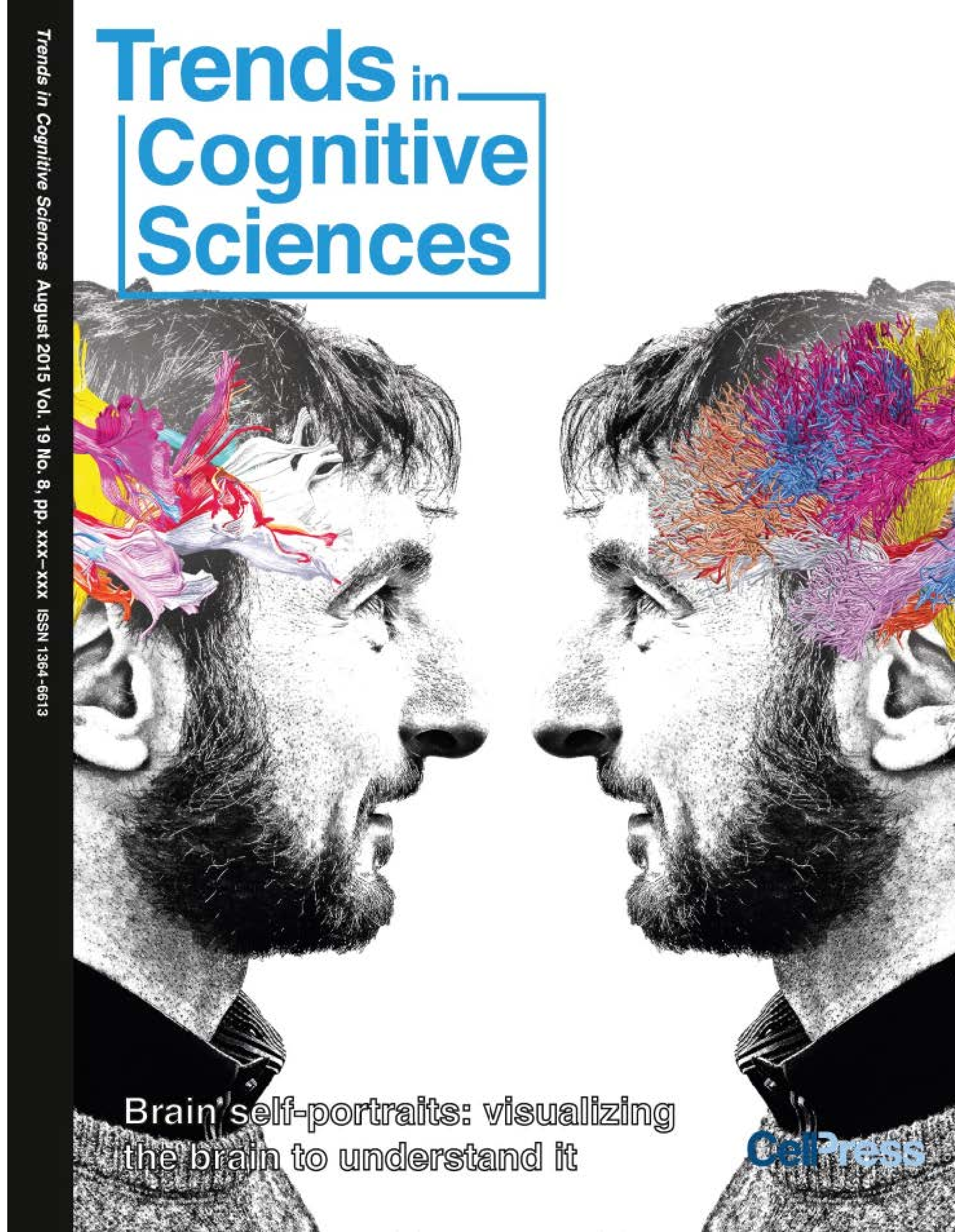
Self-portraits of the brain: Cognitive science, data visualization, and communicating brain structure and function

By Goldstone, Robert, Franco Pestilli, and Katy Börner. 2015. *Trends in Cognitive Sciences*, doi:10.1016.

Presentation at http://events.brainhack.org/global2017

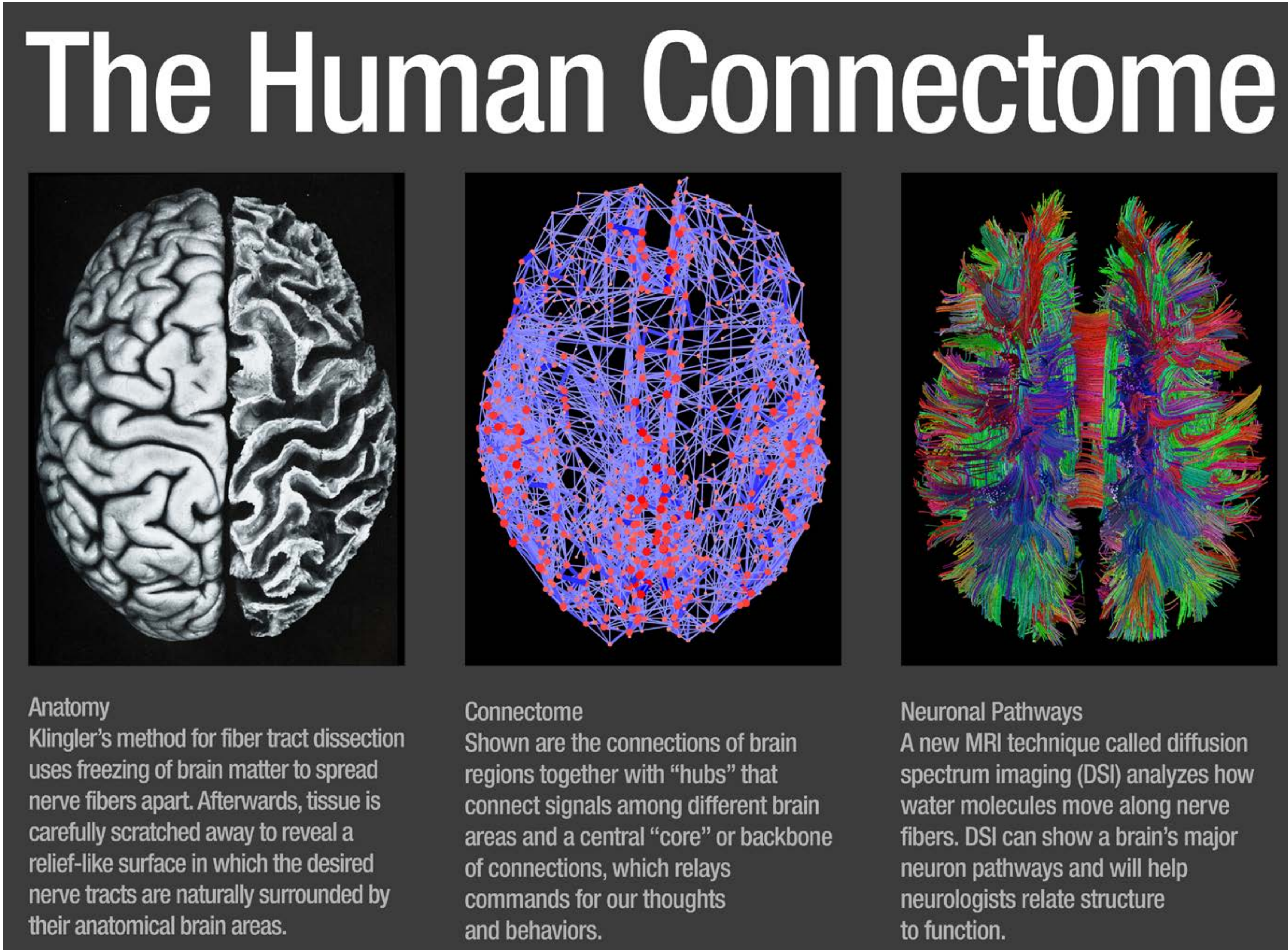
3/4/2017



Overview

- A complete understanding of the brain must incorporate information about 3D neural location, activity, timing, and task.
- Data mining, high-performance computing, and visualization can serve as tools that augment human intellect.
- Visualizations must take into account human abilities and limitations to be effective tools for exploration and communication.

