whole brain, though fMRI is noisy, compared to PET, which means that participants' performance may be affected. PET and fMRI can also prove more elaborate techniques when *conjoined* to MR spectroscopy in order that areas in the brain to be offered more detailed scanning and mapping. Finally, the use of fMRI through ASL has been found very useful in providing more accurate recordings of the spatial presence of cognitive functions.

PET and fMRI are powerful imaging techniques in the study of neuronal activity and its association to human cognition. They can correlate positively with each other in the study of neurotransmitters, such as in the case of dopamine, so that modulation between aversive stimuli to be processed and efficiently recorded. However, there is still something missing as to the understanding of how neuronal activity - being subjected to physiological changes - produces cognitive activation. To this day, a possible answer to such question is claimed to be MR spectroscopy through which metabolite changes can offer explanations as to how parts of the brain with seemingly less interactions to one another could actually be related to each other in terms of increased or decreased cognitive activation. That means, as discussed in the main part, that metabolic changes in the brain do influence physiological processes occurring in different brain regions; changes, which entail cognitive activation fluctuations precipitated by physiological processes.

Notes

i) PET, though it employs ionizing radiation* for the production of imaging data, it is considered as a type of nuclear medicine noninvasive technique based on painless medical tests (Bailey, Townsend, Valk, & Maisey, 2005). *Ionizing radiation refers to particles able to carry enough energy, so that an electron to be liberated by an atom or molecule via ionizing it. 'Ionizing radiation' is produced via artificial or natural nuclear reactions by the help of high temperature. In ionizing radiation are included alpha, beta, gamma rays, X-rays and cosmic rays (Camphausen & Coia, 2008).

ii) Also, fMRI can measure blood and oxygen flow through ASL (Anterior Spin Labeling) methods. ASL demonstrates easily and quickly hypo- and hyperperfusion in a variety of different disease cases of general or specific localised scale (Deibler et al., 2008; Noguchi et al., 2012).

iii) By *inhibitory synapse* it is meant the nerve impulse in the pre-synaptic cell which reduces the probability an action to be fired by the post-synaptic cell. By *excitatory synapse* it is meant an action taking place in a pre-synaptic cell – the release of a neurotransmitter - with the likelihood to increase an action needed in a post-synaptic cell – stimulated by the release of the neurotransmitter (cp. Chih, Engelman, & Scheiffele, 2005).

iv) Some of them are: γ–aminobutyric acid, neuropeptides, calcium-binding proteins (parvalbumin and calbindin) (Druga, 2009; Markram et al., 2004).

v) Oxygen-15 ($H_2{}^{15}O$) refers to radio-labeled water which is useful for measuring the signal intensity coming through the PET so to directly and specifically to reflect tissue perfusion (de Langen, van de Boogart, Vivian, Marcus, & Lubberink, 2008).

PsychOpen
publishing psychology

Fluorine-18 (^{18}F) is a radio-magnetic agent used in PET brain imaging to detect brain cell activity under various conditions of examination (Schirrmacher et al., 2006).

vi) Hydrogen atom refers to the radioactive tracing of brain activity under particular tests and/or trials (Antoniewicz, Kelleher, & Stephanopoulos, 2011).

vii) By 'molecular targets' are meant small molecules, proteins, nuclei acids, cells, tissues, or even parts of an organism (Kijanka et al., 2009).

viii) In such a way, the molecules transport neurotransmitters back into cells and enzymes, the synthesis or metabolism of which can be used as PET radiotracers (Thanos, Wang, & Volkow, 2008).

ix) The meaning of *deoxyhemoglobin* refers to the form of hemoglobin, which is the main protein in red blood cells, without the oxygen. When hemoglobin is loaded with oxygen its colour is red, when it is not, is purple-blue (Berg, Tymoczko, & Stryer, 2011; Toronov et al., 2003).

x) The use of blood oxygen level-dependent signal changes (BOLD) is a specific brain scan – applicable also for the rest of the body – that maps the neural activity related to blood changes as to the use of energy by cells in the brain (Huettel, Song, & McCarthy, 2009).

xi) By 'perfusion' is meant "the delivery of blood flow to a tissue or organ" (Wolf & Detre, 2007, p. 346). Another name for the perfusion in the brain is the cerebral blood flow (CBF) which is demonstrated via ml/g/min, i. e. via the reflection of the volume of blood flow per gram in the time, measured in terms of minutes (Wolf & Detre, 2007).

xii) The hemodynamic response function explains the dynamic role of the regulation of blood in the brain. It also refers to a technical principle as well whereupon fMRI is based (Stefanovic, Schwindt, Hoehn, & Silva, 2007).

xiii) MR spectroscopy analyses molecules such as protons or hydrogen ions. Commonly, is proton spectroscopy used. Its use helps to differentiate metabolites in their existing state in the brain, so that to identify lesions in it. Such metabolites are amino acids, lactate, lipid, alanine, N-acetyl aspartate, choline, creatine, and myoinositol (Stamper & Vagal, 2010).

xiv) 'Diffusion-tensor imaging' refers to the mapping of the diffusion process of molecules, primarily water, taking place in biological tissues. What such imaging can map are minute details of tissue architecture whether in normal or abnormal conditions (Mandl et al., 2008).

xv) The neurotransmitter of dopamine is concerned with the regulatory system of brain areas that are associated to motor, cognitive and motivational behaviours (Nieoullon, 2002).

xvi) By '6-[^{18}F]fluoro-L-DOPA positron emission tomography ' there can be studied cerebral kinetics and metabolism "so that reliable estimation of blood brain barrier transport, decarboxylation and release of stored 6-[^{18}F] fluorodopamine radioactivity to be measured" (Barrio et al., 1990, p. 487)

xvii) Blocked-designs, or otherwise called 'Epoch-based designs', are employed to examine across many trials images of the brain. They refer to the low temporal resolution imaging that is based on blood dynamics (Bandettini, 1994).

xviii) In event-related functional magnetic resonance imaging (efMRI) what is detected are hemodynamic response changes in the blood-oxygen level stimuli (BOLD) when neural activity is imaged with relevance to certain events (activation situations neural activity is observed through) (Henson, in press).

xix) Sinuses are parts found next to brain regions, which have no valves and the blood may flow to different directions. The aim of fMRI is to create detailed pictures of the air-filled spaces inside the skull (Wilkinson & Paley, 2008).

xx) Image-alignment algorithms refer to the specific alignment of overlapping adjacent images. In this way, it is sought the correspondence association between adjacent overlapping images of brain regions so that cognitive activation of neural pathways to be efficiently recorded (Li & Hu, 2010).

References

Aine, C. J. (1995). A conceptual overview and critique of functional neuro-imaging techniques in humans: MRI/fMRI and PET. *Critical Reviews in Neurobiology, 9*(2-3), 229-309.

