the traditional three ways of thinking: literacy (reading and writing), numeracy (mathematical ability), and articulacy (oral communication). Graphicacy, the so-called "fourth ace in the pack," is the capacity to understand and use graphics (especially maps). This focus on graphicacy was matched by the parallel notion of spatial ability, also known as spatial intelligence, that is the ability to generate, retain, retrieve, and transform two- and three-dimensional visual-spatial images. Spatial ability tests are part of the Graduate Record Examination and are used as tests for occupations such as air traffic control because spatial ability is a component of the general concept of intelligence (Carroll 1993). The capacity to think about and to create maps (in particular) is seen as a function of graphicacy and spatial ability. Differences in spatial ability, for example, as a function of age and sex purportedly could account for variations in the capacity to read maps and to use them for wayfinding and other tasks.

The second idea is the fundamental role of space and graphics in a significant mode of thinking, spatial thinking, described by a U.S. National Research Council panel (2006, 3) as being "based on a constructive amalgam of three elements: concepts of space, tools of representation, and processes of reasoning." Maps such as the famous cholera maps of John Snow are used as exemplars of the process of spatial thinking: data are spatialized and the representational forms, especially maps, can structure description, explanation, and prediction. As a learnable skill, spatial thinking underpins everyday activities, the process of scientific thinking, and many job skills. With technological supports through geographic information science (GIScience) and visualization systems, spatial thinking has become more visible and popular. Thus, maps and mapping are simultaneously exemplars of and integral components of fundamental cognitive processes.

By the end of the twentieth century, two technologies—functional magnetic resonance imaging (fMRI) and GIScience—captured the power of the intellectual apparatus of cartography in expressing the nature of human knowledge. The images generated by fMRI systems may localize the physiological roots of human knowledge in the gross and micro structures of the brain, revealing a physiological reality for the development and use of maps and mapping. Thus the classic medical atlas of the physiological structures of the brain may be matched by atlas pages depicting the location of the mapping impulse. In turn, GIScience is revolutionizing the power of the human mind by providing supports for spatial decision making. The supports are becoming tuned to the structures of human knowledge, many of which are spatial in nature. Thus GIScience is enhancing the power of the mapping impulse. In effect, both technologies use the language of maps and mapping to understand and foster the cognitive underpinnings of maps and mapping, reminding us again of the extent to which maps and minds are inextricably intertwined.

ROGER M. DOWNS

SEE ALSO: Education and Cartography: Teaching with Maps; Visualization and Maps

BIBLIOGRAPHY:

Balchin, W. G. V., and Alice M. Coleman. 1966. "Graphicacy Should Be the Fourth Ace in the Pack." *Cartographer* 3:23–28. Reprinted from *The Times Educational Supplement*, 5 November 1965.

Brewer, Cynthia A., Geoffrey W. Hatchard, and Mark Harrower. 2003. "ColorBrewer in Print: A Catalog of Color Schemes for Maps." *Cartography and Geographic Information Science* 30:5–32.

Carroll, John Bissell. 1993. *Human Cognitive Abilities: A Survey of Factor-Analytic Studies*. New York: Cambridge University Press.

Garland, Ken. 1994. *Mr Beck's Underground Map*. Harrow Weald: Capital Transport.

Golledge, Reginald G., ed. 1999. *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes*. Baltimore: Johns Hopkins University Press.

Golledge, Reginald G., et al. 1998. "A Geographical Information System for a GPS Based Personal Guidance System." *International Journal of Geographical Information Science* 12:727–49.

Gould, Peter. 1973. "On Mental Maps." In *Image and Environment: Cognitive Mapping and Spatial Behavior*, ed. Roger M. Downs and David Stea, 182–220. Chicago: Aldine.

Gould, Peter, and Rodney White. 1974. *Mental Maps*. Harmondsworth: Penguin Books.

Healy, Sue, ed. 1998. *Spatial Representation in Animals*. Oxford: Oxford University Press.

Lynch, Kevin. 1960. *The Image of the City*. Cambridge, Mass.: M.I.T. Press.

