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Varieties of Publication Patterns in Neuroscience at the Cognitive Turn

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The quantification of publication activity and impact has become a key element in the evaluation of scientific excellence. However, it is unclear to what extent this grasps the diversity of research communication that accompanies the transition of scientific fields. This contribution investigates number, categorization, and impact of publications (i.e., publication patterns) of six scientists active at the cognitive turn, which promoted the information processing perspective on neuronal processes in different communities: Horace Barlow, Theodore Bullock, Ralph Gerard, Donald MacKay, Warren McCulloch, and Werner Reichardt. The large variety of publication patterns revealed indicates the limits of standardized evaluation procedures based on publication activity.

Keywords science evaluation, computational neuroscience, information theory, cybernetics, bibliometrics, conferences, citation analysis

Introduction

The quantification and evaluation of publication activity of scientists has become an important tool to ascertain the quantity and quality of the impact of articles and authors, as well as to explore the topical and social structure of scientific communities (Shiffrin & Börner, 2004). Although the adequateness and reliability of this approach has been criticized (Adam, 2002) and alternatives—e.g., based on acknowledgements (Lee Gilles & Councill, 2004)—have been proposed, the analysis of publication activity remains a key element in the evaluation of scientific excellence.

From a historical point of view, however, this approach may miss the diversity of research communication—in particular during transition periods, when new concepts and questions enter a specific field. The work of scientists may be acknowledged much later or in completely different fields. The "publicaction patterns"—the number of publications and citations dependent on time and field—may vary considerably across scientists that were nevertheless acknowledged as key persons of the transition. This contribution investigates this phenomenon by analyzing the publication patterns of key scientific persons at the "cognitive turn," characterized as the introduction of vocabulary and concepts emerging from

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information theory and cybernetics into neuroscience. Although the citation analysis is based on the standard ISI Web of Knowledge database,[1] an alternative approach was used to identify communities and key scientists: Conferences in the fields of information theory, cybernetics, and neuroscience in the mid-1940s to the early 1970s were clustered according to similarities concerning participation. Six scientists who frequently were present in different clusters and are considered as important based on a qualitative analysis (Christen, 2006) were then chosen in order to assess their impact on different scientific communities.

This contribution is structured in three parts: In a first section, the main characteristics of the information perspective in neuroscience are briefly sketched. In a second section, conferences in the period 1946 to 1972, when the application of concepts originating in information theory and cybernetics to neuronal processes has been discussed, are analyzed. Then, based on the conference analysis, scientists who were present in different scientific communities and served in this way as distributors or promoters of the information perspective towards neuronal processes are identified. Six key persons are selected for a detailed citation analysis. The methods used for the conference and citation analysis are outlined in the Appendix.

The Information Perspective in Neuroscience

The report of the Neurosciences Research Program work session on "Neural Coding" in January 1968 begins with the sentence (Perkel & Bullock, 1968, p. 227; emphasis added):

> The nervous system is a *communication machine* and deals with information. Whereas the heart pumps blood and the lungs effect gas exchange, whereas the liver processes and stores chemicals and the kidney removes substances from the blood, the nervous system *processes information*.

This statement outlines the development within neuroscience that led to the notion of the "information processing brain" (Churchland & Sejnowski, 1992), whose basic unit—the neuron—is an entity that "transmits information along its axon to other neurons, using a neural code" (Reinagel, 2002, p. R542). Although the terms "information," its "processing," or the "neural code" are—even today—often just vaguely defined and mostly used in a rather metaphorical sense (Bennett & Hacker, 2003), their usage reflects changes in the way biology, in general, and neuroscience, in particular, have been performed during the last few decades. "Information" has become a central concept in the biological sciences. Processes in molecular biology, developmental biology, and neuroscience are often considered as processes where information is "read," "transformed," "computed," or "stored" (Oyama, 2000; Bray, 1995; Kay, 2000). This information perspective on biological processes is part of the "cognitive turn" within neuroscience and psychology (Gardner, 1985). The cognitive turn reflects a challenge to the prevailing behavioral model of human functioning, which had dismissed the need to examine "interior" mental processes and looked for lawful relationships in learning experiments. The application of the vocabulary provided by information theory (Shannon, 1948) and cybernetics (Wiener, 1948) allowed the investigation of neuronal processes such that the behavioral "black box" could be opened and even become an object of reverse engineering.

[1]The ISI Web of Knowledge is an integrated Web-based platform containing the Science Citation Index Expanded, the Social Sciences Citation Index, and the Arts & Humanities Citation Index and is hosted by The Thomson Corporation. Access (subscription necessary) via http://go5.isiknowledge.com/portal.cgi/ The data bases were accessed in February 2005 in order to perform this analysis.

The cognitive turn and the scientific conceptualization of information (Aspray, 1985) are interrelated processes. In a rather short time following the Second World War, a small group of mathematically oriented scientists developed a theoretical basis for conceptualizing "information processing" (or "computation"). They mainly created or specified the vocabulary for today's discussion about information processing in natural systems. Adapted to neuroscience, this vocabulary consists of the terms "neuronal channel," "neuronal code," "neuronal noise," and "neuronal computation" (Christen, 2006). Furthermore, cybernetics promoted a principle claiming that behavior and thought processes should be studied by the methods used for studying machines. This epistemic principle of the cybernetic research program was stringently formulated by Arturo Rosenblueth and Norbert Wiener (Rosenblueth & Wiener, 1950, p. 320):

> We believe that men and other animals are like machines from the scientific standpoint because we believe that the only fruitful methods for the study of human and animal behavior are the methods applicable to the behavior of mechanical objects as well. Thus, our main reason for selecting the terms in question was to emphasize that, as objects of scientific enquiry, humans do not differ from machines.

This principle served as an epistemic foundation for a large body of the cybernetics literature about the brain (e.g., Ashby, 1952; Young, 1964) and still serves as *credo* for neuromorphic engineering by saying that "if you really understand something, you can usually make a machine do it" (Anderson & Rosenfeld, 1988, p. xiii). In neuroscience, this shift in perspective on biological processes led to the development of computational neuroscience[2] (Sejnowski et al., 1988), wherein the brain not only became an entity that can be explained or modeled using recent technological concepts but the analysis of the brain may help to improve or to find new technology. The cognitive turn, expressed by the introduction of the information perspective in neuroscience, is thus a paradigmatic example of a transition of a scientific field.

