

Mapping Cognitive Neuroscience:

Two-dimensional perspectives on twenty years of cognitive neuroscience research

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Abbreviated Title: Mapping Cognitive Neuroscience

Total Number Actual Words: 5908

Total Number of Figures in Manuscript: 7

Total Word Equivalents: 8008

Introduction

Michael Gazzaniga and George A. Miller coined the name “cognitive neuroscience” in 1976, over martinis at the Rockefeller University Faculty Club. They chose the name to designate a new research program at the interface of systems neuroscience, computational neuroscience, and cognitive psychology. The goal of the research program would be to address the biological foundations of human cognition.

(Gazzaniga, 1984) In 1987, the James S. McDonnell Foundation, later joined by the Pew Trusts, made a commitment to grow and institutionalize this new field. One of the first initiatives McDonnell funded was the Summer Institute in Cognitive Neuroscience. Steve Kosslyn organized the first institute at Harvard University in 1988. Gazzaniga assumed the directorship of the Summer Institute the following year and has guided the institute since that time.

Gazzaniga initiated the practice of devoting every fifth Summer Institute to producing a volume that summarized the state of cognitive neuroscience at the time, presenting chapters that high-lighted both progress made in the previous four years and outstanding research questions for the future. This volume, coming 20 years after the first summer institute, is the fourth such volume. (Gazzaniga, 1995: 2000: 2004)

These Summer Institute Cognitive Neuroscience volumes (hereafter CN volumes) serve as significant resources for researchers and students in the field. Their impact comes as no surprise. Section editors and contributors were carefully picked from among the

leading authorities in the field to present critical reviews of all areas of research, from cellular neuroscience to cognitive psychology, that were deemed relevant to the cognitive neuroscience enterprise.

As compilations of state of the science review articles, the CN volumes can be viewed not as snapshots, but rather as photo-albums of the development of cognitive neuroscience. This perspective piece will capitalize on this feature of the volumes to initiate a historical look at this still relatively young field. Such a perspective is useful for established researchers and new students to assess progress the field has made, as well as to recall the origins of problems and questions in the field. Cognitive neuroscience also provides an interesting example for scholars of science to examine how an initially multi-disciplinary research program coalesces into a new research field.

In this perspective piece, I attempt to initiate this historical discussion using articles published by contributors to the CN volumes as the starting point. As a first step, I will examine how publication patterns in cognitive neuroscience and how research topics changed between 1988 and 2007. Using bibliometric methods and data visualization techniques developed by information scientists, I will generate journal-citation and topic-word maps of a small portion the cognitive neuroscience literature. Although the resulting maps are interesting and illustrative, keep in mind that they are first steps and generated from the published work of a relatively small and possibly unrepresentative sample of cognitive neuroscientists. Compared to larger studies of

disciplines and maps of the entire scientific literature, the maps below can be characterized as “toy maps,” in the same sense as early connectionist models were dubbed “toy networks.” Like the early toy networks, these toy maps illustrate trends, questions, and possibilities that might be addressed in more extensive bibliometric and historical studies.

The Author, Publication, and Topic Word Data Set

Bibliometric studies are based on published documents and relations that hold among them. Studies can be done at various levels of analysis (individual papers, authors, journals, institutions, nations, or scientific disciplines) and using various relations, among them citation, co-citation, and co-authorship. This study will begin by compiling two author sets. The first author set consists of the 150 authors who contributed chapters to the CN 1995. The second author sets consists of the 107 authors who have contributed the current volume, CN 2008. These two author sets have 20 authors in common. For the 1995 contributors, I collected from the *Web of Science* the bibliographic records for all articles these authors published in 1995. I will call this the 1995 data set. To obtain a longer historical perspective, I also collected bibliographic records for all articles these authors published in 1988, the earliest year available on the *Web of Science*. I will call this the 1988 data set. For the contributors to the current volume, I collected bibliographic records for all articles they published in 2007, the most recent complete

year available on the *Web of Science* when the search was executed. This is the 2007 data set. The journals in which the authors published in each of the three data sets, plus data on journal co-citations, provide the basis for three journal citation maps (1988, 1995, and 2007). With these maps one can visualize how publication patterns changed and see the citation flow among journals publishing cognitive neuroscientific research. Using programs developed by Loet Leydesdorff (Leydesdorff, 2004; 2005), I gathered title-word co-occurrence data for articles in the three data sets to create topic-word maps. With these maps one can visualize how research topics in cognitive neuroscience and their inter-relation might have changed between 1988 and 2007. The data for the author sets is summarized in Table 1.