This review discusses key challenges and opportunities that arise when leveraging the sophisticated perceptual and conceptual processing of the human brain to help researchers understand brain structure, function, and behavior.



VI.2 *The Human Connectome* - Patric Hagmann and Olaf Sporns - 2008

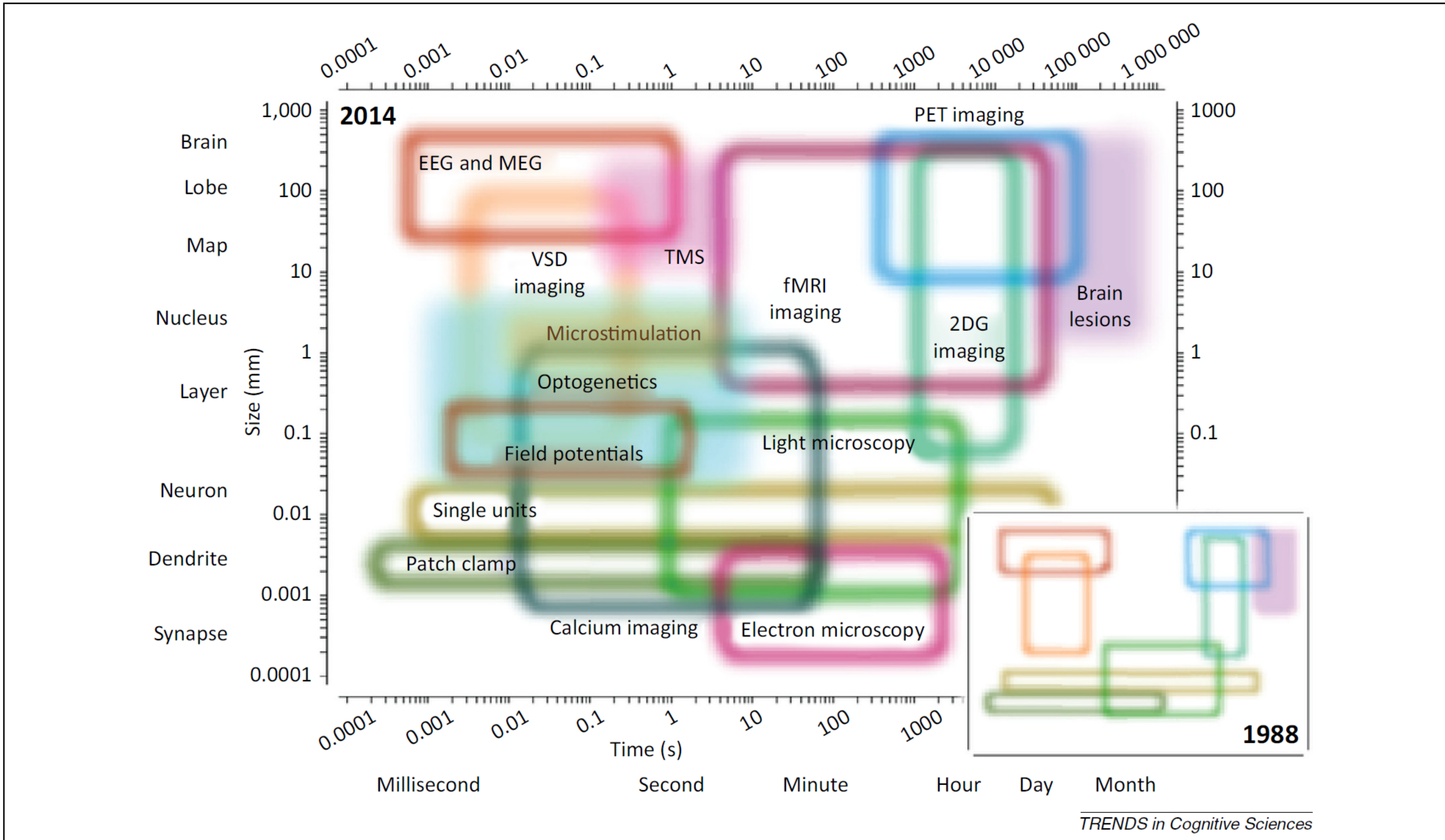


Figure 2. Spatiotemporal resolution of techniques in neuroscience. The spatiotemporal domain of neuroscience methods available for the study of the nervous system in 2014 is compared with that in 1988 [13] (inset). Colored regions represent the domain of spatial and temporal resolution for each method. Open regions represent measurement methods, and filled regions represent stimulation methods. The large gap in measurement resolution in the middle of the graph in 1988 has since been filled by the advent of *modern in vivo* neuroimaging measurements of the human brain. Reproduced, with permission, from [12].