Conference Analysis

After 1945 an increasing number of conferences dealt with the application of concepts of information theory and cybernetics to brain research. For this analysis, the major conferences in the fields of cybernetics (with focus on the Macy conferences), information theory in relation to biology, neuroscience in relation to the Neurosciences Research Program (NRP), and conferences that focus on neural modeling and theoretical aspects have been chosen. The Macy conferences—organized by the Josiah Macy, Jr. Foundation between 1946 and 1953—are widely acknowledged as one of the first attempts to establish interdisciplinary cooperation between scientists of different fields in the general context of cybernetics and systems theory (Pias, 2003, 2004). Topics related to neuroscience were regularly present on the agenda of the Macy conferences. The NRP was established in 1962 at the Massachusetts Institute of Technology (MIT) by Francis Schmitt and other collaborators (Schmitt, 1992; Swazey, 1975/1992). It intended to integrate classical neurophysiological studies with new methods provided by molecular biology and was a driving force in the establishment of contemporary neuroscience. Each conference was

[2]In Europe, the term "neuroinformatics" typically is used instead of "computational neuroscience," whereas in the United States, "neuroinformatics" refer to the development of IT (information technology) tools for neurodata management.

represented by a set of names of participants (see Appendix for details). The 38 conferences identified were clustered based on similarities concerning participants ("participants-distance"—basically the pairwise overlap of participant sets).

The analysis led to the identification of four main clusters (Figure 1). The first cluster consists of the Macy conferences (Table 1, first block). This is not surprising, because these conferences are similar in construction, as the Macy conferences were organized around a large core group. The Macy cluster is divided into two subclusters, because the first five conferences included a smaller number of visitors and because the members of the core group more reliably attended the conferences. The second cluster is formed mostly by the NRP work sessions and Intensive Study Programs (Table 1, second block). The NRP work sessions and study programs of the late 1960s and early 1970s are not part of the cluster, indicating an alternation of generations in combination with a change of focus. The third cluster, called "theory cluster," contains the conferences dealing with information theory, cybernetics, and neural modeling (Table 1, third block). This cluster splits into two subclusters, one of which contains all cybernetic and information theory conferences, whereas the second consists of conferences with a more biological focus. The remaining conferences are contained in a fourth cluster called the "biology cluster," because they deal mostly with biological topics (Table 1, fourth block). In this group, also the remaining NRP conferences are contained.

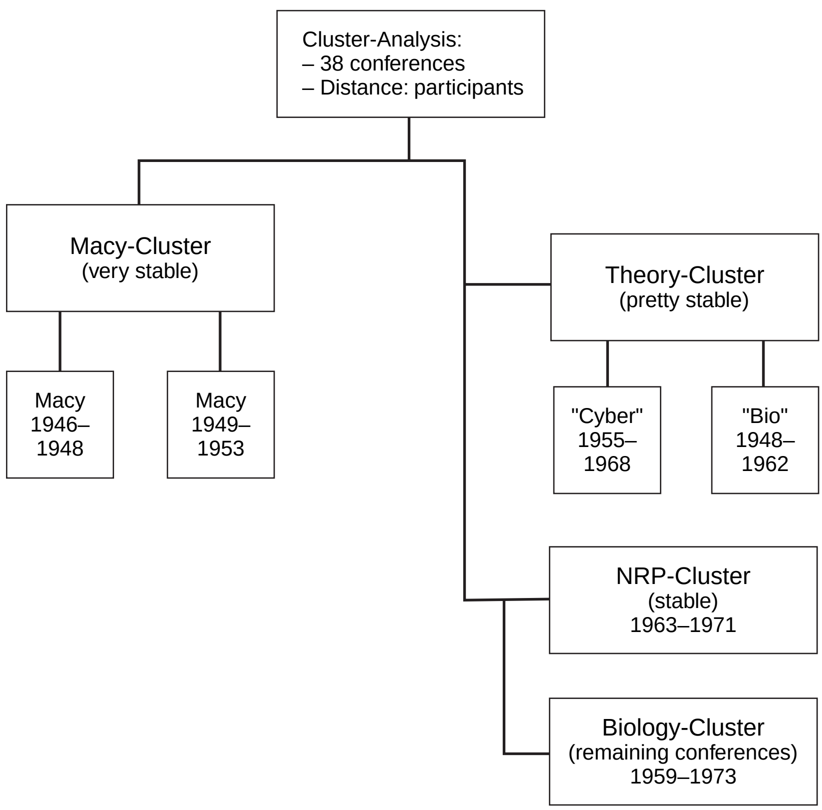

Figure 1. Cluster analysis of conferences. The result of clustering using the participant distance.

Table 1
Conferences grouped according to clusters (See Figure 1)

	Conference name	Date	Place	# P.
Macy-Cluster	1. Macy conference	08./09. March 1946	New York	21
	2. Macy conference	17./18. October 1946	New York	25
	3. Macy conference	13./14. March 1947	New York	26
	4. Macy conference	23./24. October 1947	New York	23
	5. Macy conference	Spring 1948	New York	28
	6. Macy conference	24./25. March 1949	New York	23
	7. Macy conference	23./24.March 1950	New York	24
	8. Macy conference	15./16.March 1951	New York	23
	9. Macy conference	20./21.March 1952	New York	27
	10. Macy conference	22.-24. April 1953	Princeton, NJ	28
NRP-Cluster	NRS summaries 1 (9 workshops)	1963-64	Cambridge, MA	108
	NRS summaries 2 (6 workshops)	1965-66	Cambridge, MA	102
	1. ISP	July 1966	Boulder, CO	64*
	NRS summaries 3 (6 workshops)	1967–68	Cambridge, MA	97
	NRS summaries 4 (5 workshops)	1966–1968	Cambridge, MA	108
	NRS summaries 5 (5 workshops)	1967–1969	Cambridge, MA	114
	2. ISP	21.07. – 08.08. 1969	Boulder, CO	92*
	NRS summaries 6 (5 workshops)	1968–70	Cambridge, MA	103
	NRS summaries 7 (4 workshops)	1970–71	Cambridge, MA	85

(*Continued*)

Table 1
(*Continued*)