The Journal Citation Maps

A journal citation occurs when an article in journal A cites a previously published article in journal B. In citation maps, this relation is depicted as $A \rightarrow B$, read “A cites B.” Citations flow from journal A to journal B. If the journals cite each other, this is represented as $A \leftrightarrow B$. Journal citation maps have a long history in bibliometric studies of science. On a large scale, using hundreds or thousands of journals, they can be used to visualize inter-relations among major scientific disciplines. (For example, see www.eigenfactor.org) On a smaller scale, they can be used to show how sub-disciplines (Leydesdorff, 1994; McCain, 1998)

On the small scale employed in this study, one might hope to see how cognitive neuroscience emerged from its progenitor disciplines (systems neuroscience, cognitive psychology, neuropsychology) by noting changes in co-citation patterns among the progenitor discipline journals and possibly through the appearance of new cognitive neuroscience journals. These maps also allow us to visualize the citation flow among journals and to assess how results and ideas flowed among them. For an interdisciplinary field emerging from a multi-disciplinary foundation, like cognitive neuroscience, one might be able to see how, for example, ideas and results from neuroscience fed into psychology, from psychology into neuroscience, or both.

In order to assure, clear and readily interpretable maps, the journal citation maps presented here include only journals publishing five or more articles in each of the data sets. There are around 30 journals in this category for each data set and these journals contain on average 62 percent of the articles in each set. (See Table 1.) These journals and the number of articles they published in each data appear in Table 2. These journals fall into four general categories neuroscience (N), psychology (P), general (G), and clinical medicine (C).

The Science and Social Science Citation Indexes publish annual compilations of journal citation counts for major scientific journals, the Journal Citation Reports (JCR). For the 1988 journals, the citation data came from 1987 JCR, the year closest to 1988 for which I had access to hard-copy volumes of the reports. For the 1995 and 2007 journals

data came from the on-line version of the JCR available through *Web of Science*, for 1995 the 1998 reports (the earliest year available on-line) and for 2007 the 2006 reports (the latest complete year at time of data collection).

For each of the data sets, the citation data is entered into an asymmetric matrix, where entries are the number of times row-journal A cites column-journal B. The matrix is asymmetrical because generally if journal A cites journal B n times, it is not the case the journal B cites journal A n times. Journal self-citations are omitted, so the matrix diagonal is empty. Asymmetric matrices are isomorphic to directed graphs, where in this case journals are nodes in the graph and directed edges represent the citation relation. It is these graph structures that information scientists call maps.

Journals vary widely in the number of papers published in a year and thus vary in the citation opportunities they afford and in the number of citations they make. To normalize the citation data, the relative frequency with which journal A cites journal B (the number of times journal A cites journal B divided by the total number of citations journal A made in that year) is used as a measure of similarity or relevance between journals. The asymmetric relative frequency matrices are input to *Pajek*, a network analysis and visualization program (de Nooy, Mrvar & Batagelj, 2005), that yields the directed graphs, or journal citation maps. To remove citation noise and clutter, relative frequency threshold of greater than .03 is used. Edges representing relative frequencies of .03 and less are removed from the maps. Nodes are placed in the map using the

Kamada-Kawai algorithm which represents the network as a system of springs with relaxed lengths proportional to the edge length and iteratively repositions nodes to minimize overall energy of the spring system. The node size is scaled to the journal's "importance," which will be explained below. Isolated journals in the maps, that is journals that do not cite or are not cited above the threshold by other journals, are shown in the top left of each map. Figure 1 presents the journal citation map for the 1988 data set.

Before analyzing entire maps, it is useful to focus first on portions of the maps, on sub-graphs within the larger directed graphs. Is it possible to identify subsets of journals that mutually influence one another? Are there subsets of journals where there is a citation flow from one journal in the subset to every other journal in the subset? If so, in a directed graph, these subsets of journals would form strong components of the graph. A strong component is the largest subset of nodes in the graph for which there is a directed path (a path following the direction of the arrows) from any node in the subset to any other node. A strong component in the journal citation map is then the largest subset of journals for which there is a directed citation flow from each journal in the component to any other journal in the component. One can thus identify the strong components as cohesive sets of journals that mutually seek ideas, methods, and results from one another. The strong components in the journal citation maps represent cohesive sub-disciplines of cognitive neuroscience. Figure 2 shows the strong

components of the journal citation maps for 1998 (Figure 2a), 1995 (Figure 2b), and 2007 (Figure 2c).

