(late 1880s), a classic work on the morphology of the earth's surface (1894), and together with Eduard Brückner, his successor at Vienna, the outstanding *Die Alpen im Eiszeitalter* (1901–9), based on observations of glacial deposits in Alpine valleys.

In 1906 Penck left Vienna to accept the chair of geography at the University of Berlin as the immediate successor to Ferdinand von Richthofen. In Berlin he taught at the university for twenty years (1906–26) and served as rector of the university (1917–18) as well as director of the Museum für Meereskunde. He retired in 1926 and was immediately succeeded by one of his outstanding Austrian students, Norbert Krebs. Penck continued to live and work in Berlin, but in 1943, near the climax of World War II, he was bombed out of his home and moved to Prague, where he died on 7 March 1945 at the age of 87.

Penck was one of geography's leading scholars during the late nineteenth and early twentieth centuries. In *Die Alpen im Eiszeitalter*, the culmination of his personal field research, he and Brückner divided the quaternary Ice Age in the Alps into three interglacial and four glacial periods (named after the Alpine rivers Günz, Mindel, Riss, and Würm). Acclaimed as the foundation of quaternary geology as well as a classic interpretation of human prehistory, this book was Penck's most important contribution to glaciology and quaternary geology.

During the preparation of his seminal *Morphologie der Erdoberfläche* (1894), Penck distinguished between geodesy and geophysics as fields of study and noted the lack of a standard 1:1,000,000-scale international world map series. Motivated by this unmet need, he laid out a systematic plan for this map in a momentous presentation to the Fifth International Geographical Congress in Bern, Switzerland, in 1891. His suggestion was endorsed by the delegates, but little progress occurred until November 1909, when a special conference on the International Map of the World, held in London, passed the first resolutions on the production of the new map series, including decisions on projection, prime meridian, measurement system, sheet lines, relief representation with hypsometric colors, lettering, conventional signs, and geographical names. The project moved forward after a second conference, held in Paris in 1913, passed additional resolutions, and a Central Bureau was established at the British Ordnance Survey in Southampton. As a delegate from Germany, Penck continued to work on the scientific groundwork for the map series, with a focus on its use by scholars, but he lost interest in 1914 when he realized the maps were being used for military purposes.

Penck dealt repeatedly with the topographical map series of several countries and wrote instructive studies on "Neue Alpenkarten" (1899, 1900, 1903), "Neue Karten und Reliefs der Alpen" (1904), "Aegerters Karte der Ankogel-Hochalmspitzgruppe" (1909), and "Zur Vollendung der Karte des Deutschen Reichs" (1910); he also wrote informative reviews on "Oberlerchers Glocknerrelief" (1896) and "Wolfgang Lazius' Karten von Österreich und Ungarn" (1907) (Engelmann 1960, 353, 360, 373, 376). Penck always took an active part in cartography and trained his students to use maps for the study and interpretation of landscape.

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SEE ALSO: International Map of the World; Metric System

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Perception and Cognition of Maps.

Articles in this composite move from vision and low-level tasks to explicitly cartographic studies and the examination of map symbols in psychological research.

Vision and Discrimination. Map symbols, typically graphical, provide information about the earth's surface to human map users. Before map readers can understand the meaning of a symbol, they must first detect the symbol (i.e., tell the difference between the symbol and the background) and discriminate between a particular symbol and others that appear in the map. Only then is it possible for the reader to recognize what the symbol refers to. For this reason, map reading, as an activity that relies on vision, requires cartographers to work within the constraints of the human visual system in order to produce effective maps. Consequently, the study of visual perception, particularly the visual discrimination of symbols, has been an important part of perceptual and cognitive cartography since its initial emergence in the early twentieth century.