	Conference name	Date	Place	# P.
Theory-Cluster	The Hixon Symposium	20.–25. Sept. 1948	Pasadena, CA	19
	Information Theory in Biology	Summer 1952	Urbana, IL	15*
	3. Symposium on Information Theory	12.–16. Sept. 1955	London, UK	50*
	1er congrès international de cybernétique	26.–29. June 1956	Namur, Belgium	79*
	Information Theory in Biology	29.–31. Oct. 1956	Gatlinburg, TN	32*
	Mechanisation of Thought-Processes	24.–27. Nov. 1958	Teddington, UK	211
	Self-Organizing Systems	05.–06. May 1959	Chicago, IL	19*
	4th Symposium on Information Theory	29.08. – 02.09. 1960	London, UK	53*
	Principles of Self-Organization	08./09. June 1961	Urbana, IL	39
	Information Storage and Neural Control	1962	Houston, TX	16
	Cybernetic Problems in Bionics	03.–05. May 1966	Dayton, OH	69*
	School on Neural Networks	June 1967	Ravello, Italy	22*
	Information Processing in the Nervous System	21.–24. Oct. 1968	Buffalo, NY	67
Biol.-Cluster	Principles of Sensory Communication	19.07. – 01.08. 1959	Cambridge MA	42
	Information Processing in the Nervous System	10.–17. Sept. 1962	Leiden, Netherlands	66
	Neural Theory and Modelling	04.–06. Dec. 1962	Ojai, CA	36
	1. International Symposium on Skin Senses	March 1966	Tallahassee, FL	45
	3. ISP	24.07. – 11.08. 1972	Boulder, CO	124*
	NRS summaries 8 (5 workshops)	1970–72	Cambridge, MA	113

NRS: Neroscience Research Symposium. ISP: Intensive Study Program.
*indicates that only the contributing authors of the conference proceedings and not the participants have been used to generate the name databases.

The analysis reveals a rather close connection between the clusters that emerge based on participation similarity and the thematic fields that were discussed in the conferences. This shows that the majority of participants are rather well tied to their particular scientific community. As the focus of this contribution is the distribution of the ideas of cybernetics and information theory within different scientific communities, scientists who frequently were present in at least two of the main identified clusters were analyzed further. These scientists served as the basis for choosing key persons that will be the subjects of a detailed citation analysis.

Citation Analysis

We identified 32 persons who were present in at least two clusters (see Appendix). As expected, many members of the Macy core group belong to this set (12 scientists)—indicating the strong interdisciplinary interest of those scientists. When considering only those scientists, which were present in at least three clusters (12 in total), four persons from the Macy tradition fall in this category: Julian Bigelow, Ralph Gerard, Warren McCulloch, and Heinz von Foerster. Four of the other persons of this category (Horace Barlow, John Eccles, Patrick Wall, and Cornelius Wiersma) were physiologists by training, and three (Leon Harmon, Werner Reichard, and Oliver Selfridge) descended from a basic science or engineering tradition with some affinity to biological questions. The person most evenly present in all four clusters was the British information theoretician Donald MacKay, although Warren McCulloch participated in the largest number of all conferences considered. If the 32 scientists identified are classified according to origin, we find that 15 originated from the United States and 10 migrated to the United States—indicating that the "information processing" perspective on neuronal processes has been developed to a large extent in the United States (we have to note that the analysis did not cover any sources from the Soviet Union). Within the "non-Americans," researchers from the United Kingdom dominated.

For the citation analysis, the following 6 persons out of the 32 identified were chosen: Warren McCulloch (1898–1968), the scientist with the highest number of conference participations, as he was involved in several important scientific debates concerning the "information-shift" in neuroscience—notably in neural modeling (McCulloch & Pitts, 1943), the neuronal channel capacity discussion (MacKay & McCulloch, 1952), and the establishment of the brain-computer analogy (McCulloch, 1949). Donald MacKay (1922–1987), as he was probably the intellectually most comprehensive researcher within the "information-domain" (MacKay, 1954, 1956, 1966), which is reflected in the fact that he was present in conferences of all four clusters. From the scientists mostly related to neuroscience, Ralph Gerard (1900–1974), a leading figure in neuroscience at that time, as well as the two neurophysiologists Horace Barlow (1921-) and Theodore Bullock (1915–2005) were chosen. Gerard was co-organizer and proceedings-editor of the 1962 symposium on "Information Processing in the Nervous System"—an encounter of neurophysiologists and leading theorists (modelers, mathematicians, and experts in computer and system science) that proved to be a main event in the emergence of the information perspective in neuroscience (Christen, 2006). The latter two were major figures in the early neural coding debate (Barlow, 1961a, 1961b; Bullock, 1967). Finally, Werner Reichardt (1924–1992) was chosen, as he became an important promoter of cybernetics in Germany and showed up with surprising frequency in the conferences we investigated.

The citation analysis reveals clear differences in the publication activity and scientific appreciation of the work of the six scientists (note that in the graphs the numbers of publications are scaled with ten to increase visibility). For example, the publication patterns of McCulloch (Figure 3) and Gerard (Figure 2) are very different, although they worked in quite similar fields, were both important representatives of the Macy-tradition and emerged from the same generation of scientists in terms of age. The graph of the citation analysis of Gerard (Figure 2) shows a classical behavior (Glänzel & Schoepflin, 1994): a maximum (in the mid-1960s) and a steady decay.[3] Furthermore, the work of Gerard was basically acknowledged in the same fields in which he published. An exception is his work in psychology (human sciences), which is obviously less recognized than his work in cellular biology and medicine.

