Past, present and future influences of functional magnetic resonance imaging on the development of psychology: A review of the literature

Evie E.C. Izeboud

Cognitive and Neurobiological Psychology

Abstract
Neuroimaging has become increasingly important for psychology, especially in the studies of cognitive functions, and the past two decades have seen an enormous increase in functional magnetic imaging (fMRI) research. fMRI is one of the best neuroimaging methods ever devised, merging high spatial resolution with relatively high temporal resolution. fMRI has contributed significantly to integrating cognitive psychology and neuroscience into the interdisciplinary field of cognitive neuroscience. The capabilities of fMRI are being expanded to other fields as well, like social psychology, leading to the even more interdisciplinary field of social cognitive neuroscience. Although fMRI still has some limitations regarding temporal resolution and statistics, new insights in how to overcome these limitations look promising. In the near future, the capabilities of fMRI will probably be expanded even more, yielding new discoveries in even more fields of psychology. fMRI has expanded the boundaries of psychology, leading to new interdisciplinary fields of research in psychology, and psychology itself has promoted the development of fMRI by applying it to new experimental paradigms.

Keywords: *Functional magnetic resonance imaging; Cognitive neuroscience; Positron emission tomography; Psychology*

Introduction

Neuroimaging methods have become very important for psychology and have changed the way that cognition and the brain are studied. Earlier methods such as the electroencephalogram (EEG) (first used in 1929) and other electrical neuroimaging methods, measured brain activity on good temporal scales measured in milliseconds. However, these methods do not have a very good spatial resolution, given that they are limited to global indications of brain activity without specifying the exact location of the activity. Moreover, these earlier methods generally measure activity from the parts of the brain closer to the skull such as the cortex, and less from interior parts of the brain (Rosen, Buckner, Dale, 1998). This has resulted in many cognitive studies focusing on event-related responses of the brain in general, and not of specific brain areas. Finally, mathematical methods designed to localize brain activity suffer from the "inverse" problem, meaning that different combinations of brain activity can lead to the same electrical signal on the scalp (Purves Cabeza, Huetell, & LaBar, 2013).

Later, the first hemodynamic functional neuroimaging methods (i.e., methods based on blood flow to the brain) were developed. Although this review primarily focuses on functional Magnetic Resonance Imaging (fMRI), an older related technique, Positron Emission Tomography (PET), is also discussed, because both methods are based on the same principle, and because PET contributed to the development of fMRI. In the late 1950s, PET was the first method that could measure functional processes in the brain (and rest of the body) with relatively good spatial resolution. PET measures the blood flow to active areas of the brain by injecting a radioactive substance into the blood that can be detected by the PET machine. Despite improved spatial resolution (6-15 mm) relative to electrical neuroimaging, PET misses the upper and bottom part of the brain and has low temporal resolution (40-60 seconds), meaning it isn't very accurate in measuring *when* the brain is active (Cabeza & Nyberg, 1998). Another disadvantage of PET is that a radioactive substance has to be injected into the blood, which causes increased health risks for the persons studied (Purves et al., 2013). These limitations were overcome with the development of functional fMRI, which was introduced in 1980.

Functional MRI combines high spatial resolution anatomic imaging with relatively good temporal resolution, measuring up to seconds (Rosen, et al., 1998). Functional MRI is a special imaging technique developed for the MRI scanner that creates anatomical pictures with high spatial resolution (mm) (Purves et al., 2013). The technique is based on the knowledge that active brain areas use more oxygen than less active brain areas. Oxygen reaches the brain via hemoglobin molecules in red blood cells in the blood stream. When neurons become active, local blood flow to those brain areas increases and oxygen-rich blood cells replace oxygen-depleted blood cells around two seconds later. The oxygen level peaks after about 4-6 seconds (when the neurons become active) and declines after about 10-15 seconds (when the baseline oxygen level is restored). Deoxygenated blood is more magnetic than oxygen-rich blood, which leads to a different fMRI signal. The relative spatial and temporal resolution of EEG/MEG, PET and fMRI are shown in Figure 1.