Montello, Daniel R. 2002. "Cognitive Map-Design Research in the Twentieth Century: Theoretical and Empirical Approaches." *Cartography and Geographic Information Science* 29:283–304.

National Research Council (U.S.). 2006. *Learning to Think Spatially*. Washington, D.C.: National Academies Press.

O'Keefe, John, and Lynn Nadel. 1978. *The Hippocampus as a Cognitive Map*. New York: Oxford University Press.

Passini, Romedi. 1984. *Wayfinding in Architecture*. New York: Van Nostrand Reinhold.

Robinson, Arthur H. 1952. *The Look of Maps: An Examination of Cartographic Design*. Madison: University of Wisconsin Press.

Saarinen, Thomas F. 1973. "Student Views of the World." In *Image and Environment: Cognitive Mapping and Spatial Behavior*, ed. Roger M. Downs and David Stea, 148–61. Chicago: Aldine.

Tolman, Edward Chace. 1948. "Cognitive Maps in Rats and Men." *Psychological Review* 55:189–208.

Toulmin, Stephen. 1953. *The Philosophy of Science: An Introduction*. London: Hutchinson's University Library.

Tversky, Barbara. 1981. "Distortions in Memory for Maps." *Cognitive Psychology* 13:407–33.

Subject Testing in Cartography. During the twentieth century, researchers in the area of perceptual and cognitive cartography asked questions about perception, learning, communication, reasoning, and decision making with maps. These questions were pursued by researchers from different disciplines, including cartography, geography, psychology, and education. Different researchers had different methodological and conceptual training, different research motivations, and different publication and conference outlets. However, all of these cartographic researchers addressed their questions, in part, by applying tools of empirical science—they systematically tested human subjects by observing and measuring their responses during and after map viewing and study. One focus of research was on describing, predicting, and explaining similarities and differences among people in their use and interpretation of maps, analyzing them as individuals or members of subgroups based on gender, age, or cultural background. A second focus, aligned with human factors research, examined viewing conditions that influence the ease and accuracy of using maps—conditions such as lighting, font type and color, and map orientation. A third research focus was on understanding and improving the use of maps in education, as well as education about maps and mapping. Finally, much perceptual and cognitive cartographic research, particularly by cartographers, had the aim of improving the design of maps so they would convey more information more easily and accurately. This final focus on perceptual and cognitive map design research and its testing of human subjects in cartography is reviewed in this essay.

It is likely that some of the earliest cartographers, many centuries ago, recognized that map design would influence how maps were perceived, understood, and used to make decisions. However, this intuition was not pursued systematically as behavioral and cognitive science, nor did it become a formal part of cartographic education, until the twentieth century. The notion that map design could be improved with the help of scientific research on perception and cognition was a twentieth-century phenomenon, and represented a distinct change from the long tradition of a craft approach to cartography, including trial-and-error conventions developed over the centuries about how to design maps, and informal "experiments" carried out by mapmakers on themselves, or their colleagues and assistants (Robinson 1952).

Important nineteenth-century precursors to the twentieth-century emergence of perceptual and cognitive studies in cartography included the emergence of empirical psychology in Europe and the United States, the development of thematic mapping (upon which most perceptual and cognitive cartographic research has been conducted), military efforts in Europe to develop effective methods for portraying relief on maps, and developments in art and art theory. During the twentieth century, the first call to apply psychological research to improving maps as designed objects came from the writings of the German cartographer Max Eckert (later Eckert-Greifendorff). As early as 1908 Eckert explained that "map logic" is one of the most important topics for scientific cartography; by map logic, he meant the principles for creating maps and for cartographic perception (Montello 2002, 287). He thus recognized the subjectivity involved in map communication. These ideas were further developed in his two-volume magnum opus titled *Die Kartenwissenschaft* (1921–25), in which he advocated the application of psychological research to cartography, although he neither reported any such studies with maps nor offered a detailed plan for applying psychology to understanding maps.