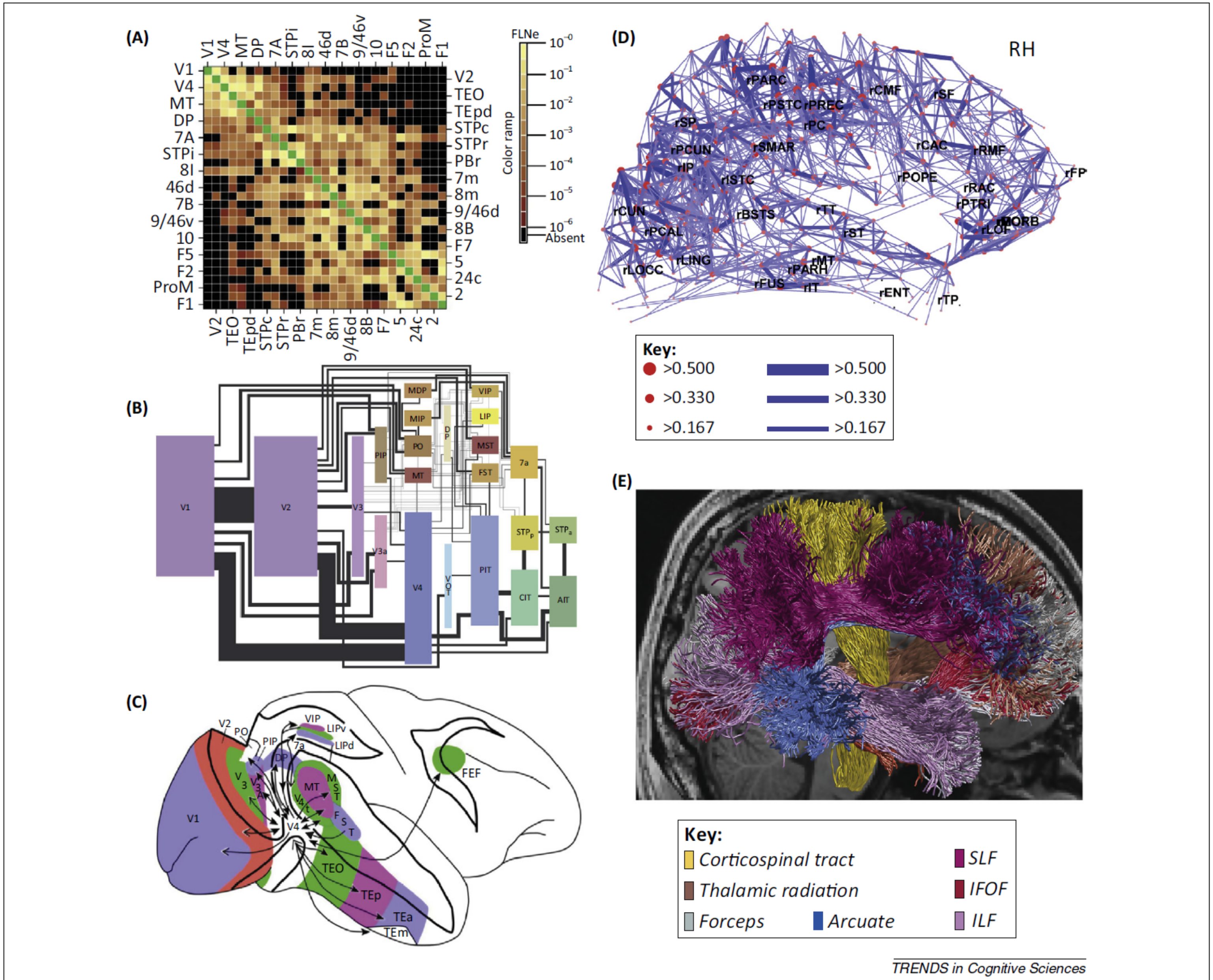


Figure 4. Visualization of connectivity data. **(A)** Tabular (asymmetric matrix) representation. Rows represent 29 tracer source areas, whereas columns represent 29 injected target areas. Color shows the strength of projection, whereby black indicates an absent connection and green indicates intrinsic projections (see color bar). **(B)** Coarse topological network layout. Schematic representation of 24 richly interconnected visual cortical areas in the macaque brain. **(C)** Neural projections to one brain region, mapped onto brain. Schematic representation of the connections of brain area V4 in the macaque brain. **(D)** Human connectome. Dorsal view of the connectivity backbone, node (red), and edges (blue). **(E)** Human white-matter tract anatomy. Seven of the major human white-matter fascicles are shown. Reproduced, with permission, from [100] (A), [63] (B), [64] (C), [65] (D), and [4] (E).

Box 1. Guided visualization design and frameworks

Making sense of data by designing appropriate visualizations is a complex process that involves not only human perception and cognition [88,89], but also data mining, visualization algorithms, and user interfaces. Different conceptualizations of the overall process have been developed to understand and optimize this process, and to improve human decision-making capabilities. Among others, process models focus on key sense-making leverage points [90], the match between pre-conceptualizations and expectations of visualization designers and visualization readers [91], major data transformation and visual mappings [92], or describing visualization design and interpretation to support workflow optimization and tool design. Key visualization types are listed in Table I.

Table I. Key visualization types

Name	Description	Examples[a]
Tables	Ordered arrangements of rows and columns in a grid; grid cells may contain geometric, linguistic, or pictorial symbols	Figure 4A
Charts	Depict quantitative and qualitative data without using a well-defined reference system	Examples are pie charts in which the sequence of 'pie slices' and the overall size of a 'pie' are arbitrary, or word clouds
Graphs	Plot quantitative and/or qualitative data variables to a well-defined reference system, such as coordinates on a horizontal or vertical axis	Figures 2, 3A, 3C
Maps	Display data records visually according to their physical (spatial) relations and show how data are distributed spatially	Figures 1A–F, 3B, 4C–E, 5A–C, 6A–D
Network layouts	Use nodes to represent sets of data records, and links connecting nodes to represent relations between those records	Figure 4B; see also network overlays on brain maps in Figure 4C,D

[a]Figures cited refer to those in the main text.

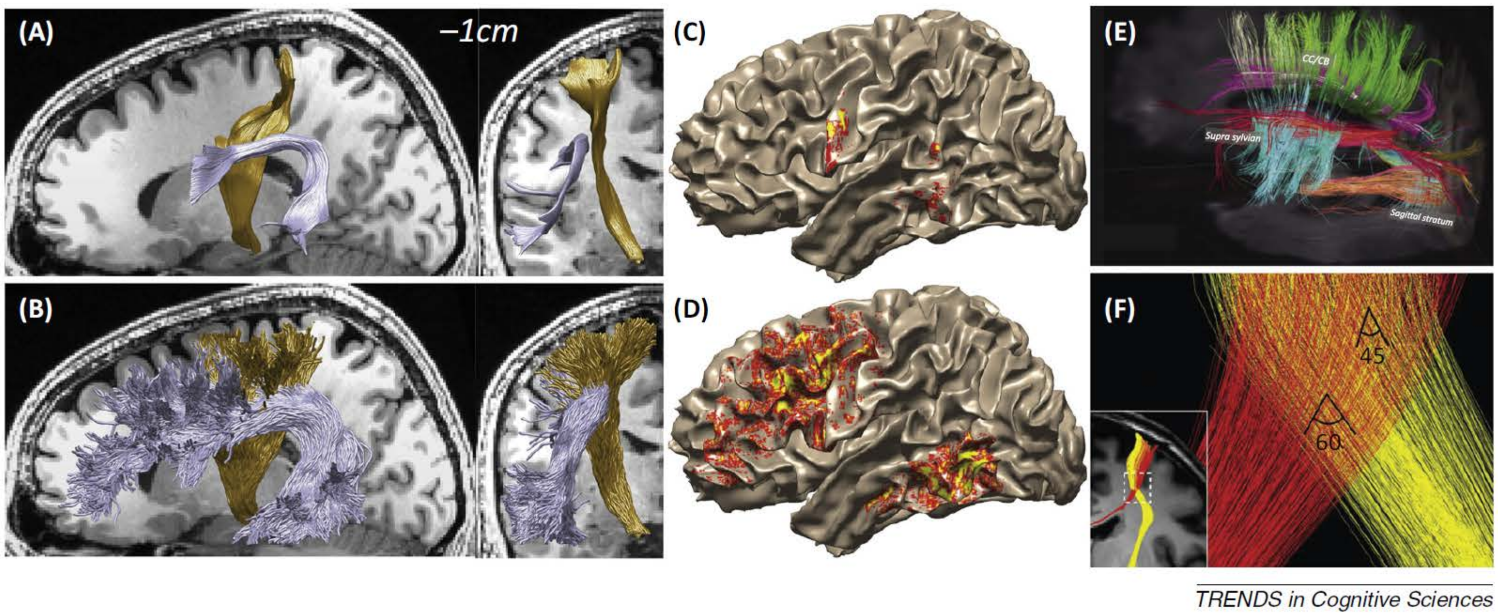


Figure 1. Anatomical visualization methods of human white matter. The panel on the left depicts trajectories of the human corticospinal tract (CST; gold) and arcuate fasciculus (AF; purple) identified using diffusion-weighted magnetic resonance imaging and deterministic **(A)** or probabilistic **(B)** tractography methods. The center panel depicts cortical projection zones of the AF estimated using deterministic **(C)** and probabilistic **(D)** tractography. The right-hand panel depicts white-matter fascicles apparently organized in sheaths with 90° crossings **(E)** [7] or crossing at different angles **(F)** [8]. Reproduced, with permission, from [4] (A–D), [7] (E), and [8] (F).