Arthur H. Robinson, in his doctoral dissertation at Ohio State University, published as *The Look of Maps* (1952), followed the suggestion by the German cartographer Max Eckert in the early 1920s by calling for the application of psychophysical research to the study of cartographic symbolization, along with more specific experimental and marketing psychology from the early twentieth century on the perception of lettering, color, and graphical structure. Psychophysics, an early branch of experimental psychology that originated in Germany during the nineteenth century, attempted to match the psychological response of human research subjects to the physical magnitude of stimuli, including visual stimuli. The interest was in a person's ability to discriminate both absolute thresholds, such as seeing a dim light or not, and difference thresholds, such as seeing one shade of blue as different from another. Psychophysics provided a highly productive set of methods for scientifically understanding the human discrimination of visual symbols on maps, including color (hue, lightness, saturation), symbol size differences (line widths, circle areas), and textural elements in patterns.

Cartographers acted on Robinson's call by devoting substantial attention to identifying and describing the just noticeable difference (JND) that would ensure that a map reader could discriminate between two symbols. This psychophysical concept refers to the smallest change in stimulus intensity that can be noticed by a human, which may well be smaller than the smallest difference that can be produced and reproduced reliably by the map production process. This research partially echoed the cartographic communication model, prominent from the late 1960s to the early 1990s, in which the function of maps was seen to be the communication to the map reader of a specific message encoded in the map by the cartographer. It would also represent some of the most important map design research carried out in the domain known variously as the human factors of maps or usability research (e.g., Board and Taylor 1977).

This body of research was wide ranging but focused on three types of symbols: grayscale, color hues, and typeface legibility. The goal of early empirical work on grayscale perception was designing symbol schemes that gave a visual impression equivalent to the values they represented (Williams 1958). For example, JNDs for discriminating gray tones are considerably smaller with light tones than dark tones. These studies drew upon earlier research by psychologists investigating the psychophysical properties of graphical stimuli, notably the studies of color hue and value by A. E. O. Munsell and his colleagues (Munsell, Sloan, and Godlove 1933). Several studies undertaken by cartographers had the aim of identifying cartographically appropriate equal-value gray tones (e.g., Williams 1958). However, the recommended scales arising from these studies often differed from one another, and it was typically unclear which scale was best suited for a particular cartographic context.

As map production technologies changed throughout the twentieth century, map perception studies focused on different characteristics of grayscales (fig. 648) (e.g., Jenks and Knos 1961; Kimerling 1975). For example, early studies, conducted when many cartographers made maps using commercially available stick-up patterns, investigated whether texture differences would change map readers' perceptions of symbol lightness. As tint screening became more widely used and cartographers gained greater control over the visual characteristics of their symbols through the use of coarser and finer screens and cross-screening (allowing the production of even-toned symbols), the focus of research shifted to quantifying the effects of perceptual shifts induced by different backgrounds and the relative contributions of symbol design and print production on lightness perception. The more widespread adoption of digital production techniques led to studies investigating laser printing and gray tones for use in classed and unclassed choropleth maps. The conclusion of some of these studies was that particular cartographic contexts demanded the use of different scales.

Changing production technologies over the course of the twentieth century also affected cartographers' use of color hues. Robinson (1952, 77–78) noted that as production technologies multiplied, cartographers became less familiar with how to specify hue most effectively in their maps. This problem was compounded by the variety of conceptual and practical systems available for measuring as well as specifying different aspects of color (e.g., Munsell, Ostwald, CIE, Birren, RGB, and CYMK), which contributed to difficulties in synthesizing the results of different research results into practical guidelines.

One of the greatest difficulties in applying perceptual studies to map design is the problem of graphical context—a single symbol often appears different to map readers when it is surrounded by different tones, hues, and patterns. Visual discrimination researchers often ignored this substantial effect, but when they did incorporate it into their research, they found it very difficult to make widely applicable general statements about symbol design and perception. As a case in point, simultaneous contrast is the perceptual phenomenon in which what

