

The Fundamental Principles of Analytical Design

Categories such as time, space, cause, and number represent the most general relations which exist between things; surpassing all our other ideas in extension, they dominate all the details of our intellectual life. If humankind did not agree upon these essential ideas at every moment, if they did not have the same conception of time, space, cause, and number, all contact between their minds would be impossible. . . .

Émile Durkheim, *Les formes élémentaires de la vie religieuse*
(Paris, 1912), 22–23.

I do not paint things, I paint only the differences between things.

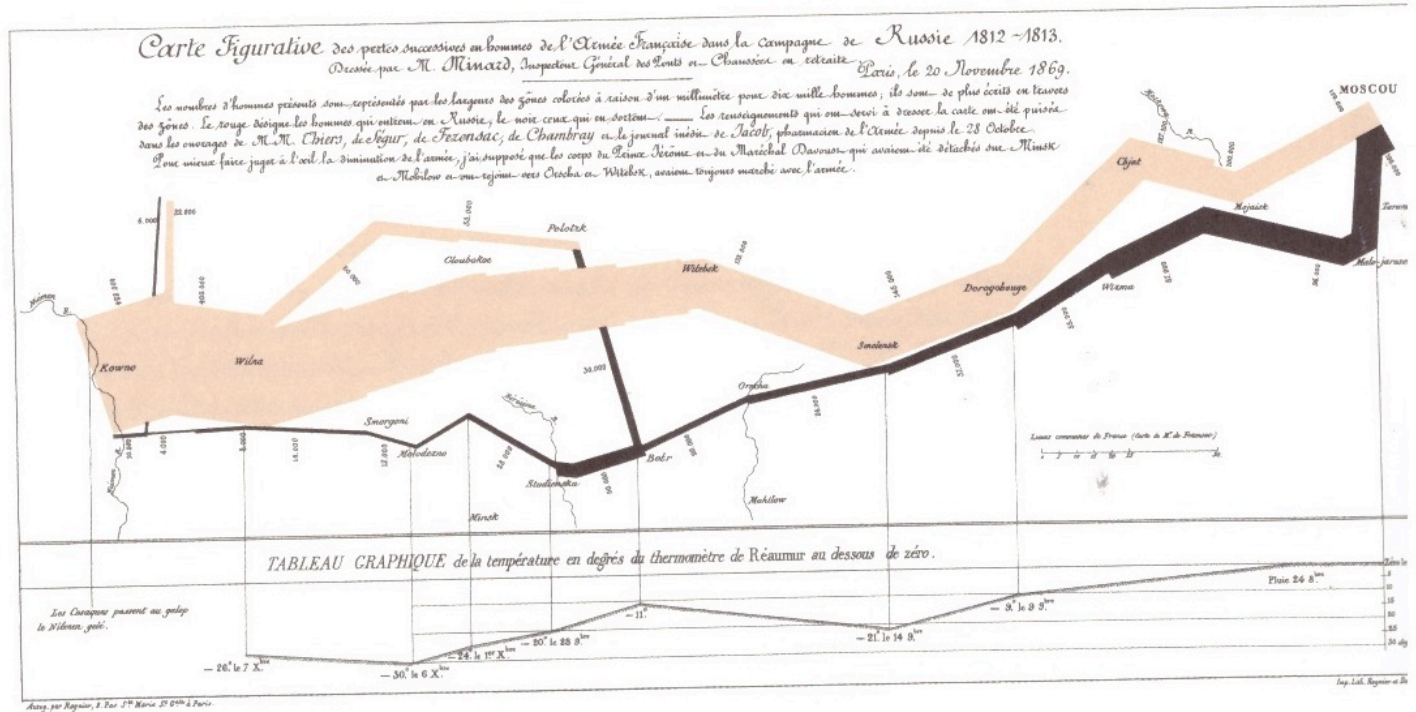
Henri Matisse, *Henri Matisse Dessins: thèmes et variations*
(Paris, 1943), 37.

EXCELLENT graphics exemplify the deep fundamental principles of analytical design in action. If this were not the case, then something might well be wrong with the principles.

Charles Joseph Minard's data-map describes the successive losses in men of the French army during the French invasion of Russia in 1812. Vivid historical content and brilliant design combine to make this one of the best statistical graphics ever. Carefully study Minard's graphic, shown in our English translation at right. A title announces the design method (figurative map) and subject (what befell the French army in Russia). Minard identifies himself and provides a credential. A paragraph of text explains the color code, the 3 scales of measurement, and the methods. Five data sources are acknowledged.

Then the Russian campaign of 1812–1813 begins.

At right, English translation of item 28 in Charles Joseph Minard, *Tableaux Graphiques et Cartes Figuratives de M. Minard, 1845–1869*, a portfolio of Minard's statistical maps at the Bibliothèque de l'École Nationale des Ponts et Chaussées, Paris, 62 × 30 cm, or 25 × 12 in. This 1869 map is the last sheet in Minard's lifetime portfolio. English translation by Dawn Finley, redrawing by Elaine Morse.



Above, the original French version. This statistical map portrays the successive losses of the French Army in Napoleon’s Russian campaign of 1812. The overall toll, French and Russian, was approximately 700,000 to 1,000,000. Described by E. J. Marey as seeming to defy the pen of the historian by its brutal eloquence,¹ Minard’s map exemplifies many of the fundamental principles of analytical design.

Principle 1: Comparisons

Beginning at the left, on the Polish-Russian border near the Nieman River, the thick tan line shows the size of the Grand Army (422,000 men, drawn from all Europe) as it invaded Russia in June 1812, as well as the army’s path. As the soldiers die, the line narrows; the flow-line indicates the number of remaining soldiers at each position on the map. Also shown are movements of auxiliary troops, who sought to protect the rear and flank of the advancing army.

In September, the 100,000 surviving troops reached Moscow, which was by then sacked, deserted, on fire. The departure from Moscow is depicted by the dark lower line, in turn linked to a temperature scale and dates in the statistical graphic at the bottom of the chart. During the retreat, it was bitterly cold and many soldiers froze and starved. Crossing back over the Nieman River with 10,000 survivors, the army struggled out of Russia. At the end, the map notes: “The Cossacks [Russian horsemen] pass the frozen Niemen at a gallop,” driving out the scattered remnants of Napoleon’s Grand Army.

¹ E. J. Marey, *La méthode graphique dans les sciences expérimentales* (Paris, 1878), 73: “Toujours il arrive à des effets saisissants, mais nulle part la représentation graphique de la marche des armées n’atteint ce degré de brutale éloquence qui semble défier la plume de l’historien.”

Les Cosaques passent au galop le Niémen gelé.