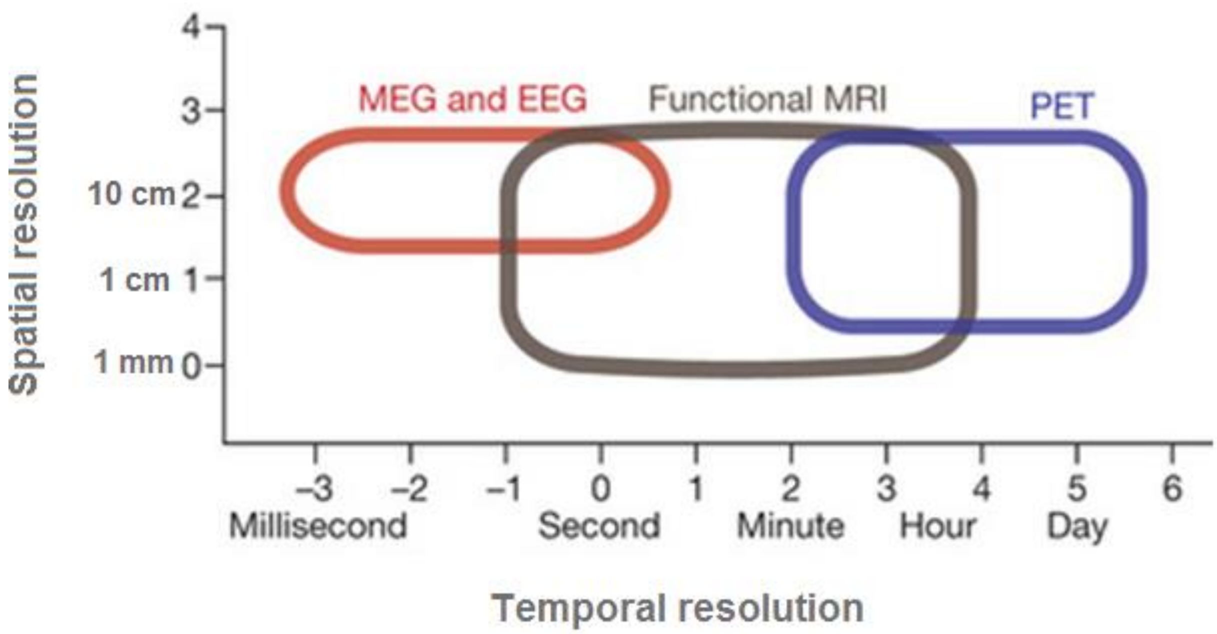

Figure 1. Illustration of the relative spatial and temporal resolution of fMRI compared with other neuroimaging methods. Note that a high resolution corresponds with a lower unit of measurement. Adapted from "From maps to mechanisms through neuroimaging of schizophrenia" by A. Meyer-Lindenberg, 2010, *Nature*, *468*(7321), p. 194.

Past

The knowledge that blood circulation and brain activity are related processes was mentioned by the famous psychologist William James in the late 19th century (1890). On this topic, James mostly referred to the Italian physiologist Angelo Mosso, who recorded the pulsation of blood in the cortex of patients with skull defects due to neurosurgical procedures. Mosso correctly concluded that the pulsation of blood increased regionally during mental activity. Unfortunately, the first decades of the 20th century provided limited research on brain activity and blood flow. This was partly due to the lack of sufficient methods to measure blood flow in the healthy and active brain. Another factor contributing to the limited development of these ideas was the work of Leonard Hill, who incorrectly concluded that there was no relationship between brain function and blood circulation (1896).

After the Second World War, research on blood circulation and brain activity received more attention, and Seymour Kety and colleagues studied brain circulation and metabolism. The technique they developed provided the foundations for PET and fMRI (Raichle, 1998). However, their technique also had its clear limitations, as illustrated by a 1955 quote from one of the proponents of this line of research, William Landau:

> “Of course we recognize that this is a very secondhand way of determining physiological activity; it is rather like trying to measure what a factory does by measuring the intake of water and the output of sewage. This is only a problem of plumbing and only secondary inferences can be made about function. We would not suggest that this is a substitute for electrical recording in terms of easy evaluation of what is going on” (as cited in Raichle, 1987).