The citations of McCulloch, however, display a sudden increase in the late 1980s—an uncommon pattern in citation analysis (Figure 3). This particularity of McCulloch's citations can be ascribed to the McCulloch-Pitts paper of 1943 (McCulloch & Pitts, 1943), which accounts for more than 40% of all citations of McCulloch's work. If this paper is

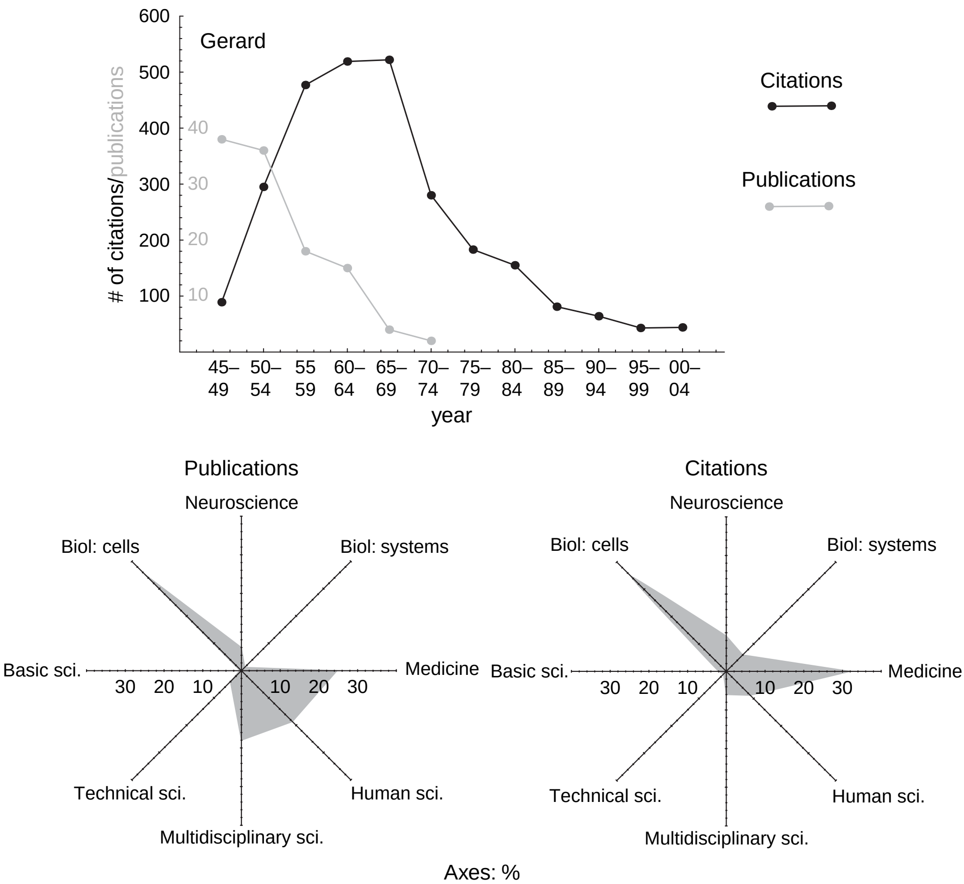

Figure 2. Citation analysis for Gerard: Above the citations and publications per five-year period (note that the number of publications in the graph is scaled with 10 to increase visibility). Below, the classification of the publications and citations of Gerard are indicated.

[3]Note that the location of the maximum in the citation graph can be affected by the onset of the database (1945).

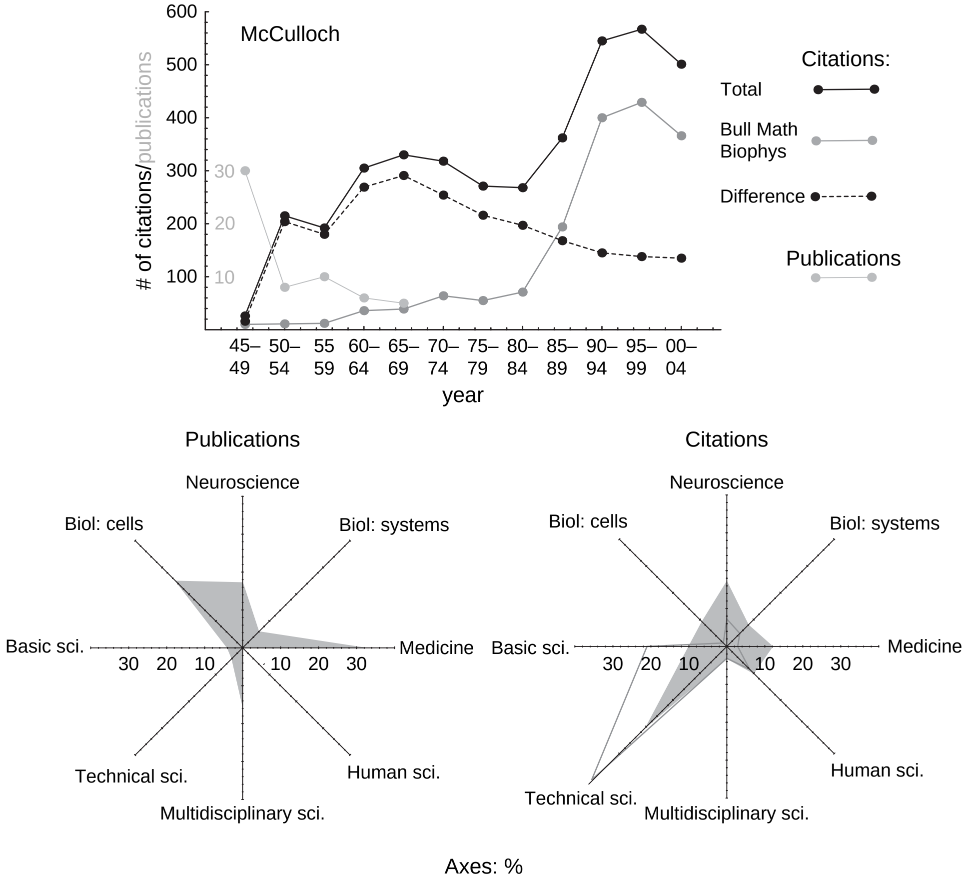

Figure 3. Citation analysis for McCulloch: Above, the number of citations (all papers, only [McCulloch & Pitts, 1943], difference between both numbers) and the number of publications per five-year period since 1945 are indicated. Below, the classification of the publications of McCulloch and the citations of his work is shown. The distribution of the citations of the McCulloch-Pitts paper is indicated by the grey line (unfilled area).

excluded from the citations, the number of citations of McCulloch per time shows the rather classical, abovementioned decay. When the impact of this paper in relation to different scientific fields is investigated, a strong bias towards the technical sciences (mostly computer science) is visible. A closer analysis shows that the sharp increase in citation of the McCulloch-Pitts paper between 1985 and 1995 is largely related to the increasing publication activity within the neural network community following the contribution of John Hopfield (1982), which made neural networks (again) a legitimate topic of research for many scientists. Although Hopfield cited the McCulloch-Pitts paper only for suggesting a binary type of neuron (no firing vs. firing at maximum rate), the paper became a “founding paper” for a growing community of scientists—the neural network and, to a lesser extent, the computational neuroscience communities. McCulloch’s work in medicine—the field with the largest fraction of McCulloch’s publications—is, however, not strongly acknowledged by the medical community.