Each of the three maps contains the same two strong components. The larger component in each map, the neuroscience component (the black nodes in Figure 2), contains journals that are categorized in Table 2 as neuroscience journals. The number of journals in the neuroscience component varies from 5 (1988, 2007) to 8 (1995). The *Journal of Neurophysiology* and *Experimental Brain Research* appear in the neuroscience strong component for all three data sets. The second, and smaller component, is a general science component (the white nodes in Figure 2) which remains constant in the three maps and contains the prestigious, multi-disciplinary journals *Nature*, *Proceedings of the National Academy of the U.S.A. (PNAS)*, and *Science*. The percentage of articles in the article sets published by journals in the neuroscience component is 12 percent in 1988, 18 percent in 1995, and 21 percent in 2007. The percentage of articles published in the prestigious general science journals is between 8 and 9 percent each year. These two strong components, containing at most five percent of the journals for each data set, publish around 30 percent of the articles written by volume contributors in each of the years. No psychology or clinical journals appear in any of the strong components.

We can interpret the neuroscience component as representing a highly cohesive, mutually influential set of journals, which captures one sub-discipline of cognitive neuroscience over the last 20 years. The existence of the general science component

indicates that contributors to cognitive neuroscience are publishing articles in this highly selective group of journals and that the contributors to CN 1995 and 2007, by publishing in these journals, are part of the scientific mainstream.

Note also that the citation flow between the two strong components is the same for the three data sets. Journals in the neuroscience component cite journals in the general science component and never conversely. Articles in the general science component serve as sources for ideas, results, and methods in neuroscience. This is no surprise. The elite journals in the general science component are highly selective and publish across all areas of science. One would expect that neuroscience articles that meet publication criteria for the elite journals would be cited by core neuroscience journals, such as the *Journal of Neurophysiology* and the *Journal of Neuroscience*. Conversely, one would not expect disciplinary journals, like the neuroscience journals, to be cited with high relative frequency in general science journals which publish articles across the scientific spectrum.

Let us now turn to interpreting entire journal citation maps, as shown in Figures 1, 3, and 4. First, one can discern the strong components, discussed above, at the center of each of the three maps. In the maps there also journals (five in 1998, four in 1995, and two in 2007) that are not connected to any other journals above the .03 threshold. In the 1988 map, all five isolated journals are psychology journals; in 1995, there is a two journal component containing two of the major psychology journals. In 2007, there is a

three journal component which consists of two neuroscience journals and a clinical journal.

The large single components are comprised overwhelmingly of neuroscience and general journals. In 1988, three psychology journals appear on the periphery of the large component, *Behavioural and Brain Science*, *Journal of Clinical and Experimental Neuropsychology*, and *Psychophysiology*. In 1995, none of the five psychology journals listed in Table 2 appear in the large component. In 2007, the three psychology journals, *Brain and Language*, *Perception* and *Psychophysiology Brain and Language* appear on the edge of the dominant neuroscience-general science component.

How might one identify “important” journals in these maps? Numerous methods for determining centrality, or prestige, of nodes in a network have been developed by graph theorists and social network analysts. (Wasserman and Faust, 1994) Here, following a suggestion by Börner, Chen, and Boyack (2003), I will identify important journals in the maps by determining each journal’s hub and authority scores. (Kleinberg, 1999) In analyses of links between pages on the World-Wide Web, Kleinberg observed that some pages were pointed to by many hyperlinks and that these pages tended to contain primary or authoritative information on a topic. He called such pages *authorities*. There were other pages which sometimes contained little primary content, but pointed to numerous pages that did. He called such pages *hubs*. Kleinberg developed a method to compute authority and hub scores for nodes in a directed graph.

This method formalizes the intuition that a good authority is pointed to by other good hubs and a good hub points to many good authorities.