Akgül, C. B., Sankur, B., & Akin, A. (2005). Spectral analysis of event-related hemodynamic responses in functional near infrared spectroscopy. *Journal of Computational Neuroscience, 18*(1), 67-83. doi:10.1007/s10827-005-5478-2

Amaro, E., & Barker, G. J. (2006). Study design in fMRI: Basic principles. *Brain and Cognition, 60*(3), 220-232. doi:10.1016/j.bandc.2005.11.009

PsychOpen
publishing psychology

Ances, B. M. (2004). Coupling of changes in cerebral blood flow with neural activity: What must initially dip must come back up. *Journal of Cerebral Blood Flow & Metabolism, 24*(1), 1-6. doi:10.1097/01.WCB.0000103920.96801.12

Antoniewicz, M. R., Kelleher, J. K., & Stephanopoulos, G. (2011). Measuring deuterium enrichment of glucose hydrogen atoms by gas chromatography/mass spectrometry. *Analytical Chemistry, 83*(8), 3211-3216. doi:10.1021/ac200012p

Aquino, K. M., Schira, M. M., Robinson, P. A., Drysdale, P. M., & Breakspear, M. (2012). Hemodynamic traveling waves in human visual cortex. *PLOS Computational Biology, 8*(3), Article e1002435. doi:10.1371/journal.pcbi.1002435

Arichi, T., Fagiolo, G., Varela, M., Melendez-Calderon, A., Allievi, A., Merchant, N., . . . Edwards, A. D. (2012). Development of BOLD signal hemodynamic responses in the human brain. *NeuroImage, 63*(2), 663-673. doi:10.1016/j.neuroimage.2012.06.054

Awh, E., Vogel, E. K., & Oh, S. H. (2006). Interactions between attention and working memory. *Neuroscience, 139*(1), 201-208. doi:10.1016/j.neuroscience.2005.08.023

Bailey, D. L., Townsend, D. W., Valk, P. E., & Maisey, M. N. (2005). *Positron emission tomography: Basic sciences*. Secaucus, NJ: Springer.

Bammer, R., Skare, S., Newbould, R., Liu, C., Thijs, V., Ropele, S., . . . Glover, G. H. (2005). Foundations of advanced magnetic resonance imaging. *NeuroRX, 2*(2), 167-196. doi:10.1602/neurorx.2.2.167

Bandettini, P. A. (1994). *Magnetic resonance imaging of human brain activation using endogenous susceptibility contrast* (Doctoral dissertation, Medical College of Winsconcin). Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.137.1342&rep=rep1&type=pdf

Bandettini, P. A. (2002). The spatial, temporal, and interpretive limits of functional MRI. In K. L. Davis, D. Charney, J. T. Coyle, & C. Nemeroff (Eds.), *Neuropsychopharmacology: The fifth generation of progress* (pp. 343-356). New York, NY: Lippincott Williams & Wilkins.

Bandettini, P. A. (2006). Functional magnetic resonance imaging. In C. Senior, T. Russell, & M. S. Gazzaniga (Eds.), *Methods in mind* (pp. 193-235). Cambridge, MA: MIT Press.

Bandettini, P. A., Wong, E. C., Hinks, R. S., Tikofsky, R. S., & Hyde, J. S. (1992). Time course EPI of human brain function during task activation. *Magnetic Resonance in Medicine, 25*(2), 390-397. doi:10.1002/mrm.1910250220

Barrio, J. R., Huang, S. C., Melega, W. P., Yu, D. C., Hoffman, J. M., Schneider, J. S., . . . Phelps, M. E. (1990). 6-[^{18}F]Fluoro-L-DOPA probes dopamine turnover rates in central dopaminergic structures. *Journal of Neuroscience Research, 27*(4), 487-493. doi:10.1002/jnr.490270408

Başar, E., Güntekin, B., & Öniz, A. (2006). Principles of oscillatory brain dynamics and a treatise of recognition of faces and facial expressions. In C. Neuper & W. Klimesch (Eds.), *Progress in brain research* (Vol. 159, pp. 43-62). doi:http://dx.doi.org/10.1016/S0079-6123(06)59004-1

Bell, V. (2004). Detect the effect of cognitive function on cerebral blood flow. In T. Stafford & M. Webb (Eds.), *Mind hacks: Tips & tools for using your brain* (pp. 22-24). Sebastopol, CA: O'Reilly Media.

Belliveau, J. W., Kennedy, D. N., Jr., McKinstry, R. C., Buchbinder, B. R., Weisskoff, R. M., Cohen, M. S., . . . Rosen, B. R. (1991). Functional mapping of the human visual cortex by magnetic resonance imaging. *Science, 254*(5032), 716-719. doi:10.1126/science.1948051

PsychOpen
publishing psychology

Benaron, D. A., Hintz, S. R., Villringer, A., Boas, D., Kleinschmidt, A., Frahm, J., . . . Stevenson, D. K. (2000). Noninvasive functional imaging of human brain using light. *Journal of Cerebral Blood Flow and Metabolism, 20*(3), 469-477. doi:10.1097/00004647-200003000-00005

Berg, J. M., Tymoczko, J. L., & Stryer, L. (2011). *Biochemistry*. New York, NY: W. H. Freeman.

Berker, E. (1996). Diagnosis, physiology, pathology, and rehabilitation of traumatic brain injuries. *The International Journal of Neuroscience, 85*(3-4), 195-220. doi:10.3109/00207459608986683

Berlin, H. A. (2011). The neural basis of the dynamic unconscious: Response to Commentaries. *Neuropsychoanalysis, 13*(1), 5-71.

Billings, J. A., Churchill, L. R., & Payne, R. (2010). Severe brain injury and the subjective life. *Hastings Center Report, 40*(3), 17-21. doi:10.1353/hcr.0.0261

Bolus, N. E., George, R., Washington, J., & Newcomer, B. R. (2009). PET/MRI: The blended-modality choice of the future? *Journal of Nuclear Medicine Technology, 37*(2), 63-71. doi:10.2967/jnmt.108.060848

Brown, G. G., Clark, C., & Liu, T. T. (2007). Measurement of cerebral perfusion with arterial spin labeling: Part 2. Applications. *Journal of the International Neuropsychological Society, 13*(3), 526-538. doi:10.1017/S1355617707070634

Buckner, R. L., Bandettini, P. A., O'Craven, K. M., Savoy, R. L., Petersen, S. E., Raichle, M. E., & Rosen, B. R. (1996). Detection of cortical activation during averaged single trials of a cognitive task using functional magnetic resonance imaging. *Proceedings of the National Academy of Sciences of the United States of America, 93*, 14878-14883. Retrieved from http://www.pnas.org/content/93/25/14878.full.pdfdoi:10.1073/pnas.93.25.14878

Buckner, R. L., & Logan, J. M. (2001). Functional neuroimaging methods: PET and fMRI. In R. Cabeza & A. Kingstone (Eds.), *Handbook of functional neuroimaging of cognition* (pp. 27-48). New York, NY: MIT Press.

