What Is an Image?

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Whether in the hands of an advertising executive or a scientist, visual images have the power either to convey information efficiently or to mislead through sleight of hand. To evaluate adequately what is being presented in a published imaging article, readers must first understand what constitutes an image. A wide range of technologies can produce an image of the brain, and those images can capture an even wider range of features of the brain tissue that is imaged (Table 1). Nevertheless, all of those images have in common a basic physical structure, and a common set of terms can be used to describe that structure.

An image is simply a two-dimensional, physical array of much smaller, two-dimensional squares or rectangles, which are elemental units of the picture called picture elements (or pixels). Each pixel corresponds to a three-dimensional square or rectangular chunk of brain tissue called a volume element (or voxel). Each pixel of the image is typically assigned either a level of visual grayness ranging from black to white (Fig. 1) or an arbitrary color that represents a numerical value. That numerical value in a pixel in turn quantifies some characteristic or feature of the tissue in the corresponding voxel of the brain being imaged. That numerical value and its corresponding grayscale representation or color-encoding may represent, for example, the degree to which x-rays pass through the tissue (in a computed tomography [CT] scan; Fig. 2), the amount of radioactivity emitted by the tissue (in positron emission tomography), the number of hydrogen nuclei in the tissue (in anatomical magnetic resonance imaging [MRI]; Fig. 2), the direction of fiber tracts in the brain (in diffusion tensor imaging [DTI] Fig. 3), the amount of oxygenated or deoxygenated hemoglobin (in functional MRI; Fig. 4), or a molecular concentration (in magnetic resonance spectroscopy [MRS] Fig. 5).

Variation in this level of grayness or its color encoding across the two-dimensional array of pixels can distinguish one type of tissue of the brain from another in the corresponding three-dimensional array of tissue voxels, or slice, of brain tissue. A stack of such slices, one on top of another, will represent a larger volume of brain tissue, possibly the entire brain, visualized at one point in time. Table 1 summarizes the technologies commonly used to image the brain, the properties of the tissue encoded in the image, and the major strengths and limitations of each of the technologies.

A similar technique is used for building images of the brain across time, which can be used to represent electrical or neurochemical functioning in a particular brain voxel. A functional MRI map of functional activity, for example, captures in each pixel the variation across time in the level of deoxygenated hemoglobin, which in turn indexes the level of neural activity, in the corresponding brain voxel. The degree to which that temporal variation in deoxyhemoglobin in each voxel correlates with the temporal variation in behavior or sensory experience of the person being imaged is assessed statistically, and that statistical index (usually a probability or *p* value) is assigned to the corresponding pixel of the image. That statistical index is then color encoded. In other words, this statistic represents the

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TABLE 1
Neuroimaging Modalities: Method, Strengths, and Weaknesses

What the Intensity or Color of Each Voxel Encodes	Strengths	Limitations
	Structural Methods	
Computed tomography (CT) Degree of absorption of an x-ray beam in 3 dimensions, reflecting density of tissue	Fast acquisition time, good spatial resolution	Exposure to ionizing radiation; poor contrast between various soft tissues
Structural magnetic resonance imaging (MRI) Intensity of radio signal emitted from water hydrogen nuclei in a magnetic field, reflecting local chemical environment	Excellent spatial resolution, excellent contrast between soft-tissue types; no ionizing radiation	Expensive; difficult for subjects with claustrophobia; sensitive to subject motion; incompatible with ferrous metals and certain medical prosthetics (e.g., pacemakers); limitations also apply to DTI, MRS, and fMRI
Diffusion tensor imaging (DTI) Extent to which water diffuses in a chosen direction, reflecting direction and integrity of neural fiber tracks	Sensitive to directionality of a cell, particularly relevant to development and function of CNS	Low spatial resolution restricts findings to major neural bundles, as opposed to individual neurons; methods for image processing and statistical analysis are still immature
	Functional Methods	
Functional MRI (fMRI) Blood oxygen level–dependent (BOLD) response reflects local proportion of oxyhemoglobin vs. deoxyhemoglobin, serving as an index of local neuronal activity	Reflects local neural activity without ionizing radiation; no need for intravenous access; much better spatial resolution than EEG (several millimeters)	Temporal resolution is low (~1 sec) relative to time scale of neural activity; absence of absolute index of neuronal activity often permits only determination of differential activity (i.e., activity relative to a control condition)
EEG Magnitude of electrical signals at surface of scalp, directly measuring neural activity in cerebral cortex	High temporal resolution (milliseconds); no ionizing radiation; equipment less expensive than for other methods	Poor spatial resolution (several centimeters); detects activity only within a few millimeters of brain surface
Magnetoencephalography (MEG) Magnitude of magnetic fields at surface of skull, reflecting intraneuronal current flow in cortical pyramidal cells	High temporal resolution (milliseconds); no ionizing radiation; does not require scalp electrodes; better spatial resolution than EEG	Usually detects activity only within a few millimeters of brain surface; expensive equipment
	Structural and Functional Methods	
Magnetic resonance spectroscopy (MRS) Series of spectral peaks at different radiofrequencies, reflecting relative concentration of various brain metabolites	Sensitive to concentration of brain metabolites without need for specially synthesized compounds or ionizing radiation (as with PET)	Low spatial and temporal resolution compared to structural MRI and fMRI; requires long scan times; often determines only relative, not absolute concentrations; only a small number of metabolites are visible to MRI scanner
Positron emission tomography (PET) Intensity of photons originating from annihilation of positrons emitted by a decaying radioactive tracer and matching electrons; positron emission reflects concentration of a specific tracer used to measure blood flow, energy metabolism, or specific neurotransmitters or their receptors	Enables measurement of very specific functional features of CNS neurons as long as an appropriate radioactive tracer can be synthesized	Low spatial and temporal resolution; exposes subject to ionizing radiation; requires an expensive cyclotron to generate radioactive tracers nearby; requires intravenous or arterial access to subject
Single-photon emission computed tomography (SPECT) Intensity of single photons emitted directly from decay of radioactive tracers, reflecting concentration of a specific tracer	Tracers have longer half-lives than PET tracers, removing necessity for an on-site cyclotron and decreasing cost of imaging compared to PET	Usually lower resolution than PET; exposes subject to ionizing radiation