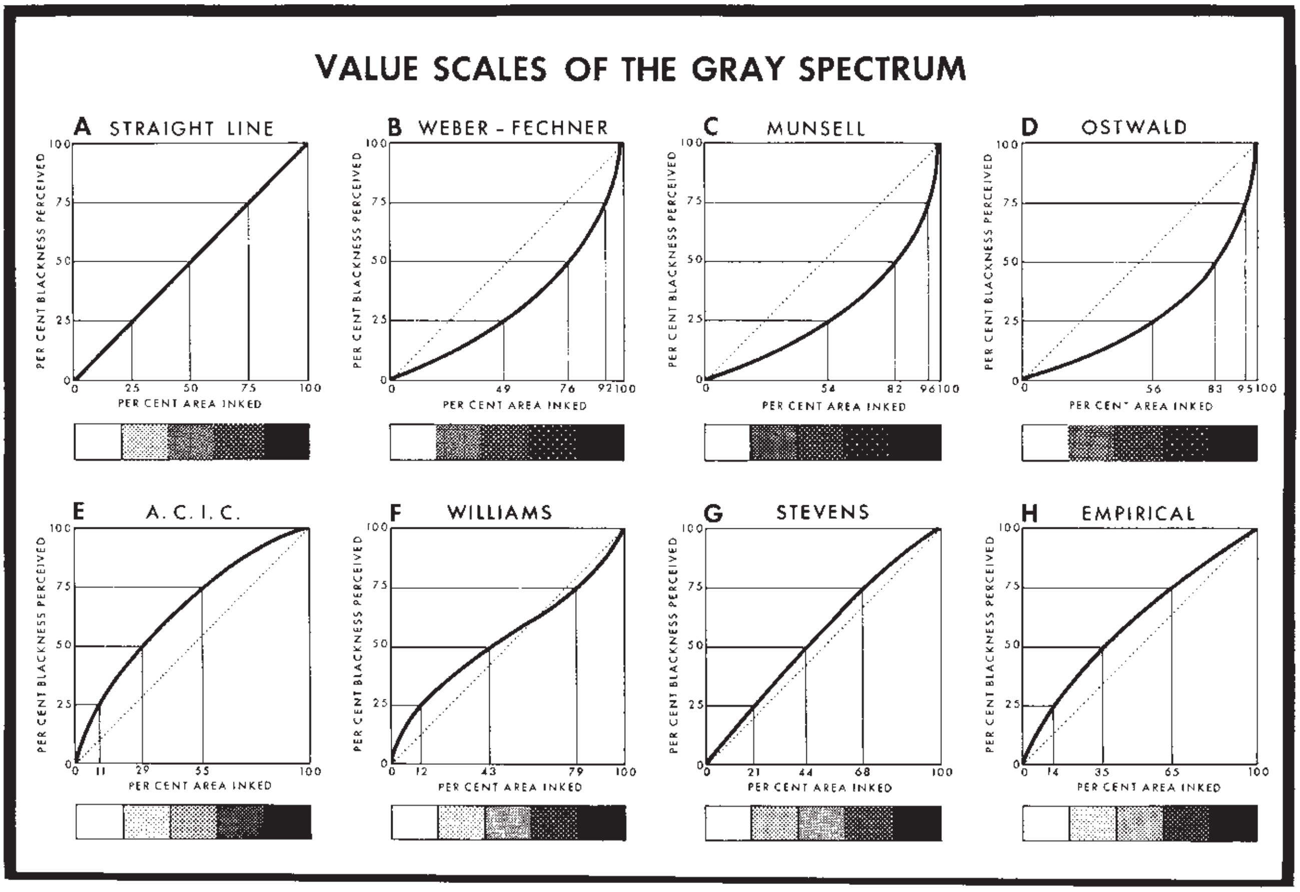

FIG. 648. VALUE SCALES OF THE GRAY SPECTRUM. The scales are from various published theories and are transferred to a common terminological and graphic base, allowing comparison of different theories when applied to self-adhesive shadings.

Size of the original: 16.3 × 23.8 cm. From Jenks and Knos 1961, 322 (fig. 2). Reproduced by permission of Taylor & Francis.

surrounds a color can cause a shift in how it appears, thereby increasing the difficulty of reliably discriminating between colors on a map. Toward the end of the twentieth century, cartographic researchers addressed the problem of designing for simultaneous contrast on maps. For example, Cynthia A. Brewer (1997) developed a model that could predict a map reader's inability to discriminate between colors because of simultaneous contrast, thereby allowing the cartographer to create discernible colors by adjusting the color scheme.