In the context of a journal citation map, journals with high authority scores are journals that are highly cited by other highly citing journals. Journals with high authority scores then would tend to serve as sources for ideas, methods, and results for the journals that cite them. A journal with a high hub score cites many other authorities and can be viewed as serving a synthesizing function, by bringing together ideas, methods, and results from numerous authority journals.

Pajek includes a function that computes authority and hub scores for directed graphs, such as the journal citation maps. It also partitions the maps into four disjoint sets of nodes. It is these partitions that are shown in the maps in Figures 1, 3, and 4. Some journals are neither authorities nor hubs (white nodes in the maps); some are both authorities and hubs (black nodes); some are authorities only (dark gray); and some are hubs only (light gray). Nodes representing the journals are scaled according to their authority and hub scores, with the white nodes representing a zero score on both measures. Dark gray nodes are sized to authority scores and light gray nodes to hub scores. Black nodes are sized to the sum of the authority and hub scores for those dual-role journals. The *Pajek* routine requires that one specify the number of authorities and hubs to be identified. I assumed that every cited journal is a potential authority and every citing journal is a potential hub. Thus, for 1988 the routine was requested to find

12 authorities and 18 hubs, for 1995 15 authorities and 24 hubs, and for 2007 14 authorities and 21 hubs.

The authority-hub journals with hub-plus-authority scores greater than .2 are shown in Table 3. All the journals in Table 3 are either neuroscience journals or general journals; that is, all journals that are in the two strong components are also both authorities and hubs. There are hub-authority journals that are not in one of the strong components, but their hub-plus-authority scores are quite low: *Behavioural and Brain Science* (score .10, a psychology journal) in the 1988 map; *Behavioral and Brain Research* (score, .11) in 1995; and *Brain Research* (score, .10) and *Neuropsychologia* (.01) in 2007.

There are relatively few pure authority journals in the maps. The three pure authority journals in the 1988 map and the two in the 1995 are all neuroscience or clinical journals. In 2007, there are three pure authority journals; *Perception* and *Psychophysiology* are psychology journals and *Neuroimage*, a neuroscience journal devoted to brain imaging studies and methods, which, as we will see in the topic maps, has become the mainstay of cognitive neuroscientific research. All these journals, with one exception, might be called degenerate pure authorities. They have authority scores less than .01, some barely over zero. The exception is *Neuroimage* in the 2007 map that has an authority score of .05.

The most common role for a journal in these citation maps is that of a pure hub. There are 9 pure hubs in the 1988 map, 13 in the 1995 map, and 11 in the 2007 map.

Table 4 shows the pure hub journals with hub scores greater than .2. All are neuroscience journals and acquire their high hub score by dint of citing authoritative journals in both the neuroscience and general science strong components.

What is the relation between psychology and neuroscience indicated by the publication patterns of the 1995 and 2008 CN contributors? If one looks at the number of psychology journals publishing more than five articles in our article sets, their number declines from eight psychology journals in 1988, to five psychology journals in 1995, to three psychology journals in 2007. The percentage of articles in each data set published in psychology journals likewise decreases from 25.0 percent in 1988, to 10.3 percent in 1995, to 7.3 percent in 2007. Based on the overall exclusion of psychology journals from the main components of the journal citation maps and using authority and hub scores as measures of journal importance, one can conclude that the cognitive neuroscience literature, at least as published by contributors to the 1988 and 2008 CN volumes, is dominated by neuroscience and general science journals. There is no significant citation flow from neuroscience to psychology or conversely, at a relative frequency threshold of .03. If one goes below this threshold and includes all instances of a psychology journal citing a non-psychology journal or conversely, for the 1995 and 2007 journal sets, where complete data were available, there are 57 instances of a psychology journal citing a non-psychology journal versus 20 instances of non-psychology journal citing a psychology journal. So for these authors and years,

whatever citation flow there is appears to occur at a very low level and tends to be from psychology to neuroscience; that is, there is a greater tendency for psychology journals to look to neuroscience journals for ideas, results, and methods than conversely.

I mentioned in the introduction that in the late 1980s computational neuroscience was also considered to be a contributing discipline to the development of cognitive neuroscience. In the 1558 articles in the three combined data sets only four articles were published in dedicated computational neuroscience journals, two published in *Computational Neuroscience* and two in *Neural Networks*. If computational neuroscience was a primary contributor to cognitive neuroscience, one can only assume that it is under-represented among the authors and articles considered here. On the basis of these publication patterns, one can conclude cognitive neuroscience appears to be a variety of neuroscience, and thus that the field is appropriately named.