Nonetheless, the introduction of new methods provided new insights, leading to increased appreciation of the importance of understanding the value of measuring blood circulation as a proxy for local brain activity (Raichle, 1987).

PET was introduced in many different countries throughout the 1970s, but was not initially embraced by most neuroscientists and cognitive scientists. In the 1980’s, skepticism disappeared and cognitive psychologists started using PET in their experiments. When fMRI in its present form was developed in 1990 (Purves et al., 2013), research with functional brain imaging expanded even more. Consequently, the integration of neuroscience and psychology via brain imaging led to the development of the field we now know as cognitive neuroscience (Raichle, 1998).

Present

The past two decades have seen an enormous growth in the field of human brain mapping, especially the use of fMRI. When searching for articles about fMRI at the end of 2007, Poldrack found over 12.000 articles mentioning fMRI in their title and/or abstract in PubMed (2008). When searching for the same keyword in the title and/or abstract at end of 2013, over 21.000 articles were found in PubMed. The significant increase in the number of studies published on fMRI during the past 20 years is displayed in Figure 2.

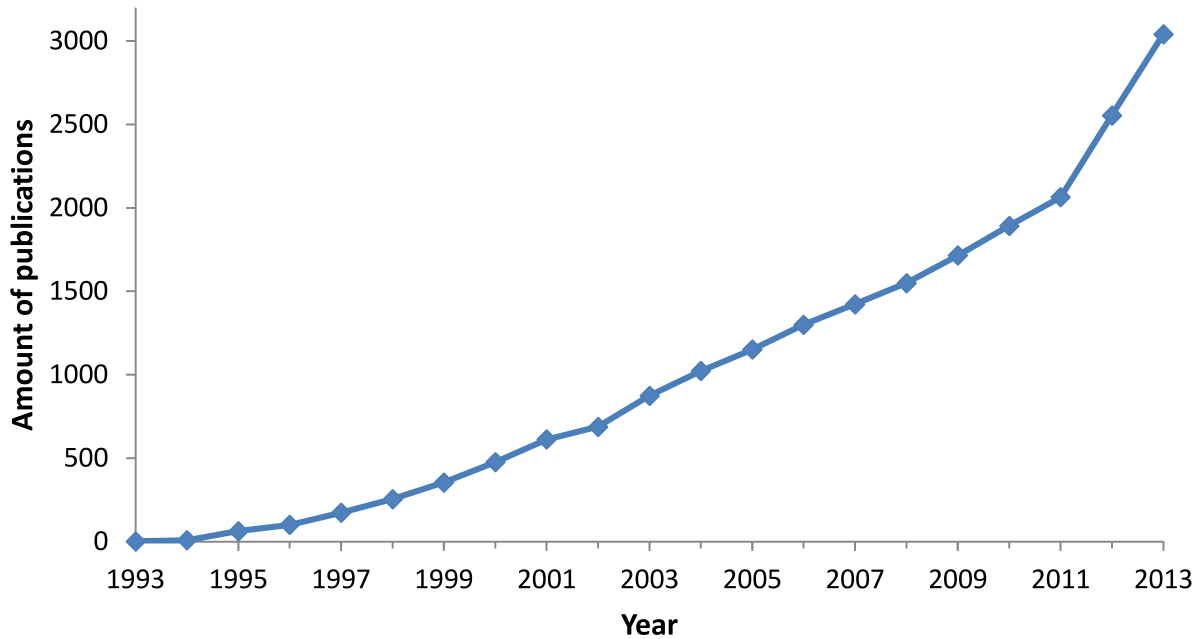

Figure 2. Number of publications found on PubMed with fMRI mentioned in the title and/or abstract for each year between 1993 and 2013.

The use of PET and fMRI has allowed inferences concerning many cognitive functions, including, but not limited to: attention, perception, imagery, language, working memory, semantic memory retrieval, episodic memory encoding, episodic memory retrieval, priming and procedural memory. In an empirical review Cabeza and Nyberg (2000), summarized activation patterns of these functions. For example, for perception and imagery, Cabeza and Nyberg reported patterns of activation in the dorsal and ventral pathways, as well as in pathways from the primary visual cortex to the secondary visual cortices. For all the other cognitive functions mentioned in the first part of this section, specific patterns of activation were observed. Cabeza and Nyberg also reported several brain regions, including the cerebellum, that were involved in a variety of cognitive functions.