Later in the century, cartographers became increasingly sensitive to individual differences among map readers and the need to accommodate these differences when designing maps. In particular, they directed substantial attention to meeting the needs of map readers with visual impairments. Computers made it much more feasible to design multiple versions of a single map. This led Brewer and Judy M. Olson to develop several different color schemes they believed would help readers with impaired color vision to read thematic maps more accurately and efficiently (fig. 649). In testing these schemes with map readers, some with normal vision and some with color-impaired vision, they found the schemes helped map readers with color vision impairment without substantially hindering those with normal color vision.

During the twentieth century, cartographic designers and researchers also focused on the discriminability of typefaces, including the ease of reading different typefaces at different sizes under various illumination conditions. J. G. Withycombe, from the U.K.'s Ordnance Survey, identified several essential requirements for type within maps including "legibility" and "distinction and contrast" (1929, 432). He also urged cartographers to free themselves from the limitations of earlier reproduction technologies, such as copperplate engraving, and embrace the wider possibilities that the new technology of lithography afforded for designing type on maps. Yet

Change in the Number of Jobs by County	Confusing Rendition: Color name	x	y	Y	R	G	B	Accommodating Rendition: Color name	x	y	Y	R	G	B
Gain > 1000	dark green	.175	.756	13	0	145	0	dark blue	.153	.064	9	50	50	250
Gain 500-999	green	.268	.658	30	115	185	0	blue	.205	.164	29	150	150	250
Gain 1-499	yellow-green	.390	.554	61	210	215	0	light blue	.255	.261	65	210	210	250
Loss 1-499	yellow-orange	.480	.484	59	255	190	0	light orange-red	.413	.360	47	255	180	180
Loss 500-999	orange	.603	.385	31	255	110	0	orange-red	.519	.380	28	230	130	130
Loss > 1000	red	.646	.353	13	190	60	0	red	.658	.342	13	200	0	0
No Data	gray	.328	.411	19	150	150	150	dark gray	(not measurable)			90	90	90

D

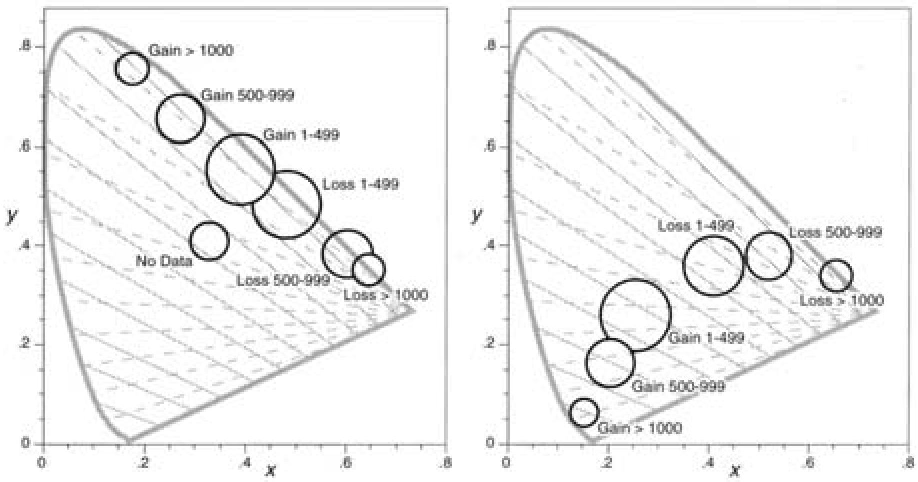

FIG. 649. COLOR HUE CONFUSIONS FOR RESEARCH SUBJECTS WITH COLOR VISION IMPAIRMENT. Map readers with color vision impairments will find it difficult to accurately and efficiently identify colors in schemes whose symbols parallel a color-confusion line (left). Color schemes that are comprised of symbols that cross color-confusion lines will be more easily differentiable for color vision impaired readers (right).
Size of the original: 9.6 × 14.5 cm. From Olson and Brewer 1997, 131 (fig. A6). Reproduced by permission of Taylor & Francis.

for several decades thereafter cartographers relied primarily on guidelines developed by typographers working with other forms of print, such as those found in books, advertisements, and other graphic posters. While Robinson's *The Look of Maps* (1952) devoted several chapters to the problem of type on maps, few of his guidelines were based on research that studied type in a cartographic context.

