

From neuroimaging to neuroethics

TO THE EDITOR—To advance awareness of ethical issues in the neurosciences^{1–3}, we studied historical and emerging trends in neuroimaging, using functional magnetic resonance imaging (fMRI) as a model. Functional MRI has had a significant impact on the neurosciences in the past decade given its wide availability, unprecedented coupling of spatial resolution and safety, and application to a broad range of normative and clinical neurobehavioral phenomena⁴. Over time, the terrain of fMRI studies has expanded from examination of basic sensorimotor and cognitive processes to topics that more directly relate to human motivation, reasoning and social attitudes. Here we provide empirical validation of these trends and explore what issues they portend for the future.

PubMed and Ovid search engines were used to identify all peer-reviewed articles involving fMRI between 1991 and 2001. We developed the following taxonomy to classify articles: motor, primary sensory, integrative sensory, basic cognition, higher-order cognition, emotion, clinical, methods development, reviews, and non-human primate. Two reviewers, who were blind to author, publication year and journal, independently coded the articles into one or two categories.

The search returned 3,426 unique fMRI articles published across 498 different journals. Regression analysis showed that papers, journals and clinical and methods studies increased significantly over time (Fig. 1; for statistical details, see **Supplementary Data** online). We also identified relative decreases and increases in the percentages of publications in different neurobehavioral categories (Fig. 2). Motor studies and

primary sensory studies decreased by approximately 2% and 7% (respectively) per year on average. Significant increases were found for the classifications of integrative sensory studies, basic cognition, higher-order cognition and emotion, ranging from 0.7% to 4% per year on average (see **Supplementary Data** for statistical details).

Brain organization of primary sensory and motor regions is particularly well understood, in part because of the topographic nature of these regions; understandably, early studies concerned with validating fMRI measures focused on those topics. Over time, however, our analysis shows a steady expansion of studies with evident social and policy implications, including studies of human cooperation and competition, brain differences in violent people and genetic influences on brain structure and function.

As fMRI continues to mature, its scope and limits will be better defined. This will include inquiry about the nature of the neural signals indexed by fMRI's vascular measurement, the brain functions that are well or poorly measured by fMRI, and the optimal statistical approaches for balancing sensitivity and false positives in fMRI data. There is, however, growing regard for the novelty and breadth of information that neuroimaging can deliver about the complexity of human behavior. This scientific and popular acceptance calls for continued interaction among neuroscientists and stakeholders (for example, from medicine, education, law and the media) to ensure that the benefits of such new knowledge outweigh the risks.

Outstanding issues about fMRI measures include individual reliability, and diagnostic and predictive validity for real-world behaviors, especially those that are potentially value-laden or culturally determined. As these become better understood, questions about statistically aberrant functional findings will need to be addressed: what might an abnormal brain activation pattern in a study of moral reasoning, deception or sexual responsiveness really mean? Such

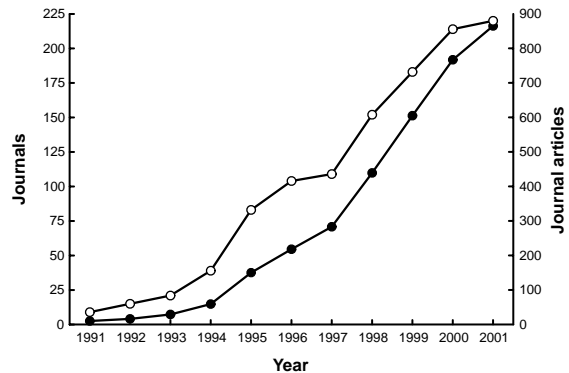


Fig. 1. fMRI studies in the peer-reviewed literature from 1991 to 2001. Open circles, number of journals; filled circles, journal articles.

findings give rise to dilemmas in the interpretation and appropriate use of data. They also pose questions about the responsible use of human subjects drawn from either healthy or vulnerable populations. For example, how should such findings be communicated to a participant⁵?

Lessons may be drawn from other fields, such as genetics, in discussing ethical issues that surround fMRI and other neuroimaging modalities. Considering these issues through proactive, multidisciplinary dialogue today will result in more acceptable and relevant standards than those that may be developed through later, external processes.

Note: Supplementary information is available on the Nature Neuroscience website.

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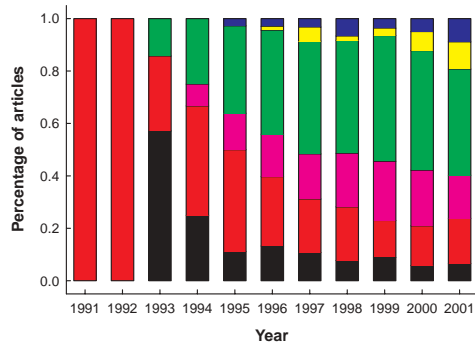


Fig. 2. Articles in each neurobehavioral classification per the total number of articles of those classifications published in each year: motor (black), primary sensory (red), integrative sensory (violet), basic cognition (green), higher-order cognition (yellow), emotion (blue).