The two physiologists investigated—Barlow and Bullock—show the highest number of citations in total. This indicates the different citation culture in biology compared to other fields, e.g., the technical sciences. There are, however, some interesting differences between Barlow and Bullock: Almost a quarter of Bullock's citations emerge from his well-known standard monograph "Structure and Function in the Nervous Systems of Invertebrates" (Bullock & Horridge, 1965), which very soon after publication was acknowledged in the community as a standard work (Figure 4). It is, however, not a work whose importance increased in time as the McCulloch-Pitts paper, because the classical decay behavior in citations can be observed. Therefore, the fact that the number of citations of the work of Bullock is still high cannot be explained by a single work. It also is notable that the impact of Bullock's work is restricted to the biological sciences—thus, in those fields where he also published.

Barlow, on the other hand, has several well-cited publications, but no single publication that accounts for a significant number of the total number of citations (Figure 5). Furthermore, he wrote on average only two to four papers per year—but the work he published was usually well acknowledged by the community. The citations increase considerably in the mid-1960s, indicating that Barlow became a prominent scientist in that period. The fact that Barlow's citations usually fall in the category of "neuroscience" (a category

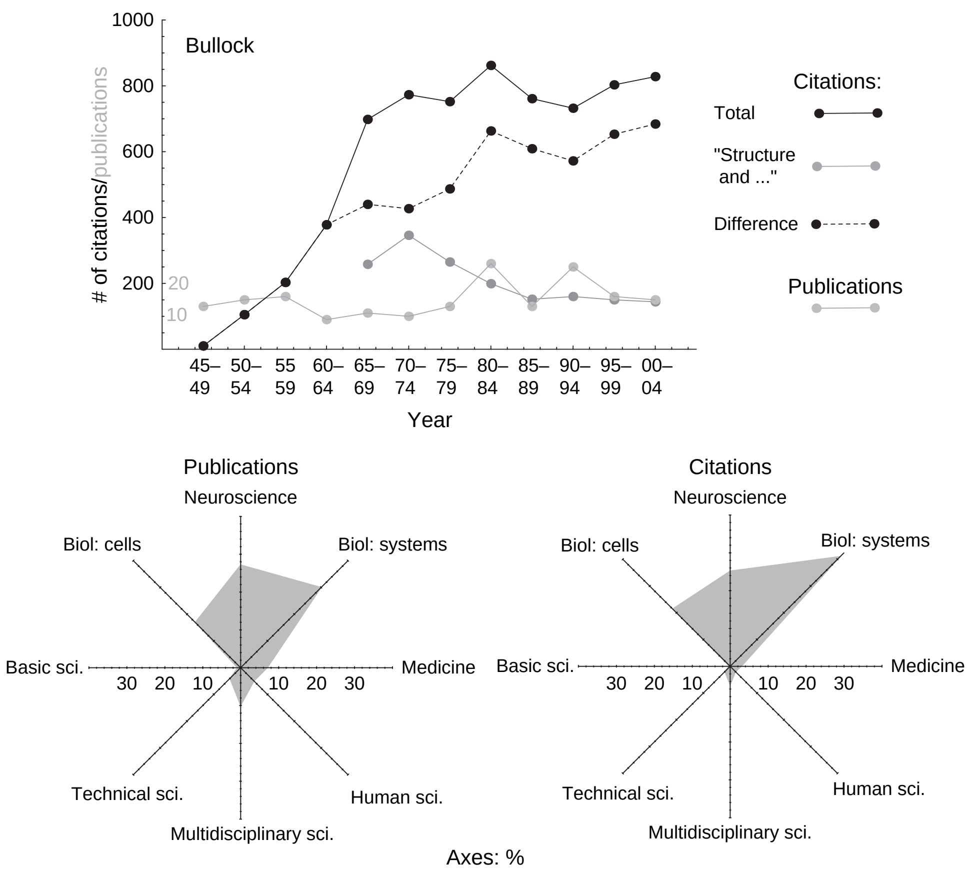

Figure 4. Citation analysis for Bullock: Above the number of citations and publications per five-year-period are indicated. Below the classification of publications and citations according to different fields is shown.