The most influential push to apply scientific studies of perception and cognition to improving map design came from Arthur H. Robinson's *The Look of Maps* (1952), which was based on his 1947 dissertation at Ohio State University. This small, mapless book put forth the proposition that the function of maps is to communicate to people. This function depends on the visual appearance of maps, and this appearance in turn depends on explicit and implicit design decisions made by mapmakers. So to understand and improve map function, cartographers need to understand the effects of design decisions on the minds of map users. "The work that makes the data intelligible to the reader . . . . is the essential cartographic technique" (Robinson 1952, 4). Robinson proposed that the best way to understand map communication was the way other mysteries of our world had best been understood—through rational thought and systematic study. This echoed Eckert's early blueprint for cartography as science, in this case behavioral and cognitive science, particularly psychology.

Daniel R. Montello (2002) discussed several other key influences on Robinson's work, including early studies on color and relief representation, map education research, writings on propaganda mapping, and an early address by the president of the Association of American Geographers, John Kirtland Wright, discussing the role of the subjective world of the cartographer in maps. Noncartographic perceptual research, such as work by German psychophysicists, also influenced Robinson in important ways. Clearly, Robinson's experiences as head of the Map Division at the U.S. Office of Strategic Services (OSS) during World War II, as well as his artistic leanings, influenced his ideas about map perception and cognition.

Publications like *The Look of Maps* offered a way to think about cartography as a discipline that attempts to pass along the cartographer's conception of the world to the mind of the map reader via the symbolic medium of the map. This was a seed for the communication model, a broad and comprehensive theoretical framework for describing and explaining cartography. From the perspective of this essay, the communication model provided a theoretical framework within which to justify human subject testing in cartography. In *The Look of Maps*, Robinson called for cartographic researchers to systematically observe and measure—collect data on—how people look at and interpret maps. This led to the application of psychophysical methods to map design research. Soon after initial psychophysical studies in cartography in the 1950s, other tasks and techniques not derived from psychophysics were also applied to the study of map perception and cognition, including tasks wherein the speed and accuracy of searching for particular targets or answering particular questions were recorded (Dobson 1983). As Montello (2002) pointed out, these various methods were used to study the perception of a variety of symbol and map designs, including region areas on conformal projections, dot-area symbols, gray tone scales, type fonts and lettering, and color. The most significant map design research on reference maps, as opposed to thematic maps, was carried out on topographic maps, including those symbolized with isolines (contours), hachures, and shaded relief. A survey for Britain's Royal Society reported many empirical human subject studies of cartographic communication done in Britain, including work done at the Experimental Cartography Unit, or ECU (Board and Buchanan 1974). Perceptual and cognitive research involving subject testing also flourished in German-language cartography (e.g., Koch 1993).

One of the most significant approaches to subject testing in cartography involved recording the eye movements of subjects as they viewed maps (Steinke 1987 provides a historical review). Recording eye movements in cartography is based on the assumption that people will look at places on a map to which they wish to attend; visual attention is the selective focusing of information processing on some parts of the visual field rather than others. So if you know where people are looking on a map, you know where they are attending to on that map—where they are attempting to pick up information visually. More precisely, to "look at" means to "foveate"—to move one's eyes so that the central area of the retina, the fovea, receives input from a place in the visual field. The fovea has the greatest concentration of visual receptor cells (particularly cones), and those cells have the densest connections to postretinal layers of the visual system. Foveated places in the visual field are perceived with greatest resolution. If time-registered locations of foveations are recorded, continuously or very frequently, a record of the temporal and spatial pattern of eye movements, a "scan path," can be diagrammed, providing a record of places to which people were not attending.

Systematic eye movement recording was conducted in psychology and various specialized fields of textual and graphical communication, such as art and advertising, during the first half of the twentieth century (citations in Steinke 1987). Several researchers outside cartography conducted studies throughout the 1950s and 1960s. A watershed event for cartography was the Symposium on the Influence of the Map User on Map Design, held in 1970 at Queen's University in Kingston, Ontario (see Castner and McGrath 1971). The meeting included talks on a variety of cognitive cartographic topics, including eye movement research. L. G. Williams, a psychologist, reported some results from his noncartographic eye movement studies, and papers by Mylon Merriam and Henry Castner cited and discussed eye movement studies and their possible implications for cartography.