Box 2. Guided visualization design and frameworks

Any visualization can theoretically be analyzed and interpreted as a path along the columns of Table I. For example, given a scientific question, the question type and detailed insight need is identified, then data of different scale(s) are acquired, a visualization type is selected, and relevant geometric symbol types are chosen and visually modified (e.g., color coded) using different graphic variable types. Finally, different interaction types might be implemented to facilitate the interactive exploration of the visualization.

When visualizing the structure and function of the brain, the data that need to be represented are high dimensional and inherently complex. Many different types of visualization can be used and many different mappings of data attributes to visual attributes are possible. To ease the design of effective visualizations, different visualization frameworks (also called taxonomies or classifications) have been developed in statistics, information visualization, and graphic design [93–99]. Recent work [14] provides predefined types for the process of data visualization, including different task types, such as temporal (answering 'when' questions), spatial ('where'), topical ('what'), and trees and network layouts ('with whom'), and common insight need types (Table I, column 1).

Given well-defined general 'task types' and specific 'insight need types,' the final visualization will also depend on the type of data (see 'data scale types; Table I, column 2), the available 'visualization types (Table I, column 3), graphic symbol types (Table I, column 4), and 'graphic variable types' (Table I, column 5; Note that each type is further detailed in [14] (e.g., 'retinal: form' includes size, shape, rotation, curvature, angle and closure; 'retinal: color' subsumes value, hue, and saturation) that can be used, and the level of interaction required by the final visualization (Table I, column 6).

Table I. Visualization framework designed to ease the selection and design of data visualizations[a]

Insight need types	Data scale types	Visualization types	Graphic symbol types	Graphic variable types	Interaction types

• Categorize/cluster
• Order/rank/sort
• Distributions (also outliers, gaps)
• Comparisons
• Trends (process and time)
• Geospatial
• Compositions (also of text)
• Correlations/relationships
	• Nominal
	• Ordinal
	• Interval
	• Ratio
		• Table
		• Chart
		• Graph
		• Map
		• Network layout
			• Geometric symbols
			  • point
			  • line
			  • area
			  • surface
			  • volume
			• Linguistic symbols
			  • text
			  • numerals
			  • punctuation marks
			• Pictorial symbols
			  • images
			  • icons
			  • statistical glyphs
				• Spatial
				  • position (x, y, z)
				• Retinal
				  • form
				  • color
				  • optics
				  • motion
					• Overview
					• Zoom
					• Search and locate
					• Filter
					• Details on demand
					• History
					• Extract
					• Link and brush
					• Projection
					• Distortion

[a]Adapted from [14].

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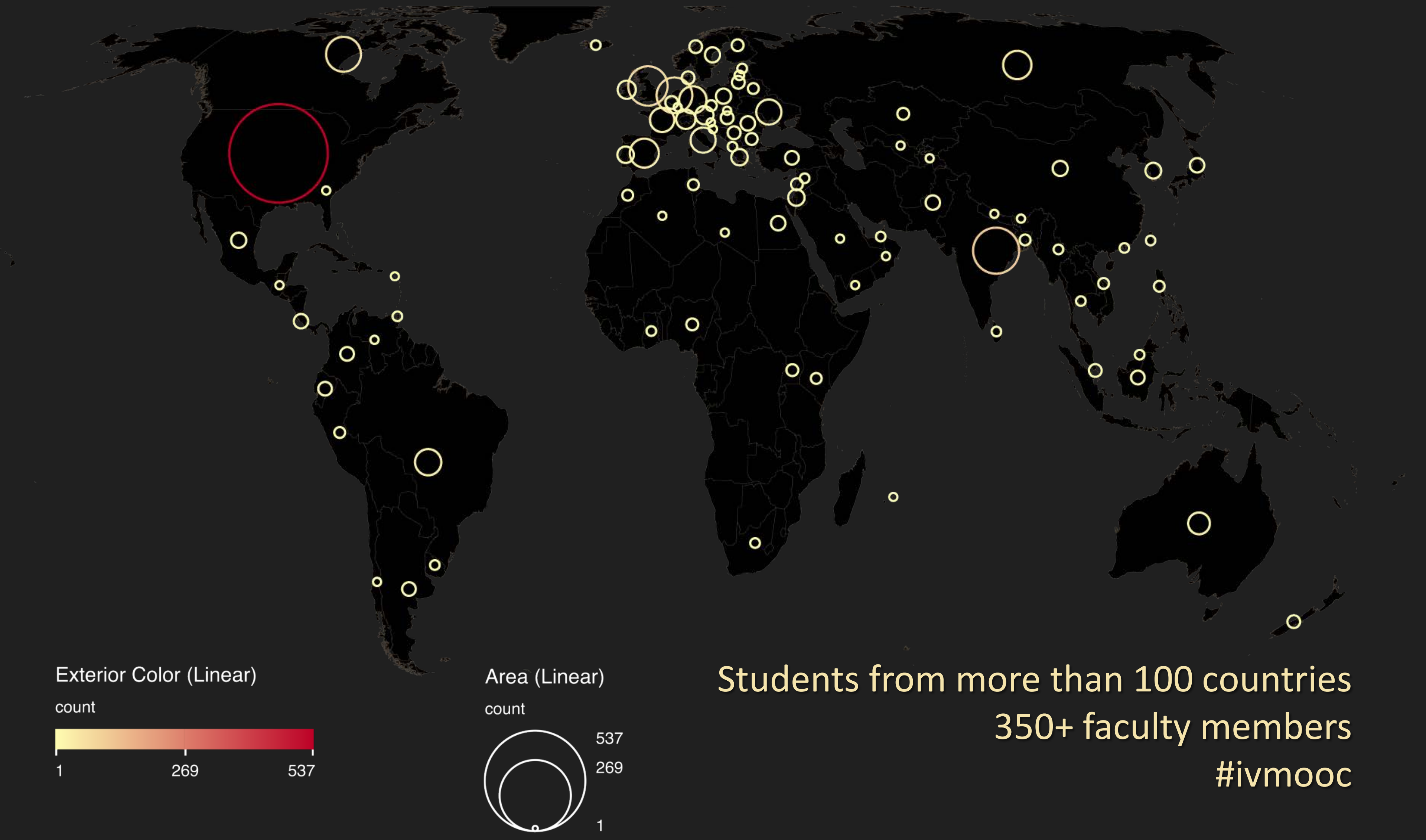

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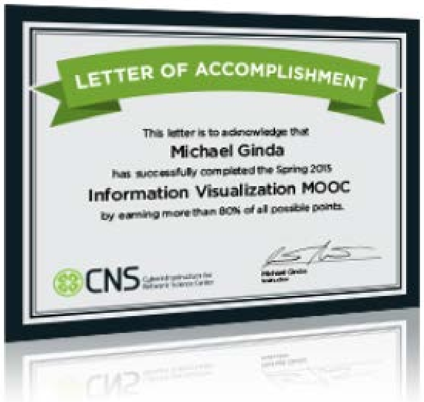
Course Schedule

Part 1: Theory and Hands-On

- **Session 1** – Workflow Design and Visualization Framework
- **Session 2** – “When:” Temporal Data
- **Session 3** – “Where:” Geospatial Data
- **Session 4** – “What:” Topical Data

Mid-Term

- **Session 5** – “With Whom:” Trees
- **Session 6** – “With Whom:” Networks
- **Session 7** – Dynamic Visualizations and Deployment