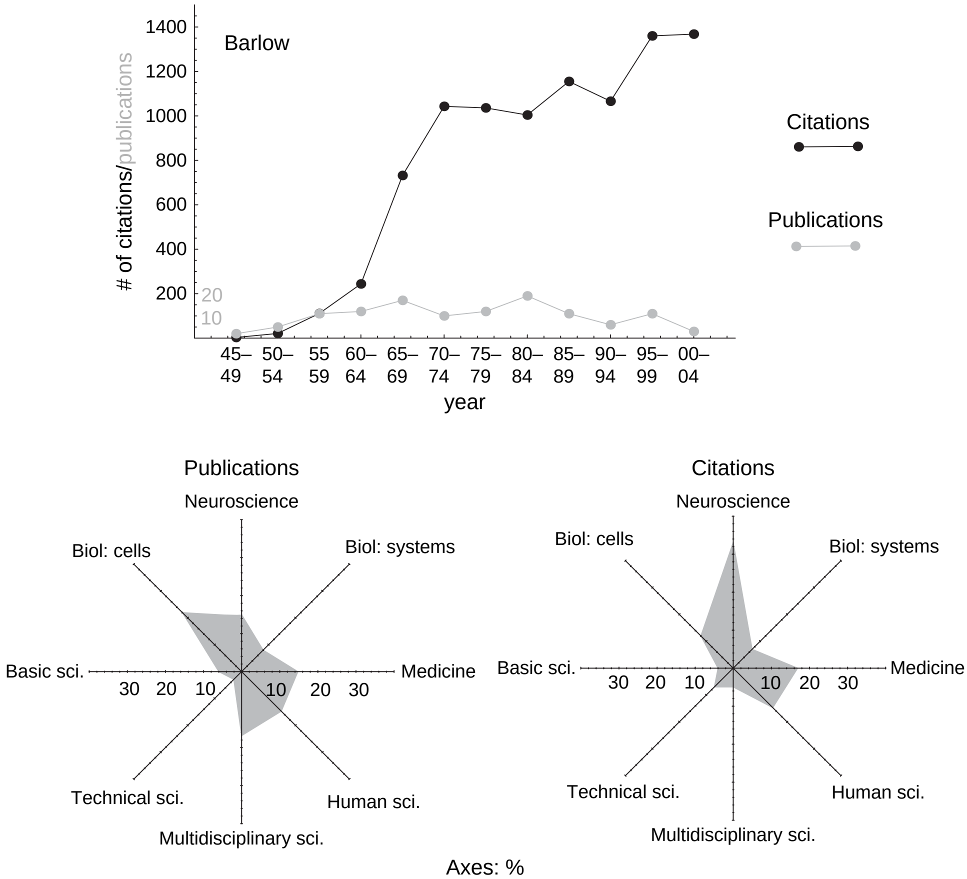

Figure 5. Citation analysis for Barlow: Above the number of citations and publications per five-year period are indicated. Below the classification of publications and citations according to different fields is shown.

to which newer journals are attributed), together with the nondecreasing curve of citations, indicate that he still is well acknowledged in neuroscience today. Interestingly, Barlow's work had some impact in the technical sciences, human sciences, and medicine as well—which probably is associated with his work on the visual system.

The two multidisciplinary European scientists—MacKay and Reichardt—also display interesting differences in the citation analysis. For both, the absolute numbers of citations are considerably smaller than those of Barlow and Bullock. At least for Reichardt, this difference reflects the bias of the ISI-database towards American and English journals; a considerable number of his publications is not contained in the ISI database, which distorts the citation analysis.[4] The citation analysis of MacKay shows a peak in the mid-1970s, when he published the most (Figure 6). His citations decay slowly, indicating, that he is still rather influential. MacKay shows publication activity in all fields, which demonstrates his broad interdisciplinary interest. Compared to all six, he is most cited in the

[4]The official Web site of the Max-Planck-Society (http://www.kyb.mpg.de/~wreichardt) lists 70 journal articles, 27 conference papers, 24 book chapters, and 5 popular scientific publications—in total 126 publications. The ISI Web of Knowledge database contained only 59 entries.

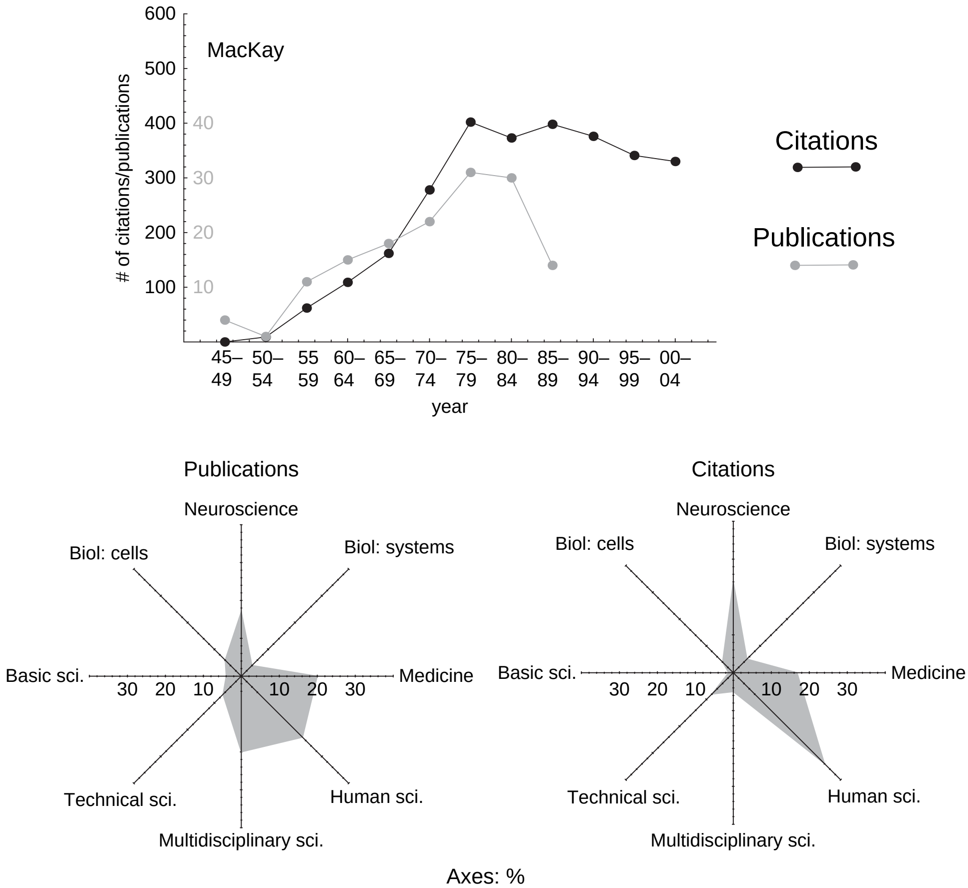

Figure 6. Citation analysis for MacKay: Above the number of citations and publications per five-year period are indicated. Below the classification of publications and citations according to different fields is shown.

category human sciences (especially in psychology). Reichardt's citations, finally, show the slowest increase of all six protagonists (Figure 7). His citations reach a peak in the early 1990s, following his death. The analysis of Reichardt's publications according to category shows a "double-peak" characteristic for interdisciplinary work, as he published in neuroscience as well as in technical science journals. His major impact, however, lies in the biological sciences.

A general comment concerns the category "multidisciplinary science," where in all cases a considerable difference between the fraction of papers published and the fraction of citations can be observed. This is a result of the effect that publications in interdisciplinary journals (e.g., "Nature" or "Science") usually are not cited again in these journals, but mostly in specialized journals. Furthermore, publications in interdisciplinary journals promote the author's own work, such that citations in these contributions often refer to the author's work that was published in specialized journals (Urs Schoepflin, Max-Planck-Institute for the History of Science, Berlin: personal communication). This explains why the fraction of publications in the field "multidisciplinary science" is usually larger than the number of citations in that field.