And it is at the Nieman River, where the invasion began and ended, that we see a small but poignant illustration of the *First Principle for the analysis and presentation of data*:

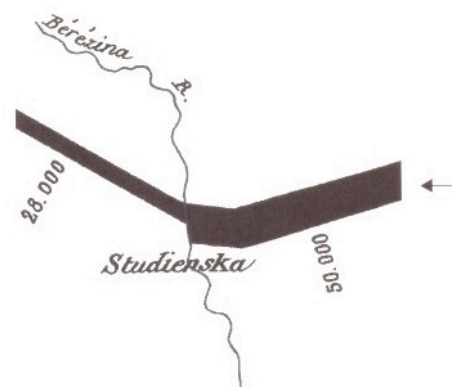
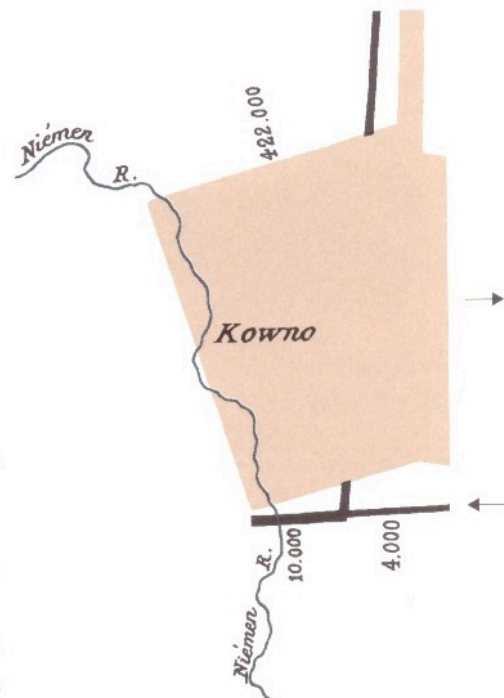
Show comparisons, contrasts, differences.

The fundamental analytical act in statistical reasoning is to answer the question “Compared with what?” Whether we are evaluating changes over space or time, searching big data bases, adjusting and controlling for variables, designing experiments, specifying multiple regressions, or doing just about any kind of evidence-based reasoning, the essential point is to make intelligent and appropriate comparisons. Thus visual displays, if they are to assist thinking, should show comparisons.

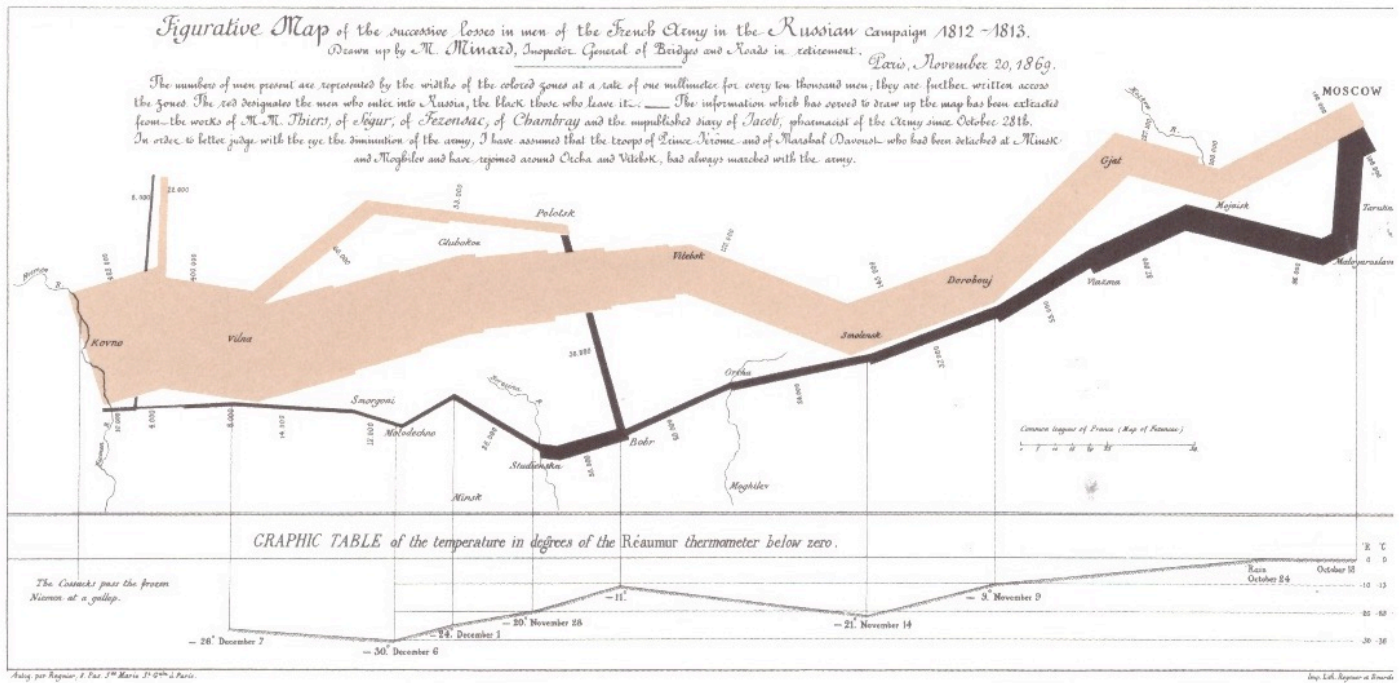
Minard makes several vivid comparisons, some over many months, others during the course of a few days. At the war’s beginning, the army crossed the Nieman River with 422,000 soldiers, shown by the number itself and represented by the width of the tan line. At the end, 10,000 soldiers returned back across the Nieman, as indicated by the number itself and the thin black line concluding the retreat. Only 1 soldier in 42 survived this futile campaign (the widths of the black /tan lines at the Nieman River were inaccurately constructed in a ratio of 1 to 28). This graphic comparison at the Nieman summarizes the slaughter, 6 months from start to finish.