It was not until cartographer Barbara Bartz Petchenik carried out a series of studies of type on maps as a part of her doctoral dissertation at the University of Wisconsin under Robinson that there was a clear acknowledgment that the function of type is fundamentally different in maps than in other forms of text, such as books. She criticized the lack of an empirical basis for recommending how to design cartographic type, highlighted the importance of searching for particular labels in map reading, and conducted a series of experiments aimed at understanding the extent to which the visual characteristics of type affected this search process (fig. 650). Although her experiments were undermined by a failure to account for interaction among variables, they highlighted the role of type characteristics and map readers' expectations in searching for labels on maps. Petchenik showed that reliable expectations about the labels and certain type characteristics (e.g., size) allowed map readers to filter out irrelevant search targets and find target labels more quickly. A series of experiments by Richard J. Phillips and his colleagues in the United Kingdom, who tracked eye movements to examine where map readers actually looked while searching maps, later reaffirmed more conclusively what Petchenik had found (Phillips, Noyes, and Audley 1978). They also demonstrated that type weight and typeface made little difference to search speed, but that the broader map context in which a label was found could have substantial effects on search efficiency if the target label was positioned close to map symbols that looked like type (e.g., other map labels or unfilled point symbols).

While the search task was useful for developing an understanding of how particular labels could be detected in and among the variety of symbols found on a map, it did not shed light on the difference between any two particular labels. Barbara Gimla Shortridge and Robert B. Welch, at the University of Kansas, used a same-different task, in which map readers judged whether two labels were the same or different in size, to develop guidelines for the minimum size differences (i.e., the JNDs) between

FIG. 650. TEST MATERIAL FOR EVALUATING LEGIBILITY OF TYPEFACES IN A MAP CONTEXT. The map at the top contains labels that differ only in size. The labels in the map at the bottom differ on three dimensions: size, typeface, and type weight.
Size of the original: 11.5 × 8.7 cm. From Bartz 1970, 105 (maps 7 and 8). Copyright © British Cartographic Society. Permission courtesy of Maney Publishing, Leeds.

labels that map readers would be able to discriminate. They demonstrated that map context was critical; the visual noise created by other map symbols hampered map readers' ability to discern differences. However, the map author who used multiple type characteristics (e.g., size and weight) could improve discrimination of differences (Shortridge and Welch 1982).

Much of the research undertaken on the visual discriminability of map symbols was criticized for using testing environments or map reading tasks that were too artificial, for being too narrowly focused on optimizing symbolization for an average map reader, and for producing results that were inconsistent as a function of small changes in instructions, tasks, or test materials. Even so, this body of research did lead to the production of more widely readable maps, particularly for readers with visual impairments. And it also inspired cartographic scholars and researchers to focus more on map users and the perceptual constraints of their visual systems rather than only on the technical aspects of map reproduction, the development of new thematic map symbols, and generalization methods, all of which were major foci of cartographic research in the twentieth century.

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SEE ALSO: Color and Cartography; Perception and Cognition of Maps: Psychophysics; Petchenik, Barbara B(artz); Robinson, Arthur H(oward); Visualization and Maps

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Perceiving, Understanding, and Remembering. Spatial thinking is essential for survival. Life would be difficult if we didn't know how to get home at night or how to bring food to our mouths. Spatial thinking is multimodal, involving all the senses: blind people can be excellent wayfinders, using sound, touch, and even smell as cues instead of visual ones. Spatial knowledge and spatial reasoning are the fundamental basis for abstract thought, from daily parlance—"she's at the top of the heap"—to sophisticated models and diagrams in science. Spatial thinking can be regarded as having two parts: mental representations and mental transformations on those representations. Mental representations