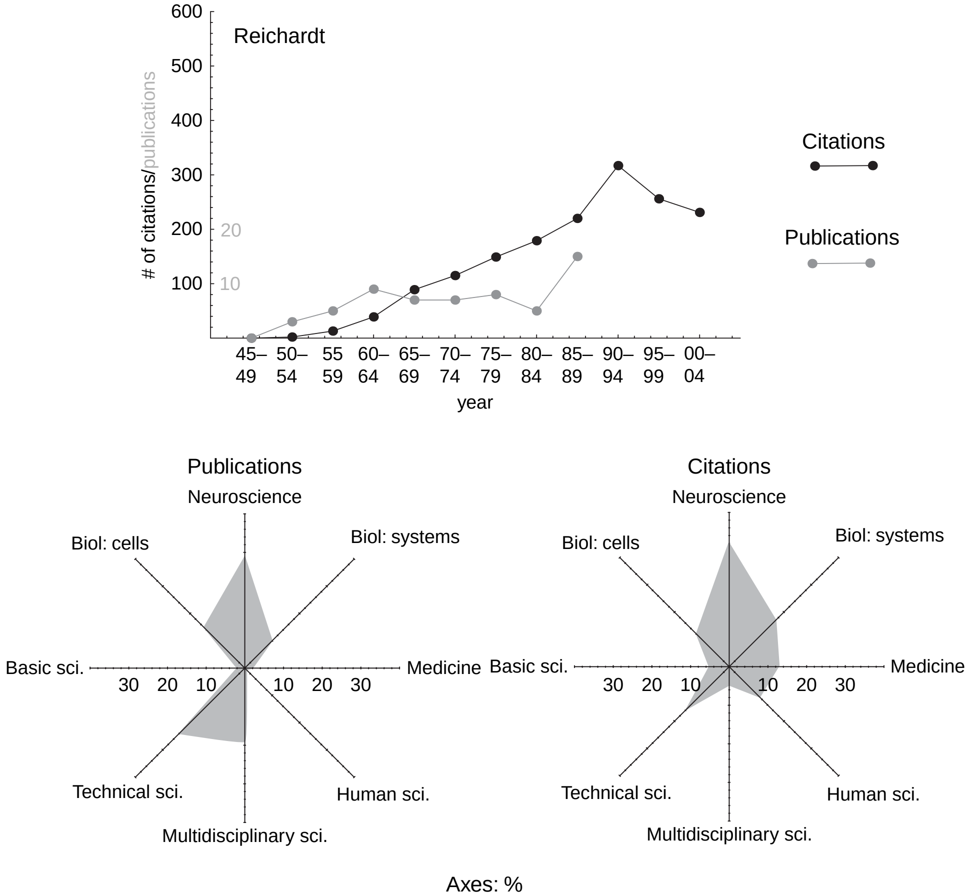

Figure 7. Citation analysis for Reichardt: Above the number of citations and publications per five-year period are indicated. Below the classification of publications and citations according to different fields is shown.

Conclusion

The analysis demonstrates that scientists whose work can be attributed to a single transition in neuroscience—the emergence of the information perspective as a part of the cognitive revolution—nevertheless display very different publication patterns. This is not per se a surprising observation, as it would be astonishing to find uniform behavior in this respect. Rather, our analysis displays the varieties of communication activities that are associated with such transitions. The following aspects are of particular relevance: first, a single publication (e.g., McCulloch) can get the status of a "founding paper" of new disciplines (in particular the neural network community) that are formed a long time after publication and in fields rather remote of the intended scope of impact (technical sciences instead of brain research). Second, in transition times, the main field of impact can be rather different than the field to which publications are attributed (e.g., McCulloch, Reichardt)—which is not surprising for transition periods, when new fields are formed. Third, high acknowledgement within certain fields is rather independent from the number of publications attributed to this field (Barlow vs. Bullock). Fourth, the peaks in publication activity and acknowledgement through citations may overlap (MacKay) or be well separated (Gerard). Fifth, language barriers affect the validity of publication and citation analysis (Reichardt). In particular the first and second aspects reflect characteristics that usually are attributed to transition periods—thus confirming, that indeed the proper persons have been chosen for this analysis.

It is important to remember the strength and limits of the quantitative methodology used in this contribution. First, by using appropriate distance measures, the clustering algorithm—that has proven to be powerful in various hard classification problems (Ott & Stoop, 2006)—also can serve for analyzing historical transition processes. The "participant-distance" is a rather simple measure and we are currently investigating more complex measures based on terms and concepts used in scientific publications. However, such methods cannot replace qualitative reflections regarding such transitions but instead serve as a complementary tool with an objective flavor. In this contribution, the cluster analysis basically confirmed the expected disciplinary group—but also showed that there are indeed *four* well-separated groups, which was not obvious from the beginning. Second, the quality of the citation analysis reflects the quality of the underlying database. This aspect is of particular relevance when the analysis covers periods at the onset of a database and includes scientists that may suffer from language biases—as the example of Werner Reichardt demonstrated. Thus, it is crucial that the quality of a citation analysis in such cases is evaluated carefully.

In summary, we find a large variety of publication patterns of scientists, who nevertheless are considered to be key figures in an important transition within neuroscience. This shows that such transitions are dynamic processes accompanied by communication activity that can only be acknowledged by a certain delay using classical citation analysis. Standardized evaluation procedures, which are tempting in times when performance-based funding dominates science policy (Herbst, 2007), may miss these aspects—in particular because such procedures usually do not span a sufficient period in order to ascertain emerging acknowledgements in fields other than the one(s) in which the person is working. This historical analysis calls for caution in this respect and suggests a more liberal, qualitative way of science evaluation in neuroscience and elsewhere.