George F. Jenks, cartography professor at the University of Kansas, attended the 1970 meeting at Queen's University. Jenks would eventually be recognized as a leader in map design research in the United States, particularly in its empirical manifestations, probably second only to Robinson in influence. At a seminar Jenks held at Kansas during the early 1970s, he and his students drew region boundaries on a dot map showing hog production in North Carolina. The class spent a great deal of time discussing variation in their regionalizations, including possible explanations for it. Armed with the interest in eye movement techniques he had picked up at the Queen's meeting, Jenks and his students conducted seminal recordings of the scan paths of viewers studying the dot map (fig. 658). Although it is safe to conclude that this eye movement study did not particularly illuminate causes for the different regionalizations of his students, it did demonstrate the feasibility (albeit with difficulty) of conducting eye movement research in cartography. In this way, it provided a stimulus for a host of subsequent research projects by several of his students and others using the technique (e.g. Chang, Antes, and Lenzen 1985).

Testing human subjects as a way to study map perception and cognition became very popular during the

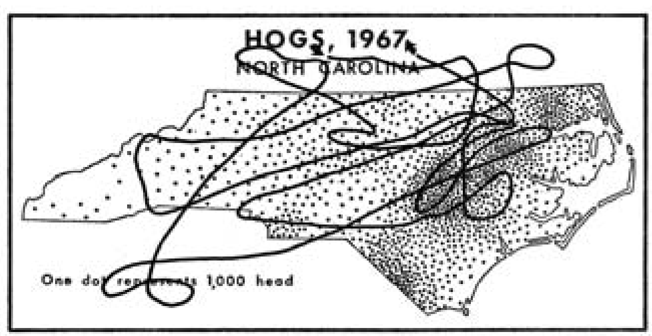

FIG. 658. HOG MAP OF NORTH CAROLINA WITH OVERLAID SCAN PATH RECORDED FROM THE EYE MOVEMENTS OF A PERSON STUDYING THE MAP.
Size of the original: 6.4 × 12.8 cm. From Jenks 1973, 30. Permission courtesy of Bertelsmann AG, Gütersloh.

1970s. Patricia P. Gilmartin (1992) reported a content analysis of research published in major English-language cartographic journals from 1964 to 1989. The period from about 1975 to 1982 had the most "user-oriented" articles (her term for research articles on map perception and cognition), peaking in 1978 and 1979 at over 30 percent of all articles in those journals—the largest single category. Before the late 1970s, historical topics were predominant; the 1980s witnessed the growth of automated cartography (geographic information systems [GIS]) as a topic. American universities where subject testing occurred from the 1960s to the 1980s included the University of Wisconsin, the University of Kansas, the University of Washington, Clark University, and Pennsylvania State University.

However, the reputation of subject testing in cartography, and perceptual and cognitive studies more broadly, suffered somewhat in the 1980s. Empirical studies, including psychophysical and eye movement studies, were criticized as lacking application to actual map production. Many cartographers had recognized the potential value of eye movement studies but came to question what such studies told the mapmaker that was novel. Conclusions such as that subjects look more at areas of the map that contain relevant information or different map designs produce different eye-scan paths were not earthshaking revelations. The most incisive critique came from Barbara Bartz Petchenik (1983), who had studied under Robinson at Wisconsin and was working in production cartography at R. R. Donnelley as map editor for the *World Book Encyclopedia*. She claimed that subject testing with maps was not helpful to map design because it was based on faulty assumptions about the way people use maps (such as that they always have a single, definite question to answer when they look at a map), and because of fundamental differences in the goals of designers and researchers (the first think synthetically, the second analytically).

Petchenik noted that the results of subject testing seemed inconsistent and context dependent; changing the nature of the map task or the precise design of the test materials often led to variability in the results. Other problems included the existence of individual differences—map users are different, and to a certain extent (sometimes great), they look at and think about maps differently. Many of the studies failed to contribute much to an accumulated understanding of map perception and cognition because they were atheoretical, observing humans viewing maps without a strong theoretical framework within which to interpret those observations. Eye movement studies, for example, produce large amounts of data whose signal is buried in considerable noise and irrelevant components. Ultimately, theory should guide our choices among the many options for analyzing these data (fixation locations, fixation durations, scan lengths, number of direction changes, etc.).