Final Exam

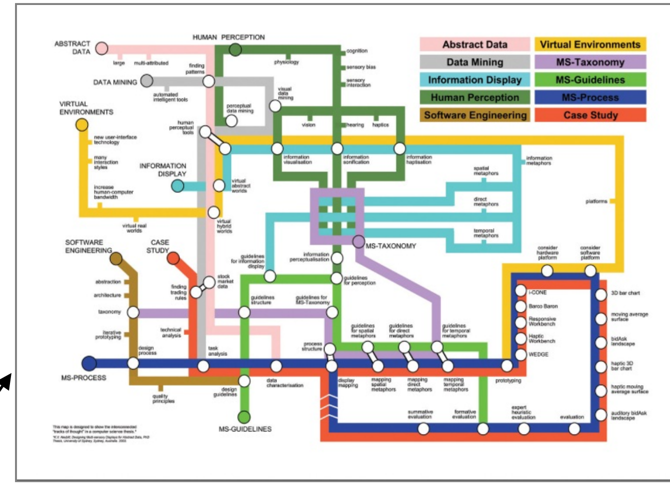
Part 2: Students work in teams on client projects.

Final grade is based on Homework and Quizzes (**10%),** Midterm (**20%**), Final (**30%**), Client Project (**30%**), and Class Participation (**10%**).

Different Question Types

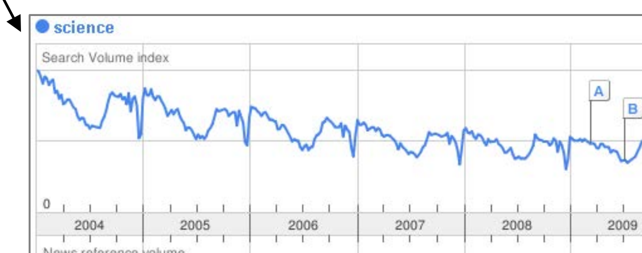
Terabytes of data

Descriptive & Predictive Models



Find your way

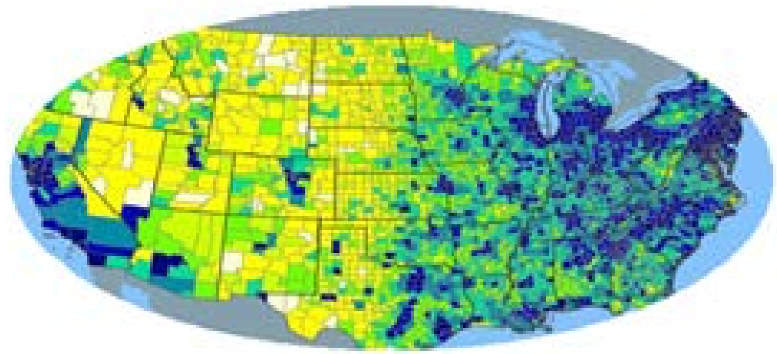
Find collaborators, friends



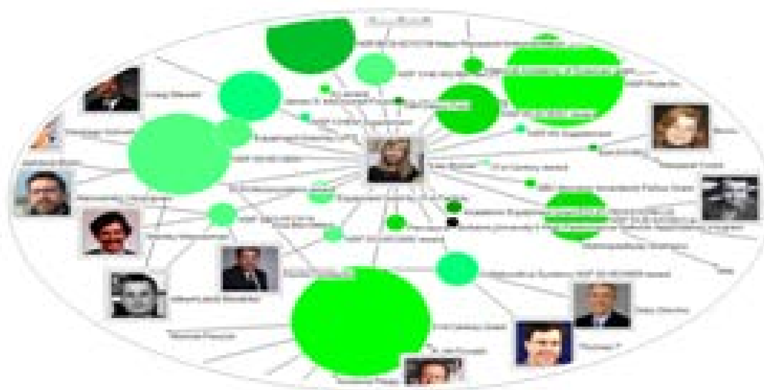
Identify trends

Different Levels of Abstraction/Analysis

Macro/Global
Population Level



Meso/Local
Group Level

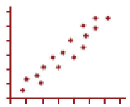
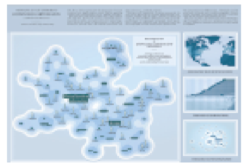
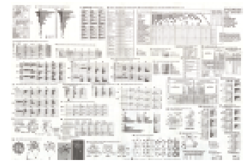
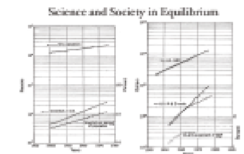
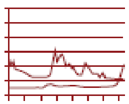
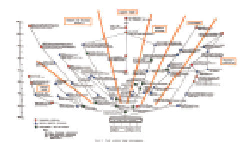
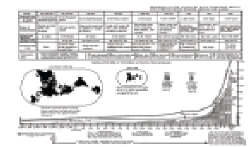
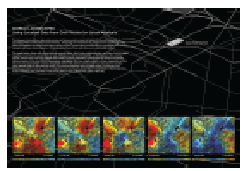
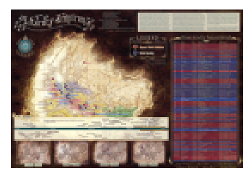
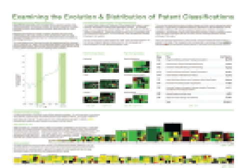
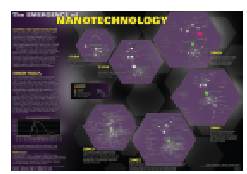
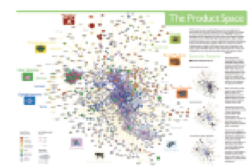
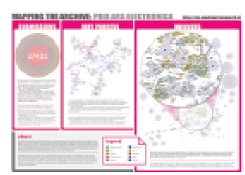


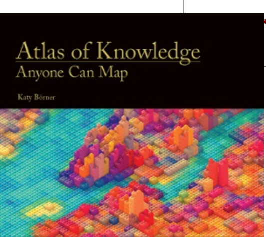
Micro
Individual Level

Tasks

LEVELS

TYPES

TYPES	MICRO: Individual Level about 1–1,000 records page 6 	MESO: Local Level about 1,001–100,000 records page 8 	MACRO: Global Level more than 100,000 records page 10 
Statistical Analysis page 44 	 Knowledge Cartography page 135	 Productivity of Russian life sciences research teams page 105	 Number of scientists versus population and R&D costs versus GNP. page 103
WHEN: Temporal Analysis page 48 	 Visualizing decision-making processes page 95	 Key events in the development of the video tape recorder page 85	 Increased travel and communication speeds page 83
WHERE: Geospatial Analysis page 52 	 Cell phone usage in Milan, Italy page 109	 Victorian poetry in Europe page 137	 Ecological footprint of countries page 99
WHAT: Topical Analysis page 56 	 Evolving patent holdings of Apple Computer, Inc. and Jerome Lemelson page 89	 Evolving journal networks in nanotechnology page 139	 Product space showing co-export patterns of countries page 93
WITH WHOM: Network Analysis page 60 	 World Finance Corporation network page 87	 Electronic and new media art networks page 133	 World-wide scholarly collaboration networks page 157



