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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.

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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 likelihood that temporal variation in neural activity within that chunk of brain tissue being imaged correlates with the temporal variation in behavior or experience of the subject. If that index passes a preassigned threshold (e.g., $p < .05$), then neural activity in that chunk of tissue is assumed to participate in the behavior or experience of the subject. That statistic is literally painted on the brain image, usually by being superimposed on a corresponding grayscale representation of brain structure to help identify where the activity is located (Fig. 4). The color-encoded image therefore represents a four-dimensional map comprising three dimensions that define spatial location and a fourth dimension that indexes change in neural activity across time.

The quality and clinical or scientific usefulness of an image depends on a number of characteristics of the information carried within and across voxels. Resolution refers to the volume of brain tissue represented by a given voxel. If the size of the tissue being imaged is held constant, then an image with higher resolution has voxels that are smaller in size but greater in number. This allows for greater discrimination of neighboring structures within the brain, but usually increases the time required to obtain the image. At lower resolution, voxels are larger and therefore are more likely to cross the boundaries of tissues and regions, making them more difficult to discriminate from each other.

Measurement of any physical properties, including those represented by brain images, inevitably involves some degree of error because no measurement process is perfect. More error, or noise, degrades the quality of an image, just as a snowy picture degrades the image on a television screen with poor reception. The portion of the measurement of a tissue property in each voxel that is accurate (the true signal from the voxel), relative to the noise present in the measurement, is termed the signal-to-noise ratio (SNR) of the image. It provides a useful summary of image fidelity. The strength of the magnetic field of an MRI scanner is an important determinant of the SNR and image quality because it determines how many hydrogen nuclei in a voxel emit radio signals during the scanning process; the larger their number, the stronger their signals are in summation and the more accurate is measurement of the tissue characteristics that those radio signals encode from each voxel. Increasing the size of the voxel (and therefore also increasing the amount of tissue it contains) also increases the number of emitting nuclei and therefore also increases the SNR, but at the expense of decreasing the resolution of the image.

Finally, contrast refers to the difference in signal strength between adjacent but distinct types of brain tissues, such as gray matter and white matter. By convention, magnetic resonance images are assigned a grayscale value that ranges from 0 (pure black) to 255 (pure

white). In an image with optimal contrast, this number would vary greatly across different types of tissue. One of the principal advantages of magnetic resonance imaging over computed tomographic imaging is that the former provides superior contrast for brain tissues that are important to discriminate for clinical and research purposes (especially gray and white matter), thereby aiding the accurate identification of cortical and subcortical structures.

In imaging, as in life, nothing comes for free. Improvement in the convenience of image acquisition (e.g., the amount of time or expense required) or a technical property of the image (e.g., resolution, contrast, SNR) inevitably comes at the expense of some other aspect of the image. In any given study, therefore, the choices made by the imager are crucial for keeping these in balance and for keeping the images optimized for the population studied, the brain feature of interest, and the hypothesis in question. In future columns, we will discuss these choices in relation to what neuroimaging is teaching us about scientifically and clinically relevant questions in child and adolescent psychiatry.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

Composition of an image. Left, Each volume element (voxel) contains either high (H) or low (L) concentrations of a physical quantity of interest. Middle, The physical quantities of interest in each voxel are encoded numerically and assigned to a corresponding picture element (pixel) of the image. Right, The numerical quantity assigned to each pixel is assigned a level of grayness ranging from black to white and displayed in an array of pixels to reveal relationships between the physical quantities of interest (in this case, their spatial relationships) that would otherwise be difficult to discern in a simple listing of those quantities.

Fig. 2.

Computed tomography and magnetic resonance imaging of brain structure. W = white matter, C = caudate, T = thalamus, CSF = cerebrospinal fluid. Reprinted with permission from *Lewis's Child and Adolescent Psychiatry*. Philadelphia: Lippincott Williams & Wilkins; 2007:217.

Fig. 3. Diffusion tensor imaging of fiber tracts. Colors depict directions of three-dimensional fiber tracts. Red = left (L) to right (R); green = posterior (P) to anterior (A); BG = basal ganglia; CC = corpus callosum. Reprinted with permission from *Lewis's Child and Adolescent Psychiatry*. Philadelphia: Lippincott Williams & Wilkins; 2007:224.

Fig. 4.

Functional magnetic resonance imaging of brain activity. This axial image (a slice parallel to the floor in a standing person) shows statistical significance of functional activity in one direction in bilateral basal ganglia, inferior frontal and anterior temporal cortex, and in the opposite direction in the anterior cingulate cortex and right anterior temporal cortex. A = anterior; P = posterior; R = right; L = left.

Fig. 5.

Magnetic resonance spectroscopy (MRS) of brain metabolites. One subregion of the brain is represented by several voxels, each of which generates a spectrum of signals from various neurometabolites. The height of each peak in the spectrum indicates the relative concentration of the corresponding metabolite. NAA = *N*-acetyl aspartate; tCr = total creatine; tCh = total choline; Glu = glutamate; Ins = myoinositol.

Table 1
Neuroimaging Modalities: Method, Strengths, and Weaknesses

What the Intensity or Color of Each Voxel Encodes	Strengths	Limitations
<i>Structural Methods</i>		
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
<i>Functional Methods</i>		
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
<i>Structural and Functional Methods</i>		
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)		

What the Intensity or Color of Each Voxel Encodes	Strengths	Limitations
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