So the difficulty of conducting and interpreting subject testing research, and the rise of GIS, led to less perceptual and cognitive research in cartography, at least in the United States and the United Kingdom (it did not decline as much in Germany). However, this decline reversed during the 1990s. The digital computer provided alternative research topics for new researchers—topics that did not involve perception and cognition—but it also made subject testing easier, assisting in the creation and presentation of test stimuli and the collection and analysis of data. Improvements in computer technology also made new information displays possible, including animations, multiscale displays, near-continuous zooming, sonifications, tactilizations, and virtual and augmented realities. Furthermore, digital technologies made geographic information displays increasingly common among laypeople as well as specialists; maps showed up on home computers, in cars, on cell phones, and in public sites from airports to museums. These continuing developments clearly inspired new interest in perceptual and cognitive research to help design more effective and enjoyable geographic information displays, and this has included an increasing application of subject testing in cartographic research.

Alan M. MacEachren's *How Maps Work* (1995), the most comprehensive review ever written of perceptual and cognitive theory in cartography, referenced many studies done after 1990, including work at Penn State and elsewhere. Clifford H. Wood and C. Peter Keller's 1996 *Cartographic Design*, based on the Symposium on Cartographic Design and Research, held at the University of Ottawa in August 1994, aimed to rectify the neglect of map design and map design research with human subjects that resulted from the digital revolution in cartography. In addition to these books, articles reporting the results of subject testing studies in cartography continue to appear in major journals (e.g., see review by Lloyd 2000). These publications suggest that the status of subject testing as an important component of academic cartography has become stronger and that researchers have moved beyond low-level perceptual approaches to the high-level cognitive approaches that involve methods such as protocol analysis and collaborative decision making studies (e.g., Slocum et al. 2001).

Subject testing research influenced the activities of academic cartographers during the twentieth century. Faculty and students spent time thinking about it and doing it. Conferences occurred, articles and books were published, money was spent, and many thousands of research subjects were tested. As a result, many courses in cartography include discussions of map perception and cognition, including subject testing. However, subject testing had much less influence on the production of maps, whether by agencies and private companies in the business of making maps or by mapmakers without professional training (e.g., many media cartographers). This is recognized by many academic cartographers and was a key discussion point in Petchenik's 1983 critique. But this influence has not been completely nil. Petchenik herself conducted subject testing as part of her job in production cartography at R. R. Donnelley. Environmental Systems Research Institute (ESRI) modified its popular GIS software ARC/INFO to let mapmakers rescale their area symbols to accommodate the perceptual effects found in psychophysical research. Cynthia A. Brewer (Brewer and Suchan 2001) did notable work on color for the U.S. Census Bureau and ESRI. In their *Atlas of United States Mortality*, the U.S. Center for Disease Control used the color scheme developed and tested by Judy M. Olson and Brewer (1997) for users with color-vision impairment.

Finally, subject testing in cartography helped focus attention on the idea that map design should be considered in terms of its effectiveness for helping people understand the world. For example, it is fairly widely recognized now that the Mercator projection is inappropriate for most general uses because of the way it distorts areas. The simple notion of "reading" a map has been greatly expanded in appreciation of the fact that there is no single universal way in which maps are "read" (Castner 1983, 97). In sum, empirical map design research with human subjects helped to create a new way of thinking and talking about maps and mapping that continues to affect the entire discipline of cartography. The needs and capacities of map users became understood as central to the design and production of maps and other geographic information displays, and the belief that the mapmaker's intuition will always lead to the best map design is much less widely held.

DANIEL R. MONTELLO

SEE ALSO: Color and Cartography; Petchenik, Barbara B(artz); Robinson, Arthur H(oward)

BIBLIOGRAPHY:

Board, Christopher, and A. Buchanan. 1974. "Evaluating Thematic Maps—Current Trends in the United Kingdom." *Cartographic Journal* 11:124–29.

Brewer, Cynthia A., and Trudy A. Suchan. 2001. *Mapping Census 2000: The Geography of U.S. Diversity*. Washington, D.C.: U.S. Department of Commerce, Economics and Statistics Administration, U.S. Census Bureau.