At the Berezina River, another comparison. During the retreat (westward, to the left), the black line crossing the river abruptly diminishes—from 50,000 to 28,000 soldiers, as 22,000 died in 2 days. This change in line weight represents, in a blunt and incomplete way, the terrible events at the Berezina, described by Philippe-Paul de Ségur (*aide de camp* to Napoleon, and a source cited by Minard):

It was the twenty-eighth of November. The Grand Army had had two whole days and nights in which to effect the crossing, and it should have been too late for the Russians to do any harm. But chaos reigned in our midst... an immense confused mass of men, horses, and vehicles besieged the narrow entrances to the bridges and began to flow over them. Those in front, pushed by the weight of those behind or halted by the river, were crushed, trampled on, or forced into the ice-filled water of the Berezina. From the horrible, formless mob there arose a sort of dull murmur which swelled at times to a wild clamor mingled with groans and awful imprecations... The confusion was so great that when Napoleon himself wished to cross at two o’clock, it was necessary to use force to clear a passage for him... Then, as in all extreme situations, hearts were laid bare, and both infamous and sublime actions were witnessed. Some there were who, determined to pass at all costs, cut a horrible way for themselves with their swords. Others opened an even crueler road for their carriages, driving them pitilessly through the helpless crowd, crushing men and women, in their odious greed sacrificing their companions in misery to save their possessions.²



² Count Philippe-Paul de Ségur, *Napoleon’s Russian Campaign* (New York, 1958), 246, 249; translated by J. David Townsend from *Campagne de Russie, Mémoires d’un Aide de Camp de Napoléon* (Paris, 1824).



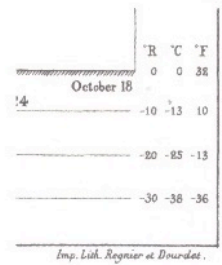
Principle 2: Causality, Mechanism, Structure, Explanation

How did nearly everyone in the Grand Army die? The mapped routes of invasion/retreat show the *location* of the bad news but do not explain what *caused* the deaths. Yet often the reason that we examine evidence is to understand causality, mechanism, dynamics, process, or systematic structure. Scientific research involves causal thinking, for Nature’s laws are causal laws. Medical analysis—prevention, diagnosis, intervention—requires causal analysis. Reasoning about reforms and making decisions also demands causal logic. To produce the desired effects, we need to know about and govern the causes; thus “policy-thinking is and must be causality-thinking.”³

Simply collecting data may provoke thoughts about cause and effect: measurements are inherently comparative, and comparisons promptly lead to reasoning about various sources of differences and variability. A vivid statement about epidemiological evidence by the distinguished medical pathologist Rudolf Virchow exemplifies this logic: “Medical statistics will be our standard of measurement: we will weigh life for life and see where the dead lie thicker, among the workers or among the privileged.”⁴

Principles of design should attend to the fundamental intellectual tasks in the analysis of evidence; thus we have the *Second Principle for the analysis and presentation of data*:

Show causality, mechanism, explanation, systematic structure.



³ Robert A. Dahl, “Cause and Effect in the Study of Politics,” in Daniel Lerner, *Cause and Effect* (New York, 1965), 88.

⁴ Rudolf Virchow, *Die Medizinische Reform* (Berlin, 1848), no. 1, 182; as quoted in Paul Farmer, *Infections and Inequalities: The Modern Plagues* (Berkeley, 1999), 1.

Minard depicted a possible causal variable by means of a graph of temperatures during the retreat—for Napoleon was defeated not only by the Russian Army but also by General Winter. Temperature is measured on a Réaumur scale, with the freezing point of water equated to 0° and boiling point of water to 80°. This is converted to the nearly universal Celsius (0° and 100°) and to Fahrenheit (32° and 212°) in scales on our English translation of Minard's graphic at left. Note that the scale starts at freezing; the *warmest* reading is 0°C or 32°F. It was very cold in Russia during November and December of 1812. The statistical graphic then brings in an another variable, *time*. Each temperature during the retreat is dated, from the rainy October departure from Moscow to the bitter cold on December 7th near the end.

The map's causal analysis is thin, merely a reminder of intense cold. Although the path of the retreating army loosely parallels the line of falling temperatures, this symbolic parallelism has no evidential value. The link between very cold temperatures and deaths is, however, made explicit in Minard's 5 historical sources that contain eye-witness accounts of the ghastly frozen soldiers. And in the striking visual-quantitative imagery of Victor Hugo's poem *L'Expiation* (at right) describing the retreat from Moscow.

*Snow, in what was left of the city behind them,
drifted into the smoke and flames.
In their retreat, the army did not know
one white field from another,
or the left flank from the right or center.
Ensigns whited out, the voices of commanders
lost, what had been an army was a herd. . . .*

*The sky made turbid snow,
over the largest army ever,
an immeasurable shroud. Each of the soldiers fell
alone, struck by raiding troops,
or by the deadlier North.
They junked the cannon to burn the carriage.
Whoever slept for a moment died. The wasteland
swallowed them whole, regiments at a time,
visible now, where they lay down to rest,
as undulations in the anonymous snow.
Fugitives, wounded men, and dying,
in caissons, stretchers, and sleds, overloading
the bridges, falling asleep by the ten thousand,
woke up, hundreds, or less.*

Selected Poems by Victor Hugo (New York, 2002), 14–17, translated by Brooks Haxton.

Principle 3: Multivariate Analysis

Minard delineates the war of 1812 by means of 6 variables: the *size* of the army, its *two-dimensional location* (latitude and longitude), the *direction* of the army's movement, and *temperature* on various *dates* during the retreat from Moscow. These 6 dimensions are shown with distinct clarity. There is no instruction manual, nor a jargon fog about a spatial-temporal hyper-space focus group executive dashboard web-based keystone methodology. Instead it is *War and Peace* as told by a visual Tolstoy.

Accounts of Napoleon's invasion of Russia are *multivariate* (that is, involving 3 or more variables). How could it be otherwise? Nearly all the interesting worlds (physical, biological, imaginary, human) we seek to understand are inevitably multivariate in nature. Simple navigational instructions reflect up to 4 dimensions, describing routes through the 3-space in which we live over the 4th dimension, time. Current-day cosmological theories claim an 11-dimensional universe. The analysis of cause and effect, initially bivariate, quickly becomes multivariate through such necessary elaborations as the conditions under which the causal relation holds, interaction effects, multiple causes, multiple effects, causal sequences, sources of bias, spurious correlation, sources of measurement error, competing variables, and whether the alleged cause is merely a proxy or a marker variable.⁵

⁵ On multivariate subtleties of evidence for causality, Austin Bradford Hill, "The Environment and Disease: Association or Causation?," *Proceedings of the Royal Society of Medicine*, 58 (1965), 295–300; posted at www.edwardtufte.com