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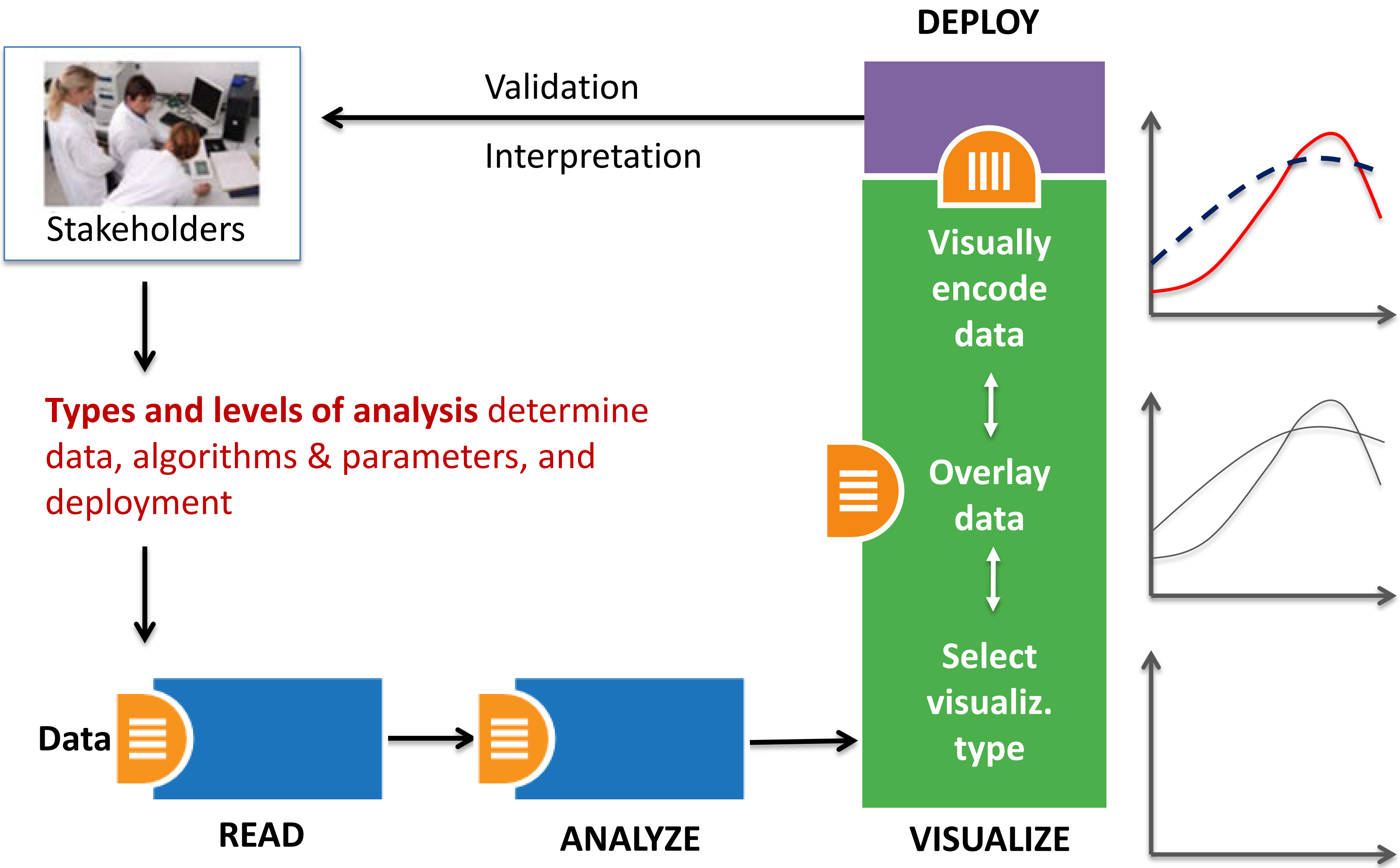
Needs-Driven Workflow Design



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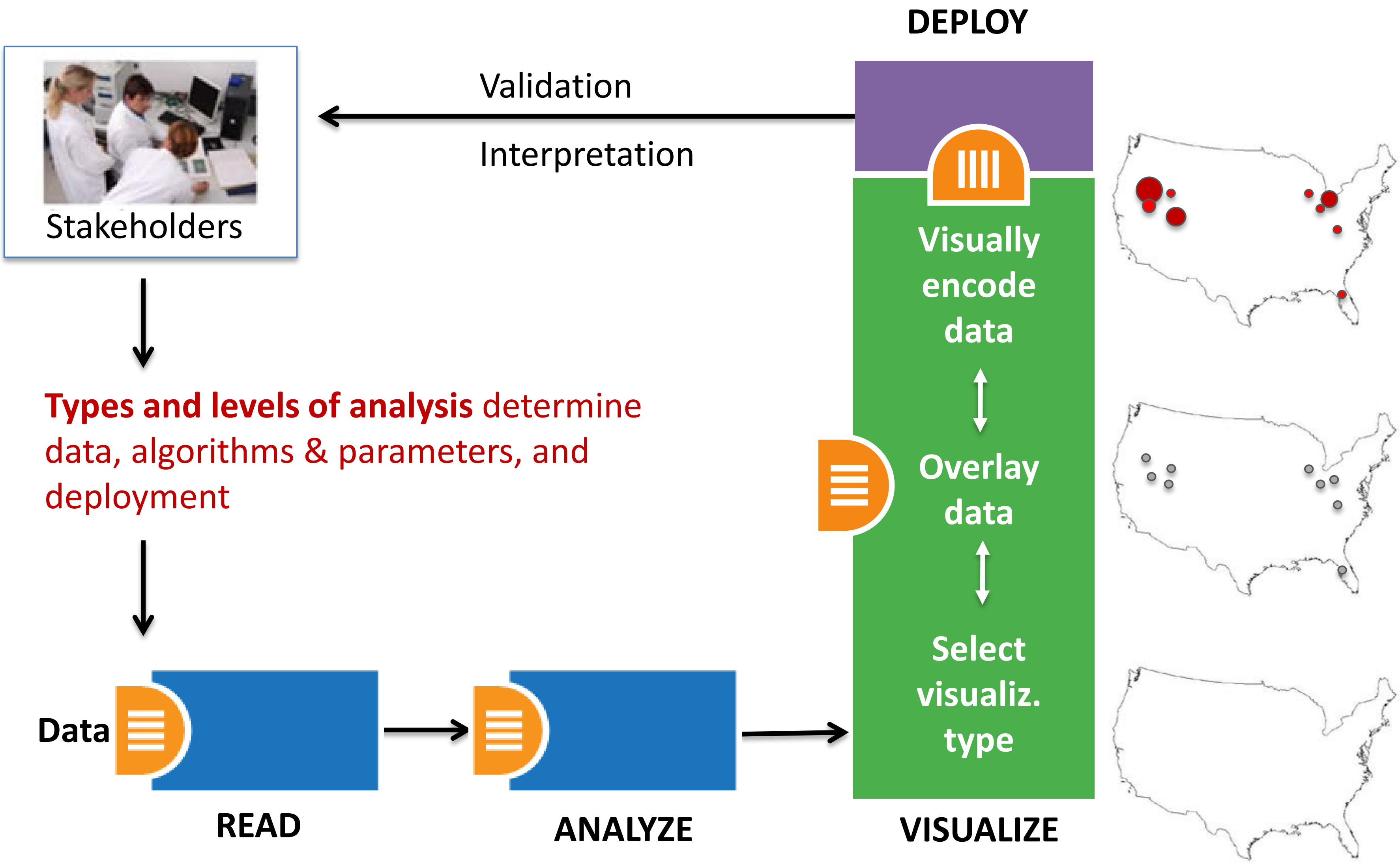

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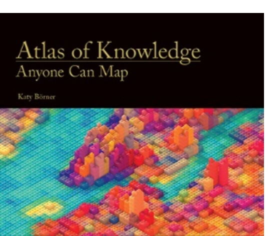
		• Table
		• Chart
		• Graph
		• Map
		• Network layout
			• Geometric symbols
			  • point
			  • line
			  • area
			  • surface
			  • volume
			• Linguistic symbols
			  • text
			  • numerals
			  • punctuation marks
			• Pictorial symbols
			  • images
			  • icons
			  • statistical glyphs
				• Spatial
				  • position (x, y, z)
				• Retinal
				  • form
				  • color
				  • optics
				  • motion
					• Overview
					• Zoom
					• Search and locate
					• Filter
					• Details on demand
					• History
					• Extract
					• Link and brush
					• Projection
					• Distortion

[a]Adapted from [14].