The journal citation maps also reveal something about the emergence of cognitive neuroscience as a field, apart from its relation to progenitor disciplines. An important step in the development of any new field is a journal dedicated to work in the field. The *Journal of Cognitive Neuroscience* began publication in 1989 and appears both in the 1995 and 2007 journal citation maps. It published 2.5 percent of the entire 1995 article set (the eighth-ranked journal in number of articles published) and 2.5 percent of the 2007 article set (the tenth-ranked journal). In both maps, the *Journal of Cognitive Neuroscience* is a pure hub with moderate hub scores, .13 in 1995 and .07 in 2007. In this

capacity, it appears to serve an interesting integrative function. In 1995, it appears to synthesize work from the *Journal of Neuroscience*, *Nature*, and *Neuropsychologia*.

Neuropsychologia, according to its website, “publishes papers that explicitly address functional aspects of the brain ...” (www.elsevier.com) and describes itself as a journal in the behavioral and cognitive neurosciences. Functional aspects of the human brain as studied in neuropsychology rely heavily on cognitive psychological models of human behavior. As one can see in the 1995 map, *Neuropsychology* also cites *Neuropsychologia*. Thus, in 1995 we can view the *Journal of Cognitive Neuroscience* as a journal integrating work in neuroscience, as found in the strong components of the citation map, with neuropsychology and through this connection to neuropsychology, to some extent with cognitive psychology.

In 2007 the *Journal of Cognitive Neuroscience* plays a similar integrating role. It once again synthesizes work from neuroscience and neuropsychology, as shown by its links to the *Journal of Neuroscience* and *Neuropsychologia*. However, it now also integrates ideas, methods, and results published in *Neuroimage*. *Neuroimage* began publication in 1993 and did not appear in the 1995 map. In 2007, however, it published 5.22 percent of the articles in that year’s data set, second only to the *Journal of Neuroscience* (8.63 percent of the articles⁰). Given that *Neuropsychologia* is the fifth-ranked journal in 2007, the *Journal of Cognitive Neuroscience* is a hub that cites and integrates work published in three of the most productive journals in the 2007 set.

Note also that *Neuroimage* is an authority journal with an authority score of .05. This journal is described as a journal that publishes imaging and modeling studies of structure-function relations in the brain. (www.elsevier.com) The emerging prominence of this journal is indicative of the central role brain imaging technologies play in contemporary cognitive neuroscience. We will see more evidence of the centrality of imaging and recording studies in the next section on topic maps in cognitive neuroscience.

Topic Maps

The stop-listed title words from articles contained in the three article sets can be used to generate topic maps of cognitive neuroscience for 1988, 1995, and 2007. (Freeware for compiling word co-occurrence matrices is referenced in Leytesdorff, 2004.) For each year, the analysis is limited to topic words that occur eleven or more times in the article titles that year. There were 38 such words for the 1988 articles, 66 words for the 1995 articles, and 59 words for the 2007 articles. Co-occurrence matrices are symmetric, so the graphs, and thus the maps, are undirected. In the matrix, each row is a vector of values giving the number times the row title word occurs with the column title word. To normalize the data and to compute distances between topic words in the map the cosine measure is used. This is the normalized inner product of the two vectors which yields the cosine of the angle between the two vectors. The cosine measure varies from 0

(no similarity between the two topic-word vectors) to 1 (identity between the two topic word vectors). The maps below are drawn using a threshold of cosine $\geq .2$. Topic words are placed within the map using the Kamada-Kawai algorithm as explained above. In these maps, each node is scaled to the logarithm of the number of occurrences of the title word in the article set for that year. The smallest nodes in each map represent 11 occurrences. The largest node occurs in the 2007 map, for *cortex* that occurs 76 times in article titles that year

At a threshold of cosine $\geq .2$, there are isolated nodes in the maps, words that despite their relatively high occurrence do not have vectors, or co-occurrence profiles, sufficient similar to any other topic words to be linked to it in the map. In the 1988 map there are 14 such isolated words, in the 1995 map 21 such words, and in the 2007 map 13 such words. These nodes have been removed from the maps.¹

The three maps are shown in Figure 5 –7. Before looking for cohesive subsets of words, it is instructive to look at the overall structure of the maps. In each year, the most frequent topic words are *visual* and *cortex*, indicating the prominence of research on the visual system in neuroscience and cognitive neuroscience. One can also see that the maps make intuitive sense, where topic words in the same proximity correspond with research topics in cognitive neuroscience; for example, *visual-spatial-attention* in 1988, *hippocampal-long-term-memory* in 1995, and *transcranial-magnetic-stimulation* in

2007. The maps indicate emergence of new methods, as with TMS, and new research areas, as shown the *memory-emotion-amygdala* branch of the 2007 map.