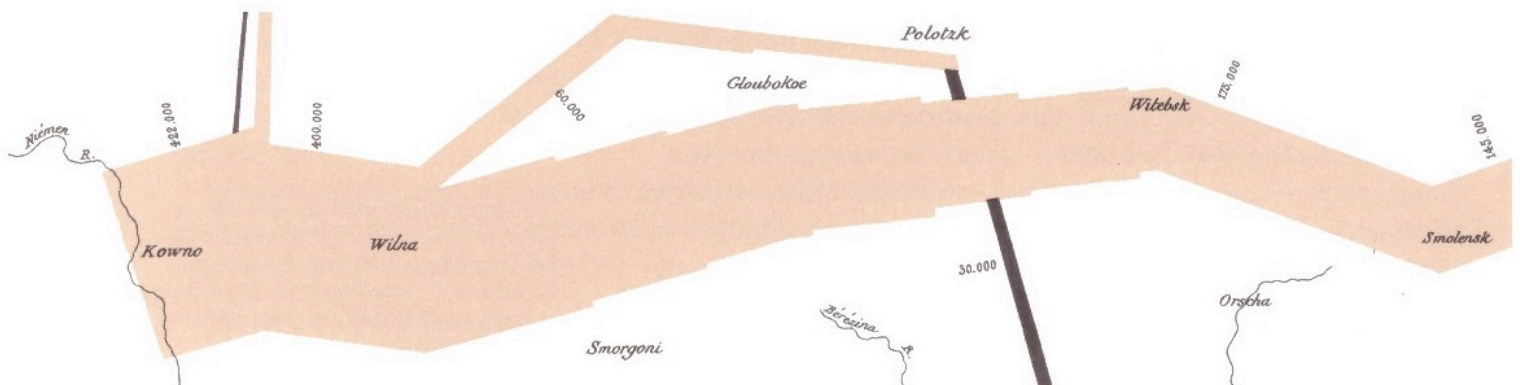
The only thing that is 2-dimensional about evidence is the physical flatland of paper and computer screen. Flatland technologies of display encourage flatland thinking. Reasoning about evidence should not be stuck in 2 dimensions, for the world we seek to understand is profoundly multivariate. Strategies of design should make multivariateness routine, nothing out of the ordinary. To think multivariate, show multivariate; the *Third Principle for the analysis and presentation of data*:

Show multivariate data; that is, show more than 1 or 2 variables.

Principle 4: Integration of Evidence

Minard brings together various modes of information in order to describe troop movements and the war's consequences: a paragraph of words, a map with narrating flow-lines, and a statistical graphic dangling from the map. In particular, at the Nieman River where the invasion began and ended, these modes of information are simultaneously mobilized: the number of troops before and after the campaign, mapped flow-lines moving in 2-space, temperature and dates, and the mocking words describing the Cossack horsemen. Contrast this graceful integration with books where all the images are collected into one big pile, printed and positioned far from their relevant text. Or those awful reports consisting entirely of words, except for all the data tables segregated and appended at the back, in organizational and intellectual disarray. Or computer applications that deal with only one type of information at a time. The evidence doesn't care what it is—whether word, number, image. In reasoning about substantive problems, what matters entirely is the *evidence*, not *particular modes* of evidence.

To integrate word and diagram, Minard uses a light unsaturated tan color to depict the invasion flow-line, which allows the place-names to show through. The tan's transparency has little visual effect on the typography for the place-names inside the flow-line, so those names belong with names *outside* the flowline, maintaining the map's surface



coherence as the army passes over the land.⁶ In 20 different figurative maps, Minard uses transparent overlays to combine words, numbers, and flow-maps within a common visual field. Cartographers have long used this technique of layering and separation, which can increase the informational depth of flatland by additional dimensions and possibly by several multiples of data density.

Words, numbers, pictures, diagrams, graphics, charts, tables belong together. Excellent maps, which are the heart and soul of good practices in analytical graphics, routinely integrate words, numbers, line-art, grids, measurement scales. Rarely is a distinction among the different modes of evidence useful for making sound inferences. It is all information after all. Thus the *Fourth Principle for the analysis and presentation of data*:

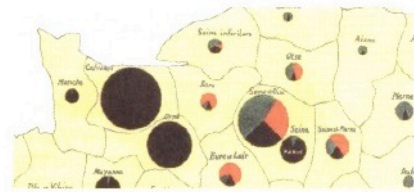
Completely integrate words, numbers, images, diagrams.

Thus tables of data might be thought of as paragraphs of numbers, tightly integrated with the text for convenience of reading rather than segregated at the back of a report. Most images and tables used in public presentations should be annotated with words explaining what is going on. In exploratory data analysis, however, the integration of evidence needs to be thought through. Perhaps the numbers or data points may stand alone for a while, so we can get a clean look at the data, although techniques of layering and separation may simultaneously allow a clean look as well as bringing other information into the scene.

More generally, the principle of information integration points to a philosophy of inquiry: a broad, pluralistic, problem-directed view of what constitutes the scope of relevant evidence. Too often in scholarly research, in social science at least, there is a certain narrowness in the choice and use of evidence. Thus many investigations of, say, political economy rely exclusively on a *single* mode of evidence: statistical data, or wordy memoirs of policy-makers, or anecdotes, or mathematical models, or metaphor, or economic or political ideology, or newspaper clippings. Research questions are framed along the lines of “How can one type of information or one particular approach be used to explain something?” rather than “How can something be explained?”⁷

Pre-specifying the mode of relevant information or the explanatory method may produce a tendentious misalignment of evidence in relation to substantive matters under investigation. The world to be explained is indifferent to scholarly specialization by type of evidence, methodology, or disciplinary field. A deeper understanding of human behavior may well result from integrating a diversity of evidence, *whatever it takes to explain something*. Like good information displays, explanatory investigations, if they are to be honest and genuine, must seek out and present all relevant evidence regardless of mode.

⁶ The text accompanying the map describes the invasion line as *rouge* or red. It appears the line never was red, even when freshly printed in 1869. Although red pigments are degraded by light, Minard’s maps are in fact bound in a non-circulating portfolio with no light exposure at the Bibliothèque de l’École Nationale des Ponts et Chaussées. Today the invasion-line color is as exactly as shown in this chapter (confirmed by color control bars in our direct photograph of Minard’s original map), with no signs of color fading. In another map by Minard (below), bright red ink has now survived 148 years, again suggesting that today’s tan invasion line was not yesterday’s *rouge*:



Detail from Charles Joseph Minard, *Carte figurative et approximative des quantités de viandes de boucherie envoyées sur pied par les départements et consommées à Paris*, 1858.

⁷ See Donald P. Green and Ian Shapiro, *Pathologies of Rational Choice Theory* (New Haven, 1996). Amusing parodies of a *priori* method-driven approaches are found in C. Wright Mills, *The Sociological Imagination* (New York, 1959) on the social sciences; Frederick C. Crews, *The Pooh Perplex* (New York, 1963) and *Postmodern Pooh* (New York, 2001) on literary criticism; *The Sokal Hoax*, compiled by the editors of *Lingua Franca* (Lincoln, Nebraska, 2000) on literary-sociological studies of science.