Appendix

Cluster Analysis of Conferences

To generate the participant-database, the following sources were used: For cybernetics, the Macy conferences (10 conferences: Pias, 2003, 2004; von Foerster, 1950; von Foerster et al., 1951, 1952, 1953, 1954) and the Web site of the American Society for Cybernetics (ASC: http://www.asc-cybernetics.org/foundations/history/MacySummary.htm\#Part1) were used. For neuroscience, the activities of the Neurosciences Research Program (NRP) in the 1960s and early 1970s, which are published in a series of proceedings and monographs (45 work sessions and 3 Intensive Study Programs: Schmitt et al., 1977; Schmitt & Worden, 1974; Schmitt et al., 1973, 1972, 1971; Schmitt, 1970; Schmitt et al., 1970, 1969, 1967; Quarton et al., 1967; Schmitt & Melnechuk, 1966), were analyzed. The meetings usually took place at MIT. For the analysis, only those work sessions were considered that were published in the seven volumes of the Neuroscience Research Symposium Summaries. The fourth Intensive Study Program of 1977 was excluded from the analysis. As a detailed analysis of clustering of topics within the NRP sessions was not the focus of the analysis, the 45 NRP work sessions have been aggregated into eight groups according to the participant lists of the Neuroscience Research Symposium Summaries, leading to 11 "conferences." Finally, all conferences that were found during the search for historical sources in Christen (2006) were considered (17 conferences. Sources: Caianiello, 1968; Cherry 1956, 1961; Fields & Abbott, 1963; Gerard & Duyff, 1964; Jeffress, 1951; Kensalo, 1968; Leibovic, 1969; National Physical Laboratory, 1959; Oestreicher & Moore, 1968; Province de Namur, 1958; Quastler, 1953; Reiss, 1964; Rosenblith, 1961; von Foerster & Zopf, 1962; Yockey et al., 1958; Yovits & Cameron, 1960).

To obtain the conference clusters, we used a clustering paradigm, which does not require prior information concerning number and size of clusters (Ott et al., 2005). The algorithm requires the definition of a similarity measure that was provided by the "participant distance," given as the size of the intersection of the participant sets of two conferences and normalized by the larger set of both. From this result, 1 is subtracted and the absolute value is taken as the distance between two conferences. Thus, a distance "0" indicates that exactly the same participants were present in both conferences, and a distance "1" indicates that no person was in both conferences. To calculate the participant distance, a database was created containing the names of all researchers that were either listed as participants or—if a participant list was not available—listed as contributors to the proceedings. The name database contained 1481 names, for which name identities were carefully checked. For the NRP work sessions, lists were aggregated according to the eight volumes of the Neuroscience Research Symposium Summaries, covering four to nine work sessions. The pair-wise comparison of all conferences led to a distance matrix that was used as input for the clustering algorithm.

Citation Analysis

Based on the conference analysis, 32 persons were identified who were present in at least four conferences and at least two clusters.[5] Persons were excluded whose multiple presences in the NRP and biology clusters were due to the fact that they participated in the two NRP conferences that fell in the biology cluster, as they represent the continuation of the NRP community into the 1970s. For six of them, a detailed bibliometric analysis has been performed using the ISI Web of Knowledge database. First, the number of papers per year present in the database for the period 1945 up to the death of the person, as well as the number of citations per year for the period of 1945–2004, has been evaluated. The presence of homonyms has been carefully checked. Publications and citations were counted in a five-year window in order to smooth annual fluctuations. Publications and citations were analyzed according to the ISI subject categories in order to investigate in which fields they published and in which fields they had the strongest impact. Categories that contained less than 1% of the citations are excluded from the analysis (Reichardt: 0.5%). The ISI subject categories refer to the journals in which a paper is published. A publication in such a journal, or a citation within a publication in such a journal, leads to a score. As the analysis led to almost 100 subject categories in which the papers of the protagonists

[5]These persons are: Horace B. Barlow, Gregory Bateson, Julian H. Bigelow, Mary A. B. Brazier, Henry W. Brosin, Theodore H. Bullock, Colin Cherry, John C. Eccles, Robert Galambos, Ralph W. Gerard, Leon D. Harmon, Heinrich Klüver, Rafael Lorente de Nó, Donald M. MacKay, Warren S. McCulloch, Frank Morrell, Vernon B. Mountcastle, Gordon A. Pask, Carl Pfaffmann, Walter H. Pitts, Henry Quastler, Anatol Rapoport, Werner E. Reichardt, Oliver G. Selfridge, Claude E. Shannon, Hans-Lukas Teuber, Heinz von Foerster, John von Neumann, Patrick D. Wall, Paul Alfred Weiss, Cornelius A. Wiersma, and Donald M. Wilson.

(or the people who cited them) fell, they have been grouped to eight classes with a comparable total number of citations and with a comparable thematic connection as follows:

- **Neuroscience:** Neurosciences
- **Biology - Systems:** Anatomy & morphology, behavioral sciences, biodiversity, conservation biology, developmental biology, ecology, endocrinology & metabolism, entomology, environmental sciences, evolutionary biology, marine & freshwater biology, microscopy, oceanography, plant sciences, zoology
- **Medicine:** Anesthesiology, cardiac & cardiovascular system, clinical neurology, ergonomics, hematology, medicine: general & internal, medicine: research & experimental, nutrition & dietetics, obstetrics & gynecology, oncology, ophthalmology, orthopedics, otorhinolaryngology, parasitology, pathology, peripheral vascular disease, pharmacology & pharmacy, psychiatry, public environmental & occupational health, radiology, nuclear medicine & medical imaging, rehabilitation, sport sciences, surgery, toxicology, tropical medicine
- **Human Sciences:** Communication, education & educational research, history & philosophy of science, humanities: multidisciplinary, information science & library science, management, operations research & management science, philosophy, psychology, psychology: applied, psychology: biological, psychology: clinical, psychology: experimental, psychology: mathematical, psychology: multidisciplinary, religion, social issues, social sciences: interdisciplinary, social sciences: mathematical methods, sociology
- **Multidisciplinary Sciences:** Multidisciplinary sciences
- **Technical Sciences:** Automation & control systems, computer science: artificial intelligence, computer science: cybernetics, computer science: hardware & architecture, computer science: information systems, computer science: interdisciplinary applications, computer science: software engineering, computer science: theory & methods, engineering: biomedical, engineering: chemical, engineering: electrical & electronic, engineering: industrial, engineering: mechanical, engineering: multidisciplinary, instruments & instrumentation, materials science: multidisciplinary, robotics, telecommunications
- **Basic Sciences:** Chemistry: multidisciplinary, chemistry: physical, electrochemistry, mathematics: applied, mathematics: interdisciplinary applications, mechanics, optics, physics: applied, physics: fluids & plasma, physics: mathematical, physics: multidisciplinary, statistics & probability
- **Biology – Cells:** Biochemistry & molecular biology, biophysics, cell biology, genetics & heredity, physiology

The relative numbers of publications and citations that fall in each of these eight categories are displayed in a spider diagram showing the relative fraction of publications and citations in each category.

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