The development of fMRI has also changed the way research is conducted. Older methods such as PET required a blocked experiment setting, because of the low temporal resolution of this method. But with fMRI it became possible to measure event-related responses in specific parts of the brain, which had a significant impact on the field of cognitive science (Rosen, et al., 1998). Moreover, this has led to new applications of neuroimaging in social psychology, resulting in the relatively new field of social cognitive neuroscience (Ochsner & Lieberman, 2001).

Another novel feature of fMRI research is the representation of activity in small units of the brain in voxels (imaging elements that are the three-dimensional analogues of two-dimensional pixels). The brain can be represented in 130,000 voxels, each being significantly active or inactive. In statistical terms, an fMRI is a collection of multiple tests, each voxel being a test. When conducting so many tests at the same time, the risk of obtaining false positives becomes very high. At the moment, there are no strict rules for correction of these multiple comparisons, and therefore this risk is often forgotten by cognitive researchers. This was illustrated by a team of cognitive neuroscientists, who had imaging produced from a dead and frozen salmon placed in an fMRI scanner (Bennett, Baird, Miller, & Wolford, 2009). When they analyzed the results without correcting for multiple comparisons, the data revealed active voxel clusters as illustrated in Figure 3. When controlling for multiple comparisons, no active voxels were found, as one would expect in a dead animal. This fascinating study raises concern regarding the accuracy of many fMRI research results that did not correct for multiple comparisons.