Principle 5: Documentation

The credibility of an evidence presentation depends significantly on the quality and integrity of the authors and their data sources. Documentation is an essential mechanism of quality control for displays of evidence. Thus authors must be named, sponsors revealed, their interests and agendas unveiled, sources described, scales labeled, details enumerated. Thorough documentation is a good sign that a report was constructed with at least some care and craft.

Minard documents his data-map of Napoleon's Russian campaign at a level of detail remarkable for 19th-century graphics and in ways appropriate to nearly all visual presentations of information:

What is the display about? Losses in men of the French Army in the Russian Campaign 1812-1813.

Who did the work? Drawn up by M. Minard

Who's that? Inspector General of Bridges and Roads in retirement.

Where and when was the work done? Paris, November 20, 1869.

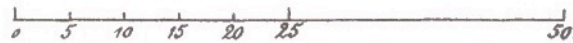
What are the data sources? The information which has served to draw up the map has been extracted from the works of M. M. Thiers, of Ségur, of Fezensac, of Chambray and the unpublished diary of Jacob, the pharmacist of the Army since October 28th.

Any assumptions? In order to better judge with the eye the diminution of the army, I have assumed that the troops of Prince Jérôme and of Marshal Davoust who had been detached at Minsk and Moghilev and have rejoined around Orcha and Vitebsk, had always marched with the army.

What are the scales of measurement?

for invasion and retreat flow-lines: one millimeter for every ten thousand men

for the underlying map: Common leagues of France (Map of Fezensac)



The French "lieue" is of variable length, approximately 2.5 miles or 4 kilometers (historically varying by up to 10%).

for the temperature: degrees of the Réaumur thermometer below zero

Who published and printed the work? Autog. par Regnier, 8. Pas. S^{te} Marie S^t G^{air} à Paris. Imp. Lith. Regnier et Dourdet.

Publicly attributed authorship indicates to readers that someone is taking responsibility for the analysis; conversely, the absence of names signals an evasion of responsibility. Readers can follow up and communicate with named sources. Also, names may have reputations for credibility—or not.

Authorship credit is to often absent from corporate and government reports; we should remember that *people* do things, not agencies, bureaus, departments, divisions. People may do better work when they receive public acknowledgement and take public responsibility for their work. The good Minard put his name on nearly all his work and personally signed with pen and ink (at right) some of the figurative maps.

Displays should name their data sources. Minard names 5 sources.⁸ Information comes from somewhere; the audience should be told where. Undocumented displays are inherently suspect. For example, opaque, vague, and undocumented accounting statements are leading indicators of financial corruption.

Data graphics are data graphics because they have *scales of measurement*. Viewers should be told about measurements. Minard provides 3 scales. Many modern graphics are undocumented: in 13 computer-science books on technical visualizations, only 20% of the published images had complete scales and labels, 60% had *no* scales or labeled dimensions at all.⁹ Even in real science, images sometimes forget about measurement scales: the astronomical pictures from the Hubble Space Telescope are usually published without indications of distance, size, or location. In business and financial displays, the common errors and lies involve corrupt measurement scales: absence of labels, undefined or imprecise measurements, tendentiously chosen base-years, excessively short time-series, inflated rather than inflation-adjusted monetary units, and time-shifting of data (such as the notorious premature revenue recognition).

Finally, for many presentations, there are issues of research integrity provoked by financial sponsorship, advocacy position, and potential conflicts of interest. Students of bureaucracy have long noted that where people stand depends upon where they sit. In medical research, the published findings are too often predictably related to the interests of the financial sponsors of the research. To assess the credibility of a report, the audience must know who paid for the study, why they paid for it, and possible conflicts of interest of the authors. High-quality medical journals now require from authors a detailed statement about financial sponsorship and possible conflicts of interest, which is then published along with the research article.¹⁰ Public documentation of sponsorship will not end corrupt presentations, but at least it alerts everyone to possibilities of bias. As J. P. Donleavy said about expecting fair play in high places: "You'll get it if enough folk are watching."¹¹

Documentation allows more effective watching, and we have the *Fifth Principle for the analysis and presentation of data*:

Thoroughly describe the evidence. Provide a detailed title, indicate the authors and sponsors, document the data sources, show complete measurement scales, point out relevant issues.

représentées par des zones maritimes vertes entre des lignes
et dont les largeurs indiquent les tonnages d'après l'Echelle.

Paris, le 14 Juillet 1855.

Ch. J. Minard

Detail from *Carte figurative et approximative de céréales qui ont circulé en 1853 sur les voies d'eau et de fer de l'Empire français*, 1855.

⁸ Minard provides last names; his 5 sources are very likely Adolphe Thiers, *Histoire du Consulat et de l'Empire* (Paris, 1862); Philippe-Paul de Ségur, *Campagne de Russie, Mémoires d'un Aide de Camp de Napoléon* (Paris, 1824); M. de Fezensac, *Journal de la campagne de Russie en 1812* (Paris, 1849) and *Souvenirs militaires* (Paris, 1863); Georges, Marquis de Chambray (anonymously published) *Histoire de l'expédition de Russie* (Paris, 1823); Pierre-Irénée Jacob's long unpublished journal, which eventually appeared in *Revue d'Histoire de la Pharmacie*, XVIII (1966), numbers 189-191.

⁹ Data in Edward Tufte, *Visual Explanations* (Cheshire, Connecticut, 1997), 21-25.

¹⁰ For example, this statement below from Wayne A. Ray, *et al.*, "COX-2 selective non-steroidal anti-inflammatory drugs and risk of serious coronary heart disease," *The Lancet*, 360 (October 5, 2002), 1073:

Contributors

W. A. Ray, M. R. Griffin, C. M. Stein, and P. G. Arbogast designed the study and wrote the protocol. W. A. Ray and P. G. Arbogast did statistical analyses. J. R. Daugherty and K. Hall contributed to the protocol and computer programming. W. A. Ray wrote the initial draft of the report, then revised by M. R. Griffin, C. M. Stein, and P. G. Arbogast.

Conflict of interest statement

W. A. Ray has worked as a consultant for Merck Research Laboratories within the past 3 years, but not within the past year. M. R. Griffin is a consultant for Merck. No funding for this study was provided by any pharmaceutical company.

Acknowledgments

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¹¹ J. P. Donleavy, *The Unexpurgated Code: A Complete Manual of Survival and Manners* (New York, 1975), 279.

Principle 6: Content Counts Most of All

How Charles Joseph Minard (1781–1870) came to construct the map of the French invasion of Russia tells us about the spirit behind one of the best graphics ever. Minard was a renowned engineer, who managed large public works projects and designed bridges, canals, docks, and roads. He had the technical skills to construct good data graphics; he could draw and see and count all at a high level; he had developed the flow-map, an architecture exactly right for depicting losses in military campaigns. But at the heart of the work was Minard's passion about the substantive content.