Visualization Framework

Insight Need Types page 26	Data Scale Types page 28	Visualization Types page 30	Graphic Symbol Types page 32	Graphic Variable Types page 34	Interaction Types page 26
• categorize/cluster • order/rank/sort • distributions (also outliers, gaps) • comparisons • trends (process and time) • geospatial • compositions (also of text) • correlations/relationships	• nominal • ordinal • interval • ratio	• table • chart • graph • map • network layout	• geometric symbols point line area surface volume • linguistic symbols text numerals punctuation marks • pictorial symbols images icons statistical glyphs	• spatial position • retinal form color optics motion	• overview • zoom • search and locate • filter • details-on-demand • history • extract • link and brush • projection • distortion



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Visualization Framework

Basic Task Types								
Bertin, 1967	**Wehrend & Lewis, 1996**	**Few, 2004**	**Yau, 2011**	**Rendgen & Wiedemann, 2012**	**Frankel, 2012**	**Tool: Many Eyes**	**Tool: Chart Chooser**	**Börner, 2014**
selection	categorize			category				categorize/ cluster
order	rank	ranking					table	order/rank/ sort
	distribution	distribution					distribution	distributions (also outliers, gaps)
	compare	nominal comparison & deviation	differences		compare and contrast	compare data values	comparison	comparisons
		time series	patterns over time	time	process and time	track rises and falls over time	trend	trends (process and time)
		geospatial	spatial relations	location		generate maps		geospatial
quantity		part-to-whole	proportions		form and structure	see parts of whole, analyze text	composition	compositions (also of text)
association	correlate	correlation	relationships	hierarchy		relations between data points	relationship	correlations/ relationships

Visualization Framework

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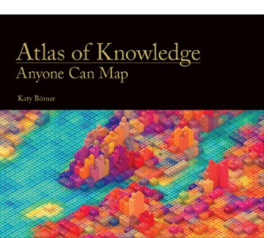
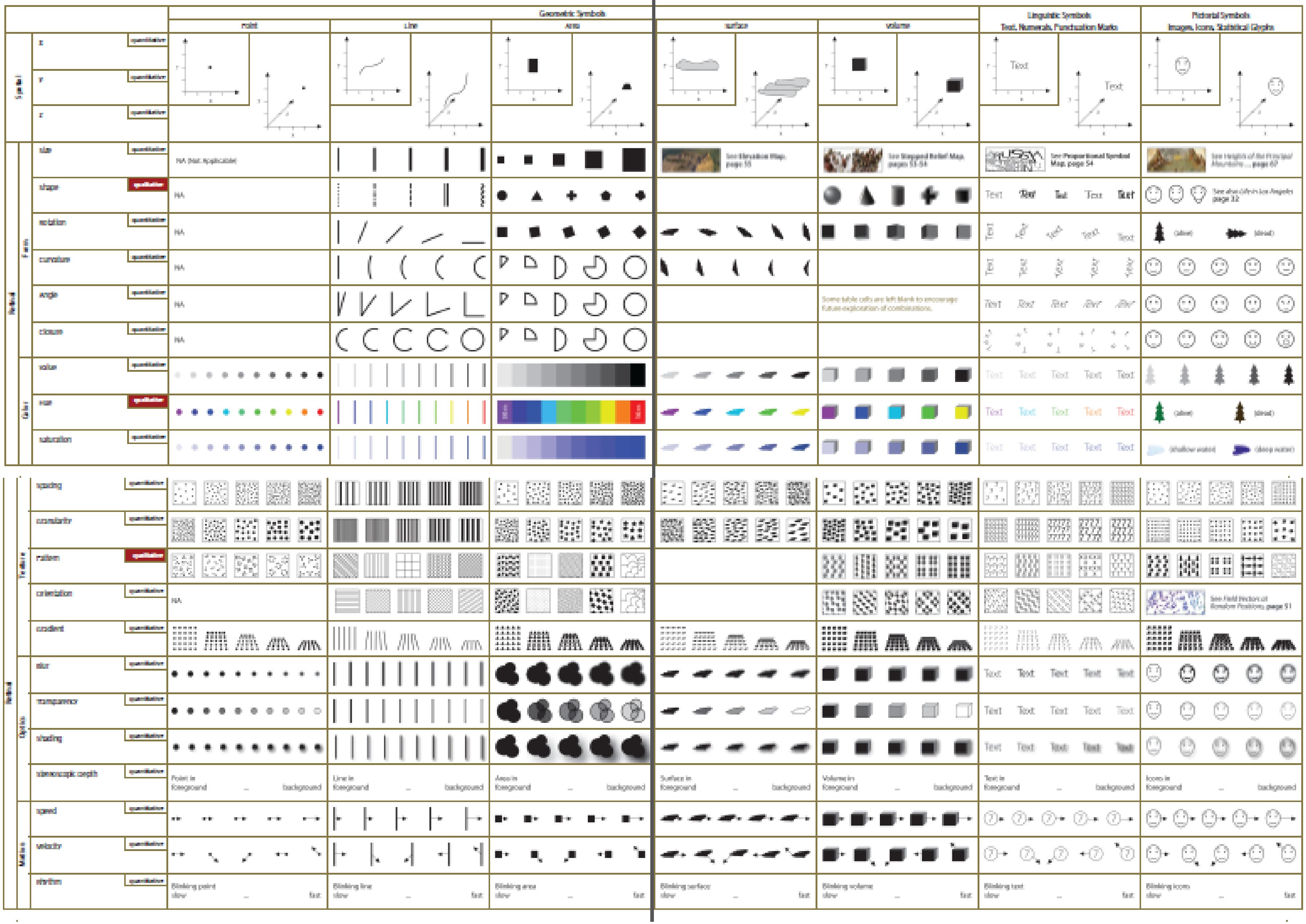


See page 24

Graphic Variable Types Versus Graphic Symbol Types

				Geometric Symbols		
				Point	Line	Area
Spatial		x	quantitative			
		y	quantitative			
		z	quantitative			
Retinal	Form	Size	quantitative	NA (Not Applicable)		
		Shape	qualitative	NA		
		Rotation	quantitative	NA		
		Curvature	quantitative	NA		
		Angle	quantitative	NA		
		Closure	quantitative	NA		
	Color	Value	quantitative			
		Hue	qualitative			380 nm … 780 nm
		Saturation	quantitative			

Graphic Variable Types Versus Graphic Symbol Types



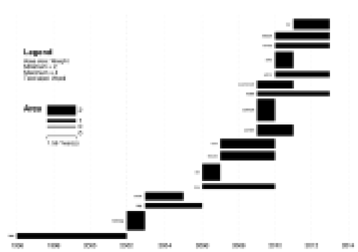
Load **One** File and Run **Many** Analyses and Visualizations