One interesting change in the maps is in the topic words that refer to methods and experimental organisms. In the 1988 map, the only two words referring to methods are *lesion* and *model*. In 1996 *lesion* is accompanied by *PET-study* and *response-potential*, the last two topic words referring to evoked response potential studies. By 2007, seven topic words, six of which refer to brain imaging and recording technologies, dominate the map. As for experimental organisms, in the 1988 map five topic words referring to experimental organisms appear (*aplysia*, *cat*, *monkey*, *primate*, *rat*), none of which refer to humans. In 1995, four topic words designate non-human organisms (*rat*, *cat*, *macaque*, *monkey*), but *human* and *patient* appear. In the 2007 map only *human* and *patient* occur as referring to experimental organisms, or more accurately participants. Over the twenty year period, method words in the maps increase, but the variety of experimental organisms, dwindles to one, humans.

For each of the three years, the map contains one large connected component and several smaller disconnected components. In 1988, there are three disconnected components. The *model-neural* component might be interpreted as representing neural networks or connectionist models. *Binding-receptor-brain* might represent neurochemistry. *Task-role* is too vague to interpret. There are also three disconnected sub-networks in the 1995 map. The largest of these, *rat-expression-receptor-differential-*

effect might again represent neurochemistry or genetics. There are six disconnected sub-networks in the 2007 map, that seem to refer to perception, neural correlates, cognitive control, motor control, object representations, and modeling.

Now let us look at the structure of the large connected components in each map. Cohesive subsets of topic words in these maps should delineate cohesive research topics that are prominent in cognitive neuroscience. One way to identify cohesive subsets of nodes in an undirected graph is to identify its k-cores. One can think of k-cores in the following way: every topic word in the map is connected to at least one other topic word. Thus, every node in the map is 1-connected or is a node in the map's 1-core. Some nodes of the 1-core are also connected to two other topic words, they are 2-connected. The largest set of 2-connected nodes is the map's 2-core. Of the set of all at least 2-connected nodes, some are 3-connected; the largest subset of these forms the 3-core. If we partition a map into its k-cores, we can envision nodes that only belong to a 1-core at the base of a mountain, where nodes belonging to higher-order cores form smaller layers of the mountain, until one arrives at the peak, the set of most densely inter-connected nodes. (Think of the large connected component of the map as a wedding cake with three layers. The first layer is analogous to a 1-core. The plastic bride and groom stand atop the layer analogous to the 3-core.)

The nodes in the topic maps are colored according to the k-core to which they belong. In these maps, the most densely connected topic words form a 3-core, shown as

white nodes in the maps. Nodes in the 2-core are black and nodes in the basic 1-core are gray.

The peak of the 1988 map is a 3-core which suggests that studies of motor control in primates was a highly cohesive research topic in that year. Note also that *cortex* is the most highly connected word in the map, having a co-occurrence profile sufficiently similar to nine other topic words to be linked to them in the map. In this map, the 3-core separates the 2-core. One part of the 2-core organizes around *visual*. *Visual* has the second highest number of connections in the map with six. The second part of the 2-core contains topic words relating to memory research. .

In the 1995 map, a single 2-core, again organized around *visual*, serves as the backbone of the map. *Visual* once again has the highest number of connections, five. Branching out from vision are five branches, four of which are descriptive of research areas (memory, visual studies in cat, and temporal lobe studies). The fifth branch of the 2-core is a methodological branch indicating the emergence of human PET studies.

The k-core structure of the 2007 map is quite different. The peak in the map is a 3-core containing nine topic words, the majority of which refer to brain imaging and brain recording. *Magnetic* and *study* are each connected with six other topic words, *imaging* and *related* with five. The 2-core is again separated into two non-contiguous parts, one representing the topic of transcranial magnetic stimulation (TMS