At age 70 Minard retired from engineering. During the next 18 years, he produced 50 maps depicting statistical data describing spatial flows and distributions of French wine, ancient languages, railroads, cotton, migration, and the military strategies of Charlemagne and Napoleon. These "figurative maps" represent Minard's substantial contribution to the practice and theory of analytical graphics.¹²

In November 1869 at age 88, Minard published his last figurative map, the extraordinary 2-color lithograph at right. Two maps are printed on a poster-sized piece of paper. Both maps have the same theme, human losses in war. The upper map recounts the diminishing army of Hannibal and his elephants wandering around the Alps into northern Italy 2,200 years ago. This account of Hannibal's unhappy adventure makes comparisons over space and time with a narrative flow-line, uses multivariate data, has a north-arrow (documentation that should appear on every map), and indicates data sources. But this story lacks the narrative power of the Russian invasion map.

Minard had seen the horrors of war. Several of his public works projects had repaired wartime destruction. Then, while planning and managing construction in 1813, he was confined in besieged Antwerp:

Minard always retained a sharp impression of some bloody episodes of the bombardment; and these are some memories which had made him leave Paris last year at the approach of the Prussians.¹³

Minard's last work is an anti-war poster. A memoir by his son-in-law, Minard's only biographer, describes the map of Napoleon's invasion:

He emphasized the losses of men which had been caused by two grand captains, Hannibal and Napoleon 1st, the one in his expedition across Spain, Gaul, and Italy, the other in the fatal Russian campaign. The armies in their march are represented as currents which, broad initially, become successively thinner. The army of Hannibal shrunk from 96,000 men to 26,000, and our grand army from 422,000 combatants to only 10,000. The image is gripping; and, especially today, it inspires bitter reflections on the cost to humanity of the madneses of conquerors and the merciless thirst for military glory.¹⁴

¹² Minard's work is catalogued in Arthur H. Robinson, "The Thematic Maps of Charles Joseph Minard," *Imago Mundi*, 21 (1967), 95–108; Gilles Palsky, *Des chiffres et des cartes: Naissance et développement de la cartographie quantitative française au XIXe siècle* (Paris, 1996); and Michael Friendly, "The Graphic Works of Charles Joseph Minard," posted on the internet. Reproductions of Minard's maps and other graphics are in Arthur H. Robinson, *Early Thematic Mapping in the History of Cartography* (Chicago, 1982); Edward Tufte, *The Visual Display of Quantitative Information* (Cheshire, Connecticut, 1983, 2001); and Gilles Palsky, *Des chiffres et des cartes . . .* (Paris, 1996).

¹³ V. Chevallier, "Notice nécrologique sur M. Minard, inspecteur général des ponts et chaussées, en retraite," *Annales des ponts et chaussées*, 2 (1871), 1–22, quotation at 6–7. Translation by Dawn Finley. A translation of this 22-page biography of Minard at www.edwardtufte.com.

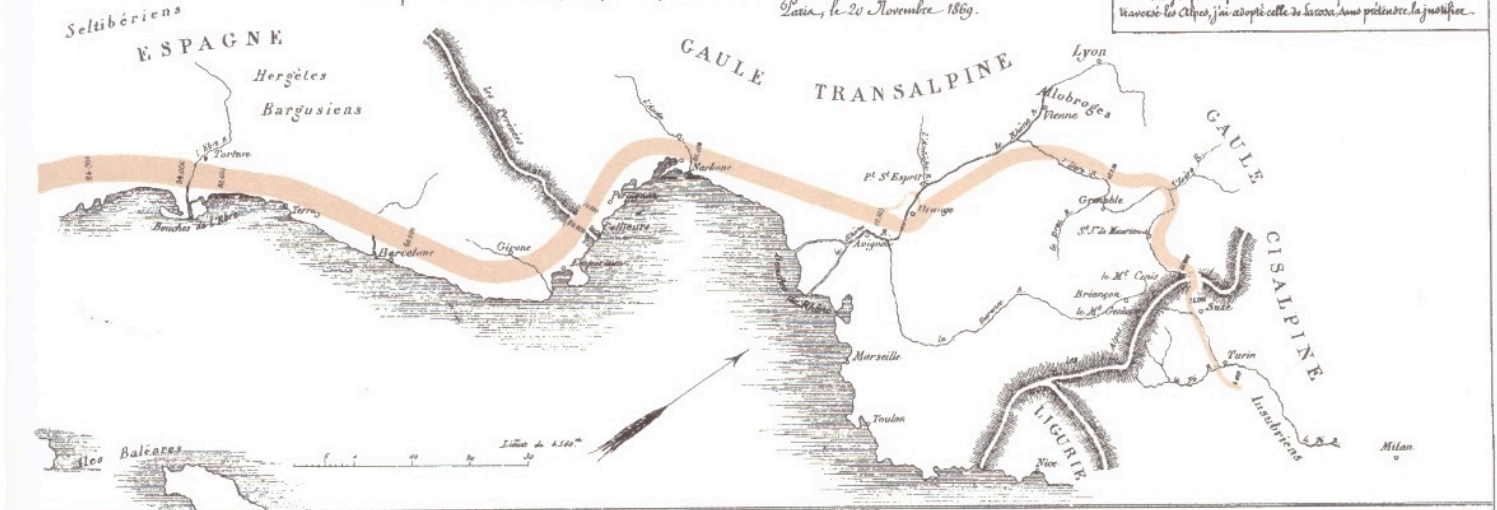
¹⁴ V. Chevallier, "Notice nécrologique sur M. Minard. . .," 17–18.

Carte Figurative des pertes successives en hommes de l'armée qu' Annibal conduisit d' Espagne en Italie en traversant les Gaules (selon Polybe).

Dessiné par M. Minard, Inspecteur Général des Ponts et Chaussées en retraite.
Paris, le 20 Novembre 1869.

Légende.

Les nombres d'hommes restans à Annibal sont représentés par la largeur des zones colorées à raison d'un millimètre pour dix mille hommes, ils sont de plus écrits en travers des zones. — Il n'y a pas d'opinion exacte sur le point où Annibal a traversé les Alpes, j'ai adopté celle de Livon, sans prétendre la justifier.



Carte Figurative des pertes successives en hommes de l'Armée Française dans la campagne de Russie 1812-1813.

Dessiné par M. Minard, Inspecteur Général des Ponts et Chaussées en retraite Paris, le 20 Novembre 1869.