Times Cited	Publication Year	City of Publisher	Country	Journal Title (Full)	Title	Subject Category	Authors
12	2011	NEW YORK	USA	COMMUNICATIONS OF THE ACM	Plug-and-Play Macroscopes	Computer Science	Borner, K
18	2010	MALDEN	USA	CTS-CLINICAL AND TRANSLATIONAL SCIENCE	Advancing the Science of Team Science	Research & Experimental Medicine	Falk-Krzesinski, HJ|Borner, K|Contractor, N|Fiore, SM|Hall, KL|Keyton, J|Spring, B|Stokols, D|Trochim, W|Uzzi, B
13	2010	WASHINGTON	USA	SCIENCE TRANSLATIONAL MEDICINE	A Multi-Level Systems Perspective for the Science of Team Science	Cell Biology |Research & Experimental Medicine	Borner, K|Contractor, N|Falk-Krzesinski, HJ|Fiore, SM|Hall, KL|Keyton, J|Spring, B|Stokols, D|Trochim, W|Uzzi, B

Statistical Analysis—p. 44

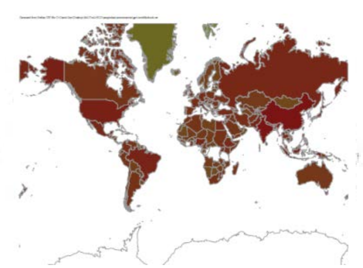
Location	*Count*	*# Citations*
Netherlands	13	292
United States	9	318
Germany	11	36
United Kingdom	1	2

Temporal Burst Analysis—p. 48



Geospatial Analysis—p. 52

Geospatial Analysis—p. 52



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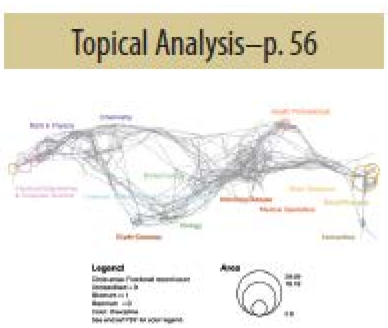
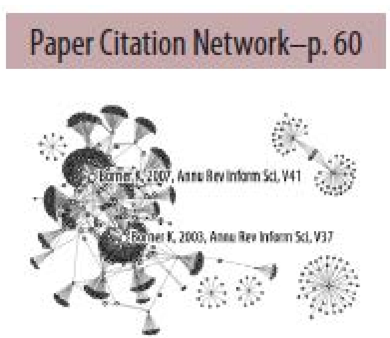
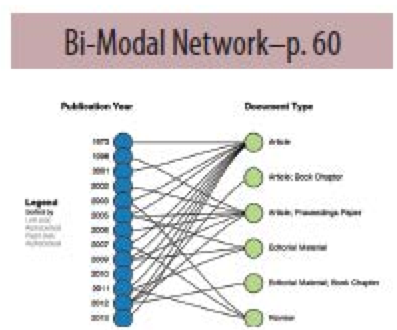
13	2010	WASHINGTON	USA	SCIENCE TRANSLATIONAL MEDICINE	A Multi-Level Systems Perspective for the Science of Team Science	Cell Biology |Research & Experimental Medicine	Borner, K|Contractor, N|Falk-Krzesinski, HJ|Fiore, SM|Hall, KL|Keyton, J|Spring, B|Stokols, D|Trochim, W|Uzzi, B







Co-author and many other bi-modal networks.

Table 1. Recommendations for visualization practices and examples from neuroscience

Recommendation	Examples
1. Devote a substantial amount of research time to creating illustrative visualizations; view visualizations not as superficial depictions of scientific understandings, but as devices for generating and communicating understandings	If you only have 60 h to do your research, spend 20 h collecting data, 20 h analyzing data, and 20 h finding the best visualization and communication method for your data analysis results
2. Consider the audience for, and purpose of, a visualization	More details for experts and exploration, but fewer details for novices and communication; display intact cortical surface for spatial fidelity, but inflate or explode surface to provide global overview of entire surface
3. Show uncertainty in visualizations	Depict uncertainty in data with error bars, opacity, saturation, thickness, ranges rather than points, and distributions rather than central tendencies
4. Use strategic simplifications and idealizations	Bundle together tracts or connectivity paths (Figure 1A, main text) to avoid overcomplicated networks; align multiple brains or trials and show their overlap by brightness, opacity, or size; display complex connectivity patterns with 2D matrices; further simplify connectivity matrices with multidimensional scaling; use latent factor methods (MDS, PCA, ICA, factor analysis, hidden Markov models, Expectation Maximization) to compress high-dimensional data sets
5. Show all critical information	Use exploded brain diagrams to show entire cortical surface without occlusion; translucency; projection of brain activity onto panels; be explicit about the conventions and tools used; user-controlled rotation
6. Align graphic symbol types and graphic variable types with data scale types to be visualized and the insight needs to be satisfied	Represent continuous dimensions by saturation, size, or position on x-axis; represent categorical dimensions by shape or color hue; use time in animation to represent time since stimulus onset; represent positive EEG voltages by displacement above, not below, a horizontal midline
7. Carefully consider how best to align data from different trials, brains, stimuli, and studies	Consider aligning brains by cortical surface and anatomical anchor points rather than volumetric coordinates; use multidimensional scaling techniques to establish second-order relational similarities between stimuli
8. Create and use interactive visualization tools that support exploratory data analysis and show how complex data unfold over time	Relevant tools include mrTools, Vistasoft, Brain Voyager, Explore DTI, Camino, FreeSurfer, PyCortex, MRI Studio, AFNI, BrainBrowser, BrainVisa, EEGLab, DSI Studio, Caret, VTK, Dipy, FLS, IPython. Connectome Visualization Utility, TrackVis, LONI, Neuroimagery that can be scanned, rotated, and scaled; user-controlled overlays on top of a base map; user-controlled animations representing brain activity over time
9. Establish infrastructures that allow for sharing of data, analysis methods, visualization algorithms, and experimental methods in support of replicable results and efficient research and training	Use Flickr to share brain imaging data and visualizations, GitHub to share code, Medline to share results, open journals such as *Scientific Data* to share data and workflows

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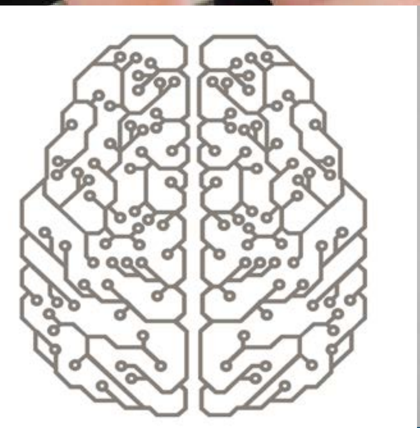

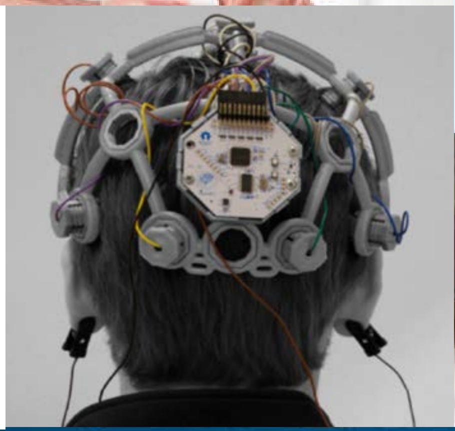

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