Castner, Henry W. 1983. "Research Questions and Cartographic Design." In *Graphic Communication and Design in Contemporary Cartography*, ed. D. R. F. Taylor, 87–113. Chichester: John Wiley & Sons.

Castner, Henry W., and Gerald McGrath, eds. 1971. *Map Design and the Map User*. Monograph 2, *Cartographica*. Toronto: B. V. Gutsell, Department of Geography, York University.

Chang, Kang-Tsung, James Antes, and Thomas Lenzen. 1985. "The Effect of Experience on Reading Topographic Relief Information: Analyses of Performance and Eye Movements." *Cartographic Journal* 22:88–94.

Dobson, Michael W. 1983. "Visual Information Processing and Cartographic Communication: The Utility of Redundant Stimulus Dimensions." In *Graphic Communication and Design in Contemporary Cartography*, ed. D. R. F. Taylor, 149–75. Chichester: John Wiley & Sons.

Eckert, Max. 1921–25. *Die Kartenwissenschaft: Forschungen und Grundlagen zu einer Kartographie als Wissenschaft*. 2 vols. Berlin: Walter de Gruyter.

Gilmartin, Patricia P. 1992. "Twenty-five Years of Cartographic Research: A Content Analysis." *Cartography and Geographic Information Systems* 19:37–47.

Jenks, George F. 1973. "Visual Integration in Thematic Mapping: Fact or Fiction?" *International Yearbook of Cartography* 13:27–35.

Koch, Wolf Günther. 1993. "Experimentelle Kartographie—nutzbare Ergebnisse und neue Fragestellungen." In *Kartographie und Geo-Informationssysteme: Grundlagen, Entwicklungsstand und Trends*, 23–31. Bonn: Kirschbaum Verlag.

Lloyd, Robert. 2000. "Understanding and Learning Maps." In *Cognitive Mapping: Past, Present and Future*, ed. Rob Kitchin and Scott Freundschuh, 84–107. London: Routledge.

MacEachren, Alan M. 1995. *How Maps Work: Representation, Visualization, and Design*. New York: Guilford Press.

Montello, Daniel R. 2002. "Cognitive Map-Design Research in the Twentieth Century: Theoretical and Empirical Approaches." *Cartography and Geographic Information Science* 29:283–304.

Olson, Judy M., and Cynthia A. Brewer. 1997. "An Evaluation of Color Selections to Accommodate Map Users with Color-Vision Impairments." *Annals of the Association of American Geographers* 87:103–34.

Petchenik, Barbara Bartz. 1983. "A Map Maker's Perspective on Map Design Research, 1950–1980." In *Graphic Communication and Design in Contemporary Cartography*, ed. D. R. F. Taylor, 37–68. Chichester: John Wiley & Sons.

Robinson, Arthur H. 1952. *The Look of Maps: An Examination of Cartographic Design*. Madison: University of Wisconsin Press.

Slocum, Terry A., et al. 2001. "Cognitive and Usability Issues in Geovisualization." *Cartography and Geographic Information Science* 28:61–75.

Steinke, Theodore R. 1987. "Eye Movement Studies in Cartography and Related Fields." In *Studies in Cartography: A Festschrift in Honor of George F. Jenks*, ed. Patricia P. Gilmartin, Monograph 37, *Cartographica* 24, no. 2:40–73.

Wood, Clifford H., and C. Peter Keller, eds. 1996. *Cartographic Design: Theoretical and Practical Perspectives*. Chichester: John Wiley & Sons.

Map-Use Skills. For much of the twentieth century, skills in using maps (hereafter referred to more simply as map skills) were of major concern in only two restricted contexts. First, in military contexts map skills were viewed as a prerequisite for tactical operations and were taught in a rigidly programmed and rote fashion. Second, in primary and secondary school contexts map (and atlas) skills were viewed as critical for studying geography (fig. 659). Students, too, were taught in a regime of rote learning that covered map reading and interpretation: keys, scales, grids, and types of maps. In neither military nor school context was there any guiding theory or an overarching question to be answered. The instructional goals were simply to teach map skills with efficiency and