Les nombres d'hommes restans sont représentés par la largeur des zones colorées à raison d'un millimètre pour dix mille hommes, ils sont de plus écrits en travers des zones. Le rouge désigne les hommes qui ont été en Russie, le noir ceux qui en sont restés. — Les renseignements qui ont servi à dresser la carte ont été puisés dans les ouvrages de M. M. Chiers, de Légué, de Fozendac, de Chambray et le journal indien de Jacob, pharmacien de l'Armée depuis le 28 Octobre. Pour mieux faire juger à l'œil la diminution de l'armée, j'ai supposé que les corps du Prince Jérôme et du Maréchal Davoust qui avaient été détachés sur Minsk et Mohilew n'en rejoignent ces Oescha et Witebsk, avaient toujours marché avec l'armée.

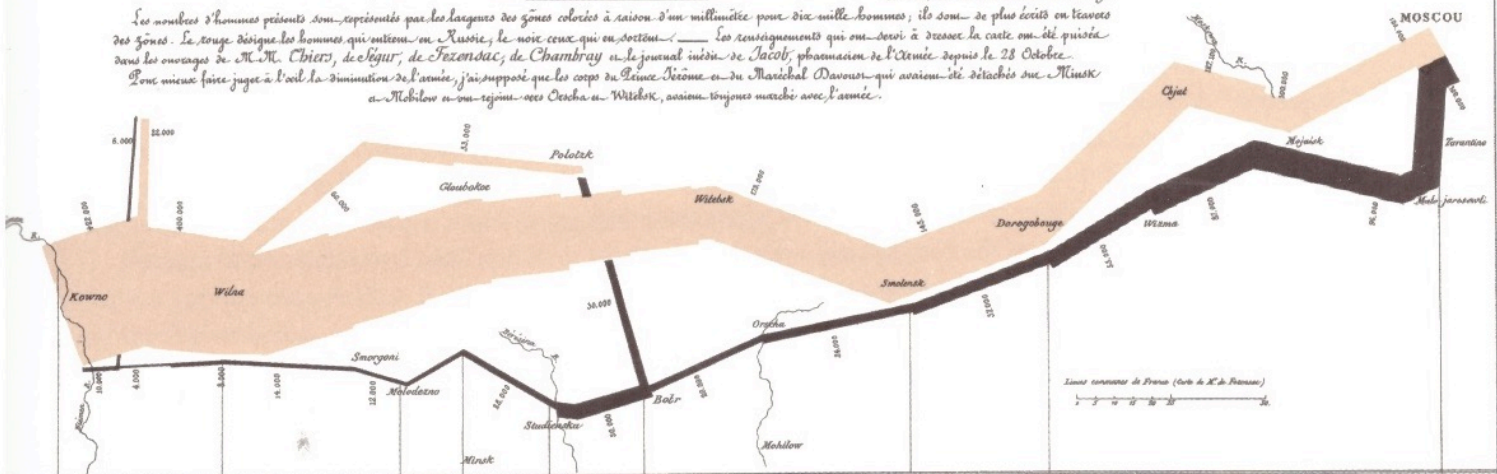
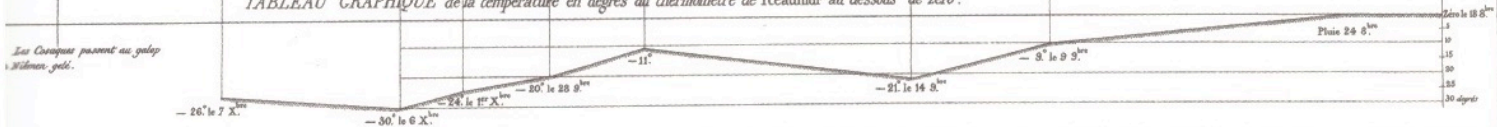
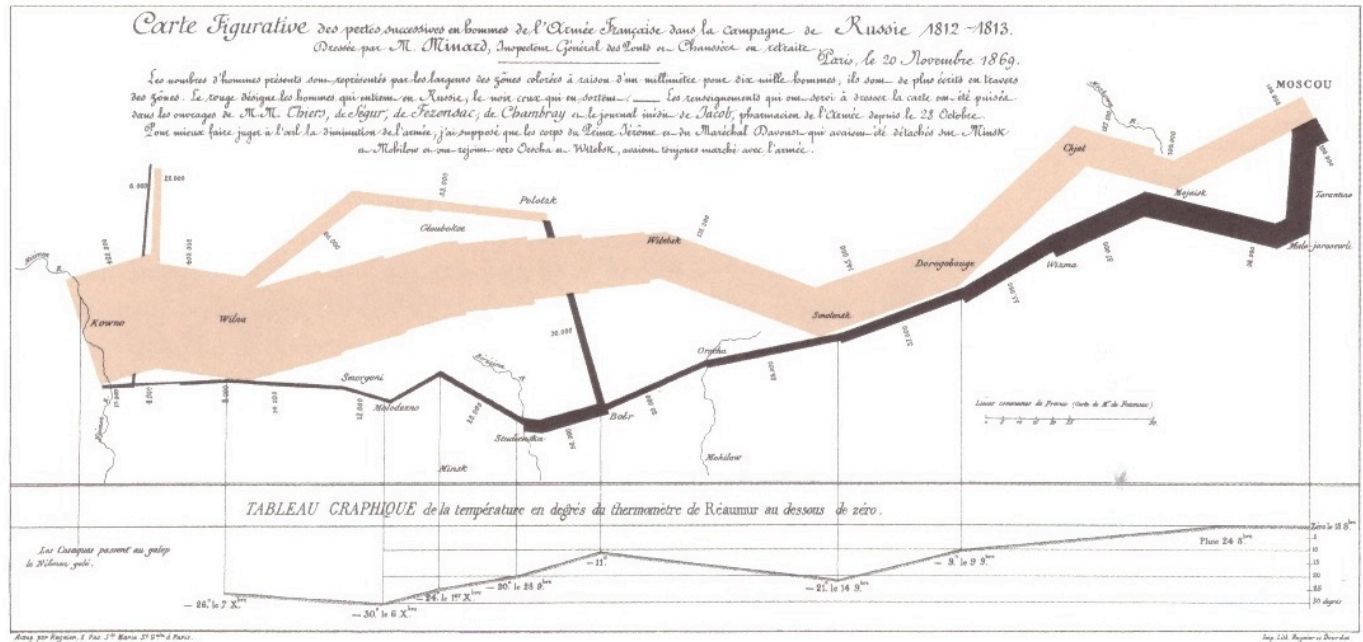


TABLEAU GRAPHIQUE de la température en degrés du thermomètre de Réaumur au dessous de zéro.