Burger, C., & Townsend, D. W. (2007). Basics of PET scanning. In G. K. von Schulthess (Ed.), *Molecular anatomic imaging: PET-CT and SPECT-CT integrated modality imaging* (pp. 16-29). Philadelphia, PA: Lippincott Williams & Wilkins.

Camphausen, K. A., & Coia, R. C. (2008). Principles of radiation therapy. In R. Pazdur, L. D. Wagman, K. A. Camphausen, & W. J. Hoskins (Eds.), *Cancer management: A multidisciplinary approach*. Retrieved from http://www.cancernetwork.com/cancer-management-11/

Cavanna, A. E., & Trimble, M. R. (2006). The precuneus: A review of its functional anatomy and behavioural correlates. *Brain, 129*(3), 564-583. doi:10.1093/brain/aw/1004

Chen, J. J., Wieckowska, M., Meyer, E., & Pike, G. B. (2008). Cerebral blood flow measurement using fMRI and PET: A cross-validation study. *International Journal of Biomedical Imaging, 2008*, Article 516359. doi:10.1155/2008/516359

Chen, S., & Li, X. (2012). Functional magnetic resonance imaging for imaging neural activity in the human brain: The annual progress. *Computational and Mathematical Methods in Medicine, 2012*, Article 613465. doi:10.1155/2012/613465

Cherry, S. R. (2006). Multimodality in vivo imaging systems: Twice the power or double the trouble? *Annual Review of Biomedical Engineering, 8*, 35-62. doi:10.1146/annurev.bioeng.8.061505.095728

Chialvo, D. R. (1997). Mapping "sameness" into "neighborness". In M. M. Novak & T. G. Dewey (Eds.), *Fractal frontiers* (pp. 23-29). Singapore City, Singapore: Word Scientific.

PsychOpen
publishing psychology

Chih, B., Engelman, H., & Scheiffele, P. (2005). Control of excitatory and inhibitory synapse formation by neuroligins. *Science, 307*(5713), 1324-1328. doi:10.1126/science.1107470

Chiou, K. S., & Hillary, F. G. (2011). Methodological considerations for using BOLD fMRI in the clinical neurosciences. In R. A. Cohen & L. H. Sweet (Eds.), *Brain imaging in behavioural medicine and clinical neuroscience* (pp. 103-116). Providence, RI: Springer Verlag.

Christen, T., Bolar, D. S., & Zaharchuk, G. (2013). Imaging brain oxygenation with MRI using blood oxygenation approaches: Methods, validation and clinical applications. *AJNR: American Journal of Neuroradiology, 34*, 1113-1123. doi:10.3174/ajnr.A3070

Cohen, L. (1989). Time-frequency distribution: A review. *Proceedings of the IEEE, 77*(7), 941-981. doi:10.1109/5.30749

Crassin, C. (2011). *Giga voxels: A voxel-based rendering pipeline for efficient exploration of large and detailed scenes* (Doctoral thesis, Université de Grenoble, Grenoble, France). Retrieved from http://maverick.inria.fr/Membres/Cyril.Crassin/thesis/CCrassinThesis_EN_Web.pdf

Crosson, B., Ford, A., McGregor, K. M., Meinzer, M., Cheshkov, S., Li, X., . . . Briggs, R. W. (2010). Functional imaging and related techniques: An introduction for rehabilitation researchers. *Journal of Rehabilitation Research and Development, 47*(2), 7-34. doi:10.1682/JRRD.2010.02.0017

de Barros, A. L. B., Tsourkas, A., Saboury, B., Cardoso, V. N., & Alavi, A. (2012). Emerging role of radiolabeled nanoparticles as an effective diagnostic technique. *EJNMMI Research, 2*, Article 39.

Deibler, A. R., Pollock, J. M., Kraft, R. A., Tam, H., Burdette, J. H., & Maldjian, J. A. (2008). Arterial spin-labeling in routine clinical practice. Part 2: Hypoperfusion pattern. *AJNR: American Journal of Neuroradiology, 29*(7), 1235-1241. doi:10.3174/ajnr.A1033

de Langen, A. J., van de Boogart, E., Vivian, E. M., Marcus, J. T., & Lubberink, M. (2008). Use of $H_2{}^{15}O$ – PET and DCE-MRI to measure tumor blood flow. *The Oncologist, 13*(6), 631-644. doi:10.1634/theoncologist.2007-0235

Démonet, J.-F., Thierry, G., & Cardebat, D. (2005). Renewal of the neurophysiology of language: Functional neuroimaging. *Physiological Reviews, 85*(1), 49-95. doi:10.1152/physrev.00049.2003

D'Esposito, M. (2008). Working memory. In M. J. Aminoff, F. Boller, D. F. Swaab, G. Goldenberg, & B. L. Miller (Eds.), *Handbook of clinical neurology* (Vol. 88, pp. 237-247). Amsterdam, The Netherlands: Elsevier.

Detre, J. A., & Wang, J. (2002). Technical aspects and utility of fMRI using BOLD and ASL. *Clinical Neurophysiology, 113*(5), 621-634. doi:10.1016/S1388-2457(02)00038-X

Devlin, J. T., Russell, R. P., Davis, M. H., Price, C. J., Wilson, J., Moss, H. E., . . . Tyler, L. K. (2000). Susceptibility-induced loss of signal: Comparing PET and fMRI on a semantic task. *NeuroImage, 11*(6), 589-600. doi:10.1006/nimg.2000.0595

Devonshire, I. M., Papadakis, N. G., Port, M., Berwick, J., Kennerley, A. J., Mayhew, J. E. W., & Overton, P. G. (2012). Neurovascular coupling is brain region-dependent. *NeuroImage, 59*(3), 1997-2006. doi:10.1016/j.neuroimage.2011.09.050

Diamanti-Kandarakis, E., Bourguignon, J.-P., Gindice, L. C., Hauser, R., Prins, G. S., Soto, A. M., . . . Gore, A. C. (2009). Endocrine-disrupting chemicals: An endocrine society scientific statement. *Endocrine Reviews, 30*(4), 293-342. doi:10.1210/er.2009-0002

PsychOpen
publishing psychology

Drevets, W. C., Price, J. L., & Furey, M. L. (2008). Brain structural and functional abnormalities in mood disorders: Implications for neurocircuitry models of depression. *Brain Structure & Function, 213*(1-2), 93-118. doi:10.1007/s00429-008-0189-x

Druga, R. (2009). Neocortical inhibitory system. *Folia Biologica, 55*(6), 201-217.

Dunn, I. F., Ellegala, D. B., Fox, J. F., & Kim, D. H. (2006). Principles of cerebral oxygenation and blood flow in the neurological critical care unit. *Neurocritical Care, 4*(1), 77-82. doi:10.1385/NCC:4:1:077

Eggebrecht, A. T., White, B. R., Ferradal, S. L., Cheu, C., Zhan, Y., Snyder, A. Z., . . . Culver, J. P. (2012). A quantitative spatial comparison of high-density diffuse optical tomography and fMRI cortical mapping. *NeuroImage, 61*(4), 1120-1128. doi:10.1016/j.neuroimage.2012.01.124

Feng, Z., Caprihan, A., Blagoev, K. B., & Calhoun, V. D. (2009). Biophysical modeling of phase changes in BOLD fMRI. *NeuroImage, 47*(2), 540-548. doi:10.1016/j.neuroimage.2009.04.076

Frackowiak, R. S., & Friston, K. J. (1994). Functional neuroanatomy of the human brain: Positron emission tomography: A new neuroanatomical technique. *Journal of Anatomy, 184*(Pt2), 211-225.

Ganguly, B. N., Mondal, N. N., Nandy, M., & Roesch, F. (2009). Some physical aspects of positron annihilation tomography: A critical review. *Journal of Radioanalytical and Nuclear Chemistry, 279*(2), 685-698. doi:10.1007/s10967-007-7256-2

Ganis, G., & Kosslyn, S. M. (2002). Neuroimaging. In V. S. Ramachandran (Ed.), *Encyclopedia of the human brain* (Vol. 3, pp. 493-505). San Diego, CA: Academic Press.

Gazzaniga, M. S. (2009). Hemispheric specialization. In M. S. Gazzaniga, R. B. Ivry, & G. R. Mangun (Eds.), *Cognitive neuroscience: The biology of the mind* (pp. 445-490). New York, NY: W. W. Norton.

Gerstl, F., Windischberger, C., Mitterhauser, M., Wadsak, W., Holik, A., Kletter, K., . . . Lanzenberger, R. (2008). Multimodal imaging of human early visual cortex by combining functional and molecular measurements with fMRI and PET. *NeuroImage, 41*(2), 204-211. doi:10.1016/j.neuroimage.2008.02.044

Goebel, R. (2007). Localization of brain activity using functional magnetic resonance imaging. In C. Stippich (Ed.), *Clinical functional MRI: Presurgical functional neuroimaging* (pp. 9-52). Heidelberg, Germany: Springer Verlag.

Goldwasser, S. M., & Reynolds, R. A. (1987). Real-time display and manipulation of 3-D medical objects: The voxel processor architecture. *Computer Vision Graphics and Image Processing, 39*(1), 1-27. doi:10.1016/S0734-189X(87)80200-1

Gore, J. C. (2003). Principles and practice of functional MRI of the human brain. *The Journal of Clinical Investigation, 112*(1), 4-9. doi:10.1172/JCI200319010

Grabowski, T. J., & Damasio, A. R. (1996). Improving functional imaging techniques: The dream of a single image for a single mental event. *Proceedings of the National Academy of Sciences of the United States of America, 93*(25), 14302-14303. doi:10.1073/pnas.93.25.14302

Grill-Spector, K., Henson, R., & Martin, A. (2006). Repetition and the brain: Neural models of stimulus-specific effects. *Trends in Cognitive Sciences, 10*(1), 14-23. doi:10.1016/j.tics.2005.11.006

Hammersley, J. (2010). *The modulation of covert attention by emotion: Automatic processing of emotional versus neutral valenced cues in a covert attention paradigm* (Doctoral dissertation). Retrieved from http://opensiuc.lib.siu.edu/dissertations/155/

PsychOpen
publishing psychology

Henson, R. N. A. (in press). Event-related fMRI: Introduction, statistical modelling, design optimisation and examples. *Japanese Journal of Cognitive Neuroscience*. Retrieved from http://www.mrc-cbu.cam.ac.uk//personal/rik.henson/personal/henson-jjcn.pdf

Hill, D. L. G., Batchelor, P. G., Holden, M., & Hawkes, D. J. (2001). Medical image registration. *Physics in Medicine and Biology, 46*(3), R1-R45. doi:10.1088/0031-9155/46/3/201

Hoge, R. D., & Pike, G. B. (2001). Quantitative measurement using fMRI. In P. Jezzard, P. M. Matthews, & S. M. Smith (Eds.), *Functional magnetic resonance imaging: An introduction to methods* (pp. 159-174). Oxford, United Kingdom: Oxford University Press.

Horwitz, B., Friston, K. J., & Taylor, J. G. (2000). Neural modeling and functional brain imaging: An overview. *Neural Networks, 13*(8-9), 829-846. doi:10.1016/S0893-6080(00)00062-9

Hoshi, Y., & Tamura, M. (1993). Dynamic multichannel near-infrared optical imaging of human brain activity. *Journal of Applied Physiology, 75*(4), 1842-1846.

Huettel, S. A., Song, A. W., & McCarthy, G. (2009). *Functional magnetic resonance imaging* (2nd ed.). Sunderland, MA: Sinauer.

Huppert, T. J., Jones, P. B., Devor, A., Dunn, A. K., Teng, I. C., Dale, A. M., & Boas, D. A. (2009). Sensitivity in neural-hemodynamic coupling to alterations in cerebral blood flow during hypercapnia. *Journal of Biomedical Optics, 14*(4), Article 044038. doi:10.1117/1.3210779

Ito, H., Ibaraki, M., Kanno, I., Fukuda, H., & Miura, S. (2005). Changes in cerebral blood flow and cerebral oxygen metabolism during neural activation measured by positron emission tomography: Comparison with blood oxygenation level-dependent contrast measured by functional magnetic resonance imaging. *Journal of Cerebral Blood Flow and Metabolism, 25*(3), 371-377. doi:10.1038/sj.jcbfm.9600030

Jenkins, B. G. (2012). Pharmacologic magnetic resonance imaging (phMRI): Imaging drug action in the brain. *NeuroImage, 62*(2), 1072-1085. doi:10.1016/j.neuroimage.2012.03.075

Jespersen, S. N., & Østergaard, L. (2012). The roles of cerebral flow, copillary transit time heterogeneity, and oxygen tension in brain oxygenation and metabolism. *Journal of Cerebral Blood Flow and Metabolism, 32*(2), 264-277. doi:10.1038/jcbfm.2011.153

Jimura, K., & Braver, T. S. (2010). Age-related shifts in brain activity dynamics during task switching. *Cerebral Cortex, 20*(6), 1420-1431. doi:10.1093/cercor/bhp206

Kelly, A. M. C., & Garavan, H. (2005). Human functional neuroimaging of brain changes associated with practice. *Cerebral Cortex, 15*(8), 1089-1102. doi:10.1093/cercor/bhi005

Khalil, M. M. (2011). Positron emission tomography (PET): Basic principles. In M. M. Khalil (Ed.), *Basic sciences of nuclear medicine* (pp. 179-213). Heidelberg, Germany: Springer.

Kiebel, S. J., & Friston, K. J. (2004). Statistical parametric mapping for event-related potentials: I. Generic considerations. *NeuroImage, 22*(2), 492-502. doi:10.1016/j.neuroimage.2004.02.012

Kienast, T., Hariri, A. R., Schagenhauf, F., Wrase, J., Sterzer, P., Buchholz, H. G., . . . Heinz, A. (2008). Dopamine in amygdala gates limbic processing of aversive stimuli in humans. *Nature Neuroscience, 11*(12), 1381-1382. doi:10.1038/nn.2222

PsychOpen
publishing psychology

Kijanka, G., Barry, R., Chen, H., Gould, E., Seidlits, S. K., Schmid, J., . . . Murphy, D. (2009). Defining the molecular target of an antibody derived from nuclear extract of Jurkat cells using protein arrays. *Analytical Biochemistry, 395*(2), 119-124. doi:10.1016/j.ab.2009.08.039

Kim, S.-G., & Bandettini, P. A. (2010). Principles of functional MRI. In S. H. Faro & F. B. Mohamed (Eds.), *BOLD fMRI: A guide to functional mapping for neuroscientists* (pp. 3-22). New York, NY: Springer Verlag.

Kim, S.-G., & Ogawa, S. (2012). Biophysical and physiological origins of blood oxygenation level-dependent fMRI signals. *Journal of Cerebral Blood Flow and Metabolism, 32*(7), 1188-1206. doi:10.1038/jcbfm.2012.23

Kim, S.-G., Richter, W., & Uğurbil, K. (1997). Limitations of temporal resolution in functional MRI. *Magnetic Resonance in Medicine, 37*(4), 631-636. doi:10.1002/mrm.1910370427

Kim, D.-S., Rowen, I., Olman, C., Kim, S.-G., Uğurbil, K., & Toth, L. J. (2004). Spatial relationship between neuronal activity and BOLD functional MRI. *NeuroImage, 21*(3), 876-885. doi:10.1016/j.neuroimage.2003.10.018

Kirov, I. I., Tal, A., Babb, J. S., Herbert, J., & Cohen, O. (2013). Serial proton MR spectroscopy of gray and white matter in relapsing-remitting MS. *Neurology, 80*(1), 39-46. doi:10.1212/WNL.0b013e31827b1a8c

Kitson, S. L., Cuccurullo, V., Ciarmiello, A., Salvo, D., & Mansi, L. (2009). Clinical applications of positron emission tomography (PET) imaging in medicine: Oncology, brain diseases and cardiology. *Current Radiopharmaceuticals, 2*(4), 224-253. doi:10.2174/1874471010902040224

Knutson, B., & Cooper, J. C. (2005). Functional magnetic resonance imaging of reward prediction. *Current Opinion in Neurology, 18*(4), 411-417. doi:10.1097/01.wco.0000173463.24758.f6

Kurzban, R. (2010). Does the brain consume additional glucose during self-control tasks? *Evolutionary Psychology, 8*(2), 244-259.

Kwan-Hoong, N. G., Ahmad, A. C., Nizam, M. S., & Abdullah, B. J. J. (2003). Magnetic resonance imaging: Health effects and safety. *Proceedings of the International Conference on Non-Ionizing Radiation at UNITEN (ICNIR2003), Electromagnetic Fields and Our Health*, Paper 4. Retrieved from http://www.who.int/peh-emf/meetings/archive/en/paper04ng.pdf

Kwong, K. K., Belliveau, J. W., Chesler, D. A., Goldberg, I. E., Weiskoff, R. M., Poncelet, B. P., . . . Rosen, B. R. (1992). Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation. *Proceedings of the National Academy of Sciences of the United States of America, 89*(12), 5675-5679.

Lane, R. D., Waldstein, S. R., Chesney, M. A., Jennings, J. R., Lovallo, W. R., Kozel, P. J., . . . Cameron, O. G. (2009). The rebirth of neuroscience in psychosomatic medicine, Part I: Historical context, methods, and relevant basic science. *Psychosomatic Medicine, 71*(2), 117-134. doi:10.1097/PSY.0b013e31819783be

Laureys, S., Peigneux, P., & Goldman, S. (2002). Brain imaging. In H. A. H. D'haenen, J. A. Den Boer, & P. Willner (Eds.), *Biological psychiatry*, (Vol.1, pp. 155-166). Chichester, United Kingdom: John Wiley & Sons.

Lawrence, A. J., & Heinz, A. (2011). Imaging - The interface with pharmacology: Looking to the future. *British Journal of Pharmacology, 163*(8), 1563-1564. doi:10.1111/j.1476-5381.2011.01294.x

Leenders, K. L., Gibbs, J. M., Frackowiak, R. S. J., Lammertsma, A. A., & Jones, T. (1984). Positron emission tomography of the brain: New possibilities for the investigation of human cerebral pathophysiology. *Progress in Neurobiology, 23*(1-2), 1-38. doi:10.1016/0301-0082(84)90010-8

PsychOpen
publishing psychology

Leite, C. S. F. (2009). *Functional connectivity measures in memory networks using independent component analysis* (Master's thesis, Instituto Superior Técnico-Universidade Técnica de Lisboa, Lisbon, Portugal). Retrieved from https://dspace.ist.utl.pt/bitstream/2295/576672/1/tese_54202.pdf

Leopold, K. (2007). *Technologically enhanced naturally occurring radioactive materials*. (Doctoral thesis, University of Duisburg-Essen, Duisburg-Essen, Germany). Retrieved from http://d-nb.info/988995603/34

Li, B., & Freeman, R. D. (2007). High-resolution neurometabolic coupling in the lateral geniculate nucleus. *The Journal of Neuroscience, 27*(38), 10223-10229. doi:10.1523/JNEUROSCI.1505-07.2007

Li, X., & Hu, Z. (2010). Rejecting mismatches by correspondence function. *International Journal of Computer Vision, 89*(1), 1-17. doi:10.1007/s11263-010-0318-x

Linden, D. E. J. (2006). How psychotherapy changes the brain: The contribution of functional neuroimaging. *Molecular Psychiatry, 11*(6), 528-538. doi:10.1038/sj.mp.4001816

Liu, T. T., & Brown, G. G. (2007). Measurement of cerebral perfusion with arterial spin labeling: Part 1. Methods. *Journal of the International Neuropsychological Society, 13*(3), 517-525. doi:10.1017/S1355617707070646

Logothetis, N. K. (2008). What we can do and what we cannot do with fMRI. *Nature, 453*(7197), 869-878. doi:10.1038/nature06976

Logothetis, N. K., Pauls, J., Augath, M., Trinath, T., & Oeltermann, A. (2001). Neurophysiological investigation of the basis of the fMRI signal. *Nature, 412*(6843), 150-157. doi:10.1038/35084005

Lu, H., Golay, X., Pekar, J. J., & van Zijl, P. C. M. (2004). Sustained post-stimulus elevation incerebral oxygen utilization after vascular recovery. *Journal of Cerebral Blood Flow and Metabolism, 24*(7), 764-770. doi:10.1097/01.WCB.0000124322.60992.5C

Mandl, R. C. W., Schnack, H. G., Zwiers, M. P., van der Schaaf, A., Kahn, R. S., & Hulshoff-Pol, H. E. (2008). Functional diffusion tensor imaging: Measuring task-related fractional anisotropy changes in the human brain along white matter tracts. *PLoS ONE, 3*(11), Article e3631. doi:10.1371/journal.pone.0003631

Mangia, S., Tkác, I., Gruetter, R., van de Moortele, P. F., Giove, F., Maraviglia, B., & Ugurbil, K. (2006). Sensitivity of single-voxel 1H-MRS in investigating the metabolism of the activated human visual cortex at 7 T. *Magnetic Resonance Imaging, 24*(4), 343-348. doi:10.1016/j.mri.2005.12.023

Markram, H., Toledo-Rondiguez, M., Wang, Y., Gupta, A., Silberberg, G., & Wu, C. (2004). Interneurons of the neurocortical inhibitory system. *Neuroscience, 5*(10), 793-807. doi:10.1038/nrn1519

Marrelec, G., Ciuciu, P., Pélégrini-Issac, M., & Benali, H. (2004). Estimation of the hemodynamic response in event-related functional MRI: Bayesian networks as a framework for efficient Bayesian modeling and inference. *IEEE Transactions on Medical Imaging, 23*(8), 959-967. doi:10.1109/TMI.2004.831221

Marsman, A., van den Heuvel, M. P., Klomp, D. W. J., Kahn, R. S., Luijten, P. R., & Hulshoff-Pol, H. E. (2013). Glutamate in schizophrenia: A focused review and meta-analysis of H-MRS studies. *Schizophrenia Bulletin, 39*(1), 120-129. doi:10.1093/schbul/sbr069

Massoud, T. F., & Gambhir, S. S. (2003). Molecular imaging in living subjects: Seeing fundamental biological processes in a new light. *Genes & Development, 17*(5), 545-580. doi:10.1101/gad.1047403

PsychOpen
publishing psychology

Massimini, M., Huber, R., Ferrarelli, F., Hill, S., & Tononi, G. (2004). The sleep slow oscillation as a traveling wave. *The Journal of Neuroscience, 24*(31), 6862-6870. doi:10.1523/JNEUROSCI.1318-04.2004

Matthews, P. M., Johansen-Berg, H., & Reddy, H. (2004). Non-invasive mapping of brain functions and brain recovery: Applying lessons from cognitive neuroscience to neurohabilitation. *Restorative Neurology and Neuroscience, 22*(3-5), 245-260.

McIntyre, M., Richter, W., Morden, D., Wennerberg, A., & Frankenstein, U. (2003). Blood oxygenation level dependent functional magnetic resonance imaging. *Concepts in Magnetic Resonance Part A, 16A*(1), 5-15. doi:10.1002/cmr.a.10049

McKeefry, D. J., Gouws, A., Burton, M. P., & Morland, A. B. (2009). The noninvasive dissection of the human visual cortex: Using fMRI and TMS to study the organization of the visual brain. *The Neuroscientist, 15*(5), 489-506. doi:10.1177/1073858409334424

Michel, C. M., Seeck, M., & Landis, T. (1999). Spatiotemporal dynamics of human cognition. *News in Physiological Sciences, 14*(5), 206-214.

Minati, L., Grisoli, M., & Bruzzone, M. G. (2007). MR spectroscopy, functional MRI, and diffusion-tensor imaging in the aging brain: A conceptual review. *Journal of Geriatric Psychiatry and Neurology, 20*(1), 3-21. doi:10.1177/0891988706297089

Mintun, M. A., Lundstrom, B. N., Snyder, A. Z., Vlassenko, A. G., Shulman, G. L., & Raichle, M. E. (2001). Blood flow and oxygen delivery to human brain during functional activity: Theoretical modeling and experimental data. *Proceedings of the National Academy of Sciences of the United States of America, 98*(12), 6859-6864. doi:10.1073/pnas.111164398

Moeller, S. J., Tomasi, D., Honorio, J., Volkow, N. D., & Goldstein, R. Z. (2012). Dopaminergic involvement during mental fatigue in health and cocaine addiction. *Translational Psychiatry, 2*(10), Article e176. doi:10.1038/tp.2012.110

Moridani, M. K. (2009). Functional brain imaging with use of a new and powerful neuroimaging technique. *Journal of Biomedical Science and Engineering, 2*(3), 173-176. doi:10.4236/jbise.2009.23029

Mukamel, R., & Fried, I. (2012). Human intracranial recordings and cognitive neuroscience. *Annual Review of Psychology, 63*, 511-537. doi:10.1146/annurev-psych-120709-145401

Myers, R. (2002). The application of PET-MR image registration in the brain. *British Journal of Radiology, 75*(Suppl. 9), S31-S35.

Nadal, M., Munar, E., Àngel Capó, M., Roselló, J., & Cela-Conde, C. J. (2008). Towards a framework for the study of the neural correlates of aesthetic preference. *Spatial Vision, 21*(3-5), 379-396. doi:10.1163/156856808784532653

Nieoullon, A. (2002). Dopamine and the regulation of cognition and attention. *Progress in Neurobiology, 67*(1), 53-83. doi:10.1016/S0301-0082(02)00011-4

Noguchi, T., Yoshiura, T., Hiwatashi, A., Togao, O., Yamashita, K., Nagao, E., & Honda, H. (2012). Arterial spin-labeling magnetic resonance imaging: The timing of regional maximal perfusion-related signal intensity revealed by a multiphase technique. *Japanese Journal of Radiology, 30*(2), 137-145. doi:10.1007/s11604-011-0025-8

Ogawa, S., Lee, T. M., Kay, A. R., & Tank, D. W. (1990). Brain magnetic resonance imaging with contrast dependent on blood oxygenation. *Proceedings of the National Academy of Sciences of the United States of America, 87*(24), 9868-9872.

Olman, C. A., Inati, S., & Heeger, D. J. (2007). The effect of large veins on spatial localization with GE BOLD at 3 T: Displacement, not blurring. *NeuroImage, 34*(3), 1126-1135. doi:10.1016/j.neuroimage.2006.08.045

PsychOpen
publishing psychology

Otte, A., & Halsband, U. (2006). Brain imaging tools in neurosciences: An interdisciplinary approach. *Journal of Physiology, Paris, 99*(4-6), 281-292. doi:10.1016/j.jphysparis.2006.03.011

Petersen, S. E., & Dubis, J. W. (2012). The mixed block/event-related design. *NeuroImage, 62*(2), 1177-1184. doi:10.1016/j.neuroimage.2011.09.084

Phelps, M. E. (2000). Positron emission tomography provides molecular imaging of biological processes. *Proceedings of the National Academy of Sciences of the United States of America, 97*(16), 9226-9233. doi:10.1073/pnas.97.16.9226

Pichler, B. J., Kolb, A., Nägele, T., & Schlemmer, H.-P. (2010). PET/MRI: Paving the way for the next generation of clinical multimodality imaging applications. *The Journal of Nuclear Medicine, 51*(3), 333-336. doi:10.2967/jnumed.109.061853

Pichler, B. J., Wehrl, H. F., & Judenhofer, M. S. (2008). Last advances in molecular imaging instrumentation. *The Journal of Nuclear Medicine, 49*(Suppl. 2), 5S-23S. doi:10.2967/jnumed.108.045880

Pike, V. W. (2009). PET radiotracers: Crossing the blood-brain barrier and surviving metabolism. *Trends in Pharmacological Sciences, 30*(8), 431-440. doi:10.1016/j.tips.2009.05.005

Pillai, J. J. (2010). The evolution of clinical functional imaging during the past 2 decades and its current impact on neurosurgical planning. *AJNR: American Journal of Neuroradiology, 31*(2), 219-225. doi:10.3174/ajnr.A1845

Pinel, J. P. J. (2003). *Biopsychology* (5th ed.). Boston, MA: Pearson Education.

Poline, J.-B., Breeze, J. L., Ghosh, S., Gorgolewski, K., Halchenko, Y. O., Hanke, M., . . . Kennedy, D. N. (2012). Data sharing in neuroimaging research. *Frontiers in Neuroinformatics, 6*(9), 1-13. doi:10.3389/fninf.2012.00009

Poser, B. A., van Mierlo, E., & Norris, D. G. (2011). Exploring the post-stimulus undershoot with spin-echo fMRI: Implications for models of neurovascular response. *Human Brain Mapping, 32*(1), 141-153. doi:10.1002/hbm.21003

Posner, M. I., & Raichle, M. E. (1994). *Images of mind*. New York, NY: Scientific American Books.

Price, R. R., Allison, J., Massoth, R. J., Clarke, G. D., & Drost, D. J. (2002). Practical aspects of functional MRI. *Medical Physics, 29*(8), 1892-1912. doi:10.1118/1.1494990

Prichard, J. W., & Brass, L. M. (1992). New anatomical and functional imaging methods. *Annals of Neurology, 32*(3), 395-400. doi:10.1002/ana.410320316

Pruessmann, K. P., Weiger, M., & Boesiger, P. (2000). Sensitivity-Encoded MRI. *MedicaMundi, 44*(2), 10-16.

Raichle, M. E. (1994). Images of the mind: Studies with modern imaging techniques. *Annual Review of Psychology, 45*, 333-356. doi:10.1146/annurev.ps.45.020194.002001

Raichle, M. E., Grubb, R. L., Gato, M. H., Eichling, J. O., & Ter-Pogossian, M. H. (1976). Correlation between regional cerebral blood flow and oxidative metabolism. *Archives of Neurology, 33*(8), 523-526. doi:10.1001/archneur.1976.00500080001001

Rex, S., Meyer, P. T., Baumert, J.-H., Rossaint, R., Fries, M., Büll, U., & Schaefer, W. M. (2008). Positron emission tomography study of regional blood flow and flow-metabolism coupling during general anaesthesia with xenon in humans. *British Journal of Anaesthesia, 100*(5), 667-675. doi:10.1093/bja/aen036

Robbins, T. W. (2005). Chemistry of the mind: Neurochemical modulation of prefrontal cortical function. *The Journal of Comparative Neurology, 493*(1), 140-146. doi:10.1002/cne.20717

PsychOpen
publishing psychology

Roche, R. A. P., Commins, S., & Dockree, P. M. (2009). Cognitive neuroscience: Introduction and historical perspective. In R. A. P. Roche & S. Commins (Eds.), *Pioneering studies in cognitive neuroscience* (pp. 1-18). Maidenhead, United Kingdom: McGraw-Hill.

Roß, T. L., & Ametamey, S. M. (2011). PET chemistry: An introduction. In M. M. Khalil (Ed.), *Basic sciences of nuclear medicine* (pp. 65-101). Heidelberg, Germany: Springer Verlag.

Sattler, B., Lee, J. A., Lonsdale, M., & Coche, E. (2010). PET/CT (and CT) instrumentation, image reconstruction and data transfer for radiotherapy planning. *Radiotherapy and Oncology, 96*(3), 288-297. doi:10.1016/j.radonc.2010.07.009

Schei, J. L. (2011). *Optical imaging of neural and hemodynamic brain activity* (Doctoral dissertation). Retrieved from http://www.physics.wsu.edu/research/high-pressure/Dissertations/Jennie%20Thesis.pdf

Schirrmacher, R., Brandmöller, F., Schirrmacher, E., Theus, O., Tillmanus, J., Siessmeier, T., . . . Junkschat, K. (2006). F-Labeling of peptided by means of an organosilicon-based fluoride acceptor. *Angewandte Chemie, 45*(36), 6047-6050. doi:10.1002/anie.200600795

Schleim, S., & Roiser, J. P. (2009). fMRI in translation: The challenges facing real-world applications. *Frontiers in Human Neuroscience, 3*, Article 63.

Schon, K., Tinaz, S., Somers, D. C., & Stern, C. E. (2008). Delayed match to object or place: An event-related fMRI study of short-term stimulus maintenance and the role of stimulus pre-exposure. *NeuroImage, 39*(2), 857-872. doi:10.1016/j.neuroimage.2007.09.023

Schwartz, S., Maquet, P., & Frith, C. (2002). Neural correlates of perceptual learning: A functional MRI study of visual texture discrimination. *Proceedings of the National Academy of Sciences of the United States of America, 99*(26), 17137-17142. doi:10.1073/pnas.242414599

Seto, E., Sela, G., McIlroy, W. E., Black, S. E., Staines, W. R., Bronskill, M. J., . . . Graham, S. J. (2001). Quantifying head motion associated with motor tasks used in fMRI. *NeuroImage, 14*(2), 284-297. doi:10.1006/nimg.2001.0829

Shadlen, M. N., & Newsome, W. T. (1996). Motion perception: Seeing and deciding. *Proceedings of the National Academy of Sciences of the United States of America, 93*(2), 628-633. doi:10.1073/pnas.93.2.628

Shibasaki, H. (2008). Human brain mapping: Hemodynamic response and electrophysiology. *Clinical Neurophysiology, 119*(4), 731-743. doi:10.1016/j.clinph.2007.10.026

Shmueli, K., de Zwart, J. A., van Gelderen, P., Li, T.-Q., Dodd, J., & Duyn, J. H. (2009). Magnetic susceptibility mapping of brain tissue in vivo using MRI phase data. *Magnetic Resonance in Medicine, 62*(6), 1510-1522. doi:10.1002/mrm.22135

Slagter, H. A., Tomer, R., Christian, B. T., Fox, A. S., Colzato, L. S., King, C. R., . . . Davidson, R. J. (2012). PET evidence for a role for striatal dopamine in the attentional blink: Functional implications. *Journal of Cognitive Neuroscience, 24*(9), 1932-1940. doi:10.1162/jocn_a_00255

Stam, C. J., & van Straaten, E. C. W. (2012). The organization of physiological brain networks. *Clinical Neurophysiology, 123*(6), 1067-1087. doi:10.1016/j.clinph.2012.01.011

Stamper, T. O., & Vagal, A. (2010). *Magnetic resonance (MR) spectroscopy: Basic level.* Retrieved from Mayfield Clinic & Spine Institute website: http://www.mayfieldclinic.com/PDF/PE-MRspectroscopy.pdf

PsychOpen
publishing psychology

Stefanovic, B., Schwindt, W., Hoehn, M., & Silva, A. C. (2007). Functional uncoupling of hemodynamic from neuronal response by inhibition of neuronal nitric oxide synthase. *Journal of Cerebral Blood Flow and Metabolism, 27*(4), 741-754. doi:10.1038/sj.jcbfm.9600377

Stephan, K. E. (2004). On the role of general system theory for functional neuroimaging. *Journal of Anatomy, 205*(6), 443-470. doi:10.1111/j.0021-8782.2004.00359.x

Sternberg, S. (2011). Modular processes in mind and brain. *Cognitive Neuropsychology, 28*(3-4), 156-208. doi:10.1080/02643294.2011.557231

Stevens, M. C., Calhoun, V. D., & Kiehl, K. A. (2005). Hemispheric differences in hemodynamics elicited by auditory oddball stimuli. *NeuroImage, 26*(3), 782-792. doi:10.1016/j.neuroimage.2005.02.044

Sutton, B. P., Ouyang, C., Karampinos, D. C., & Miller, G. A. (2009). Current trends and challenges in MRI acquisition to investigate brain function. *International Journal of Psychophysiology, 73*(1), 33-42. doi:10.1016/j.ijpsycho.2008.12.020

Tancredi, L. R., & Brodie, J. D. (2007). The brain and behavior: Limitations in the legal use of functional magnetic resonance imaging. *American Journal of Law & Medicine, 33*(2-3), 271-294.

Tate, D. F., Shenton, M. E., & Bigler, E. D. (2012). Introduction to the brain imaging and behavior special issue of neuroimaging findings in mild traumatic brain injury. *Brain Imaging and Behavior, 6*(2), 103-107. doi:10.1007/s11682-012-9185-0

Thanos, P. K., Wang, G.-J., & Volkow, N. D. (2008). Positron emission tomography as a tool for studying alcohol abuse. *Alcohol, Research, & Health, 31*(3), 233-237.

Toronov, V., Walker, S., Gupta, R., Choi, J. H., Gratton, E., Hueber, D., & Webb, A. (2003). The role of changes in deoxyhemoglobin concentration and regional cerebral blood volume in the fMRI BOLD signal. *NeuroImage, 19*(4), 1521-1531. doi:10.1016/S1053-8119(03)00152-6

Turner, R., & Jones, T. (2003). Techniques for imaging neuroscience. *British Medical Bulletin, 65*(1), 3-20. doi:10.1093/bmb/65.1.3

Uludağ, K. (2008). Transient and sustained BOLD responses to sustained visual stimulation. *Magnetic Resonance Imaging, 26*(7), 863-869. doi:10.1016/j.mri.2008.01.049

Vazquez, A. L., Masamoto, K., Fukuda, M., & Kim, S.-G. (2010). Cerebral oxygen delivery and consumption during evoked neural activity. *Frontiers in Neuroenergetics, 2*, Article 11. doi:10.3389/fnene.2010.00011

Velikyan, I. (2011). Positron emitting [68Ga]Ga-based imaging agents: Chemistry and diversity. *Medicinal Chemistry, 7*(5), 345-379. doi:10.2174/157340611796799195

Volkow, N. D., Rosen, B., & Farde, L. (1997). Imaging the living human brain: Magnetic resonance imaging and positron emission tomography. *Proceedings of the National Academy of Sciences of the United States of America, 94*(7), 2787-2788. doi:10.1073/pnas.94.7.2787

Wagner, H. N., Jr. (1985). Nuclear medicine in the 1990s: The challenge of change. *The Journal of Nuclear Medinice, 26*(7), 679-686.

Wager, T. D., Hernandez, L., Jonides, J., & Lindquist, M. (2007). Elements of functional neuroimaging. In J. T. Cacioppo, L. G. Tassinary, & G. G. Berntson (Eds.), *The handbook of psychophysiology* (pp. 19-55). Cambridge, MA: Cambridge University Press.

PsychOpen
publishing psychology

Ward, J. (2010). *The student's guide to cognitive neuroscience* (2nd ed.). Hove, United Kingdom: Psychology Press.

Weng, X., Ding, Y.-S., & Volkow, N. D. (1999). Imaging the functioning human brain. *Proceedings of the National Academy of Sciences of the United States of America, 96*(20), 11073-11074. doi:10.1073/pnas.96.20.11073

Whelan, R. R. (2007). Neuroimaging of cognitive load in instructional multimedia. *Educational Research Review, 2*(1), 1-12. doi:10.1016/j.edurev.2006.11.001

Wilkinson, I. D., & Paley, M. N. J. (2008). Magnetic resonance imaging: Basic principles. In R. C. Grainger, D. Allison, A. Adam, & K. Dixon (Eds.), *Diagnostic radiology: A textbook of medical imaging* (5th ed.). New York, NY: Churchill Livingstone.

Wolf, R. L., & Detre, J. A. (2007). Clinical neuroimaging using arterial spin-labeled perfusion MRI. *Neurotherapeutics, 4*(3), 346-359. doi:10.1016/j.nurt.2007.04.005

Yeo, R. A., Gasparovic, C., Merideth, F., Ruhl, D., Doezema, D., & Mayer, A. R. (2011). A longitudinal proton magnetic resonance spectroscopy study of mild traumatic brain injury. *Journal of Neurotrauma, 28*(1), 1-11. doi:10.1089/neu.2010.1578

Zaharchuk, G., Straka, M., Marks, M. P., Albers, G. W., Moseley, M. E., & Bammer, R. (2010). Combined arterial label and dynamic susceptibility contrast measurement of cerebral blood flow. *Magnetic Resonance in Medicine, 63*(6), 1548-1556. doi:10.1002/mrm.22329

Zaidi, H., & Del Guerra, A. (2011). An outlook on future design of hybrid PET/MRI systems. *Medical Physics, 38*(10), 5667-5689. doi:10.1118/1.3633909

About the Author

Dr. **George Varvatsoulias** CPsychol CSci Expert Witness, studied Theology and Practical Theology in Thessaloniki/Greece. In England he studied Psychology, Psychology of Religion, Evolutionary Psychology and Cognitive-Behavioural Therapy as well as he holds a Doctorate in Psychology of Religion. He has published more than 43 articles in peer-reviewed journals and three books. He works as a Cognitive-Behavioural Practitioner at the West London Mental Health NHS (National Health Service) Trust where he sees clients with co-morbid conditions. He is also a Visiting Research Fellow for the topic of Psychology of Religion at Glyndŵr University in Wrexham/Wales UK.

PsychOpen is a publishing service by Leibniz Institute for Psychology Information (ZPID), Trier, Germany.
www.zpid.de/en

PsychOpen publishing psychology