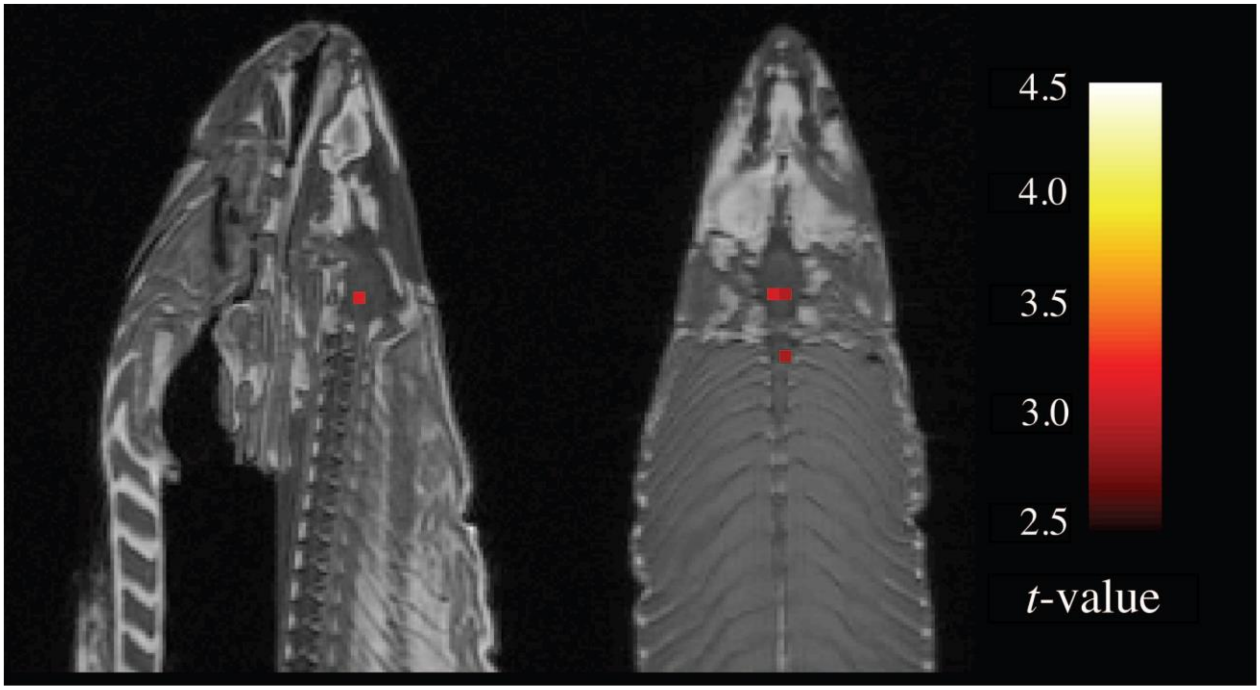

Figure 3. Activity supposedly found in an fMRI study of a dead salmon when not correcting for multiple comparisons. Retrieved from “Neural correlates of interspecies perspective taking in the post-mortem Atlantic Salmon: An argument for multiple comparisons correction.” by C. M. Bennett, M. B. Miller and , G. L. Wolford, 2009, *Journal of Serendipitous and Unexpected Results, 1*, p. 1-5.

Future

The development of hemodynamic functional neuroimaging has resulted in many insights and created possibilities for future research, but the shift of attention to these techniques has several implications for the future. First there is the challenge of limited temporal resolution of fMRI. Because fMRI measures brain activity indirectly via blood flow, there is always a signal delay because it takes a few seconds for oxygen-rich blood to reach the brain when it is active. Furthermore, there is a variance in how much delay there is in different parts of the brain that is not yet fully understood (Rosen, et al.,1998). However, techniques are being developed that make it possible to measure fMRI in real-time with a very high temporal resolution (up to 268 ms; Posse et al. 2012). Taking these current developments into consideration, it is conceivable that in the future fMRI can be measured on an even higher temporal scale.

Secondly, there is a problem with the statistical power of current research with fMRI. The statistical power of research reflects the change that a significant effect is found when there is an effect, and nothing is found when there is no effect. The statistical power of most neuroscientific research, including fMRI research, is considered low. This results in overestimated effect sizes and low reproducibility for results (Button et al., 2013). One of the most obvious ways of increasing the statistical power of studies is to increase the sample size of experiments. This is also one of the recommendations of Button et al. (2013), but increasing sample sizes is not always financially possible. A possible solution to this problem lies in more open access to data from others, which is currently promoted to make scientific research more efficient.

Poldrack (2012) has examined possible positive future developments of fMRI. Poldrack calls for more methodological rigor, increasing the focus on connectivity and pattern analysis in the brain instead of specific regions, greater statistical power with the help of open databases, and an increase in the use of ontologies and computational models. Such developments could augment the robustness and clinical validity of neuroimaging methods and ensure its future application.

Conclusion

A fMRI is a hemodynamic neuroimaging method based on the flow of oxygen-rich blood to the brain (Purves et al., 2013). Active brain areas use more oxygen, and thus brain activity can be measured indirectly, with a higher spatial resolution then all other non-invasive neuroimaging methods (Rosen, et al., 1998). This has led to a shift of attention in cognitive psychology and other disciplines outside psychology like neuroscience and medicine from *when* the brain is active to exactly *where* this activity takes place.

Current fMRI research is shifting from where in the brain activity takes place, to how cognitive processes work. fMRI has the event-related capabilities that cognitive scientists want as well as the anatomic imaging capabilities neuroscientist want. Not surprisingly, the method has greatly contributing to combining elements of cognitive psychology and neuroscience, to create the new interdisciplinary field of cognitive neuroscience.

The role of fMRI is likely to become more prominent in the future, due to absence of competition from other techniques. It is conceivable that fMRI has the potential to provide not only greater understanding into where but also *how* cognitive processes take place, which would be beneficial for psychology as a whole. FMRI has already been applied to cognitive psychology, resulting in the interdisciplinary fields of cognitive neuroscience (Raichle, 1998) and social cognitive neuroscience (Ochsner, & Lieberman, 2001). In the future, fMRI may be applied to clinical psychology and provide insights into the mechanisms of psychological disorders. FMRI could be applied to developmental psychology and pedagogy to gain more insight into how children learn and develop mentally.

It can be concluded that fMRI has expanded the boundaries of psychology, leading to new interdisciplinary fields of research in psychology, and also that psychology itself promoted the further development of fMRI by applying it to new experimental paradigms. At present there are some methodological problems that need to be resolved in order to promote the robustness and clinical validity of neuroimaging methods, and to ensure their future application.

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