Charles Joseph Minard, *Tableaux Graphiques et Cartes Figuratives* de M. Minard, 1845-1869, item 28 in a portfolio of Minard's statistical maps at the Bibliothèque de l'École Nationale des Ponts et Chaussées, Paris. 62 × 54 cm, or 25 × 21 in, redrawn.



Minard's focus on the human costs of war is subtly reinforced by his choice of content. *Minard never mentions Napoleon.* That the word "Napoleon" does not appear on the map of Napoleon's march indicates here at least full attention is to be given to memorializing the dead soldiers rather than celebrating the surviving celebrity.

Minard's work exemplifies the spirit behind excellent analytical graphics: a good knowledge of the content and a deep caring about the substance. *The Sixth Principle for the analysis and display of data:*

Analytical presentations ultimately stand or fall depending on the quality, relevance, and integrity of their content.

This suggests that the most effective way to improve a presentation is to get better content. It also suggests that design devices and gimmicks cannot salvage failed content.

The content principle points to priorities in analytical design work: this is a content-driven craft, to be evaluated by its success in assisting thinking about the substance. Thus the first questions in constructing analytical displays are not "How can this presentation use the color purple?" Not "How large must the logotype be?" Not "How can this presentation use the Interactive Virtual Cyberspace Protocol Display Technology?" Not decoration, not production technology. The first question is *What are the content-reasoning tasks that this display is supposed to help with?* Answering this question will suggest choices for content elements, design architectures, and presentation technologies.

Relevance of Principles of Analytical Design

THE purpose of an evidence presentation is to assist thinking. Thus presentations should be constructed so as to assist with the fundamental intellectual tasks in reasoning about evidence: describing the data, making multivariate comparisons, understanding causality, integrating a diversity of evidence, and documenting the analysis. Thus the Grand Principle of analytical design: *The principles of analytical design are derived from the principles of analytical thinking.* Cognitive tasks are turned into principles of evidence presentation and design.

If the intellectual task is to make comparisons, as it is in nearly all data analysis, then “Show comparisons” is the design principle. If the intellectual task is to understand causality, then the design principle is to use architectures and data elements that show causality. The Grand Principle helps answer the most difficult question of all in the theory of analytical design: *How are principles of design derived?*

THE fundamental principles of analytical design apply broadly, and are indifferent to language or culture or century or the technology of information display. Nearly everyone everywhere, one way or another, reasons about causality, makes comparisons, navigates through 3-space and time. The principles are applicable to the design of the first map scratched into stone 6,000 years ago, and also to modern scientific displays. On both that stone and that computer screen, it is necessary to escape the flatland surface to compare multivariate data, to integrate and document evidence, to reason about dynamics, mechanism, causality.

Perhaps these intellectual tasks and their consequent design principles have a grander universality: if we to ever see the analytical presentations of intelligent beings from other planetary systems, those designs will make multivariate causal comparisons. Competence in these fundamental intellectual tasks is what it takes for sentient and communicating beings to survive, thrive, and evolve in a world governed by the universal laws of Nature — for the character of Nature’s laws is that they are causal, operate at every multivariate space-time point, reveal themselves by difference and comparison, and, indeed, are utterly indifferent to what particular sentient beings think about those laws. The universal character of physical laws provokes certain universal analytical tasks, here turned into the principles for the presentation of evidence.

Because these principles are rooted in fundamental cognitive tasks, they are relevant for *producing presentations* and for *consuming presentations*. Thus consumers of evidence presentations should look for appropriate comparisons, assessments of causality, multivariateness, use of relevant data, credible documentation, content-reasoning. There is a symmetry of thinking in the wise production and the wise consumption of evidence. At a good evidence presentation, we’re all in it together.

What about analytical displays of evidence involving *human behavior*, often so distant from any kind of lawlike understanding? Social science lacks the wonderfully convenient simplifying guarantee of the physical sciences that empirical observations are always somehow the expression of knowable invariant laws that operate at every space-time point. Lacking this mind-focusing guarantee, the study of human behavior is sometimes overwhelmed with multivariate uncertainties about causality, as analysis of after-the-fact historical patterns yields loose, fragile, poorly resolved explanations. Consider medical research seeking to identify successful treatments, a field advantaged by a wealth of resources and rewards, by clear explanatory goals, by the capacity to conduct randomized controlled experiments, and by a basis in universal physical laws. Even with such advantages, the substantive results in medical research tend toward the marginal and unsatisfying (“21% of the treatment group survived compared to 15% of the controls”) rather than the certain (“this treatment always produces a cure”).

Indeed, perhaps the single most important finding of social science—the unanticipated consequences of human action—is a finding about the impediments in predicting consequences of human behavior.¹⁵ Such uncertainty is epidemic because people can act on the basis of knowledge about patterns of human behavior, and thereby modify (uncertainly, to be sure) those patterns. Many investigations of human activities seek to unveil particular historical experiences in order to alter, avoid, or continue those experiences in the future. Thus the hope of Minard in making his anti-war poster.

Compared to evidence presentations about *nature* (physical science), presentations about *human behavior* (medicine and social science) are more descriptive, more verbal, less visual, less quantitative. For example, the physical and biological sciences publish statistical graphics that depict a median > 1,000 numbers (data for *Nature* and *Science*, 2006). In contrast, for applied research in medicine, statistical displays show an average 45 numbers per graphic (data for *The Lancet*, 2006). Also evidence published in major scientific journals such as *Nature* and *Science* is distinctly more visual and nonverbal than the evidence published in major journals in medicine and social science.

Despite such differences in modes of evidence and in explanatory style, physical science and studies of human behavior share some key underlying explanatory and intellectual patterns. To this point, the editor-compiler of 1,045 grand summary findings about human behavior that had some reasonable supporting evidence offered a threefold grander summary of social science knowledge:

- (1) Some do, some don't.
- (2) The differences aren't very great.
- (3) It's more complicated than that.¹⁶

¹⁵ Robert K. Merton, “The Unanticipated Consequences of Social Action,” *American Sociological Review*, 1 (December 1936), 894–904.

¹⁶ Bernard Berelson, “Citation Classic: Bernard Berelson and Gary Steiner, *Human Behavior: An Inventory of Scientific Findings* (New York, 1964),” in Neil J. Smelser, ed., *Contemporary Classics in the Social and Behavioral Sciences* (Philadelphia, 1987), 335.

These summary statements reflect the universal analytic issues of (1) causality, (2) comparison, and (3) multivariate complexity. Human activities, after all, take place in intensely comparative and multivariate contexts filled with causal ideas: intervention, purpose, responsibility, consequence, explanation, intention, action, prevention, diagnosis, strategy, decision, influence, planning. Thus the fundamental principles of analytical design are relevant for displays of evidence describing human behavior, as we have seen in Minard's *French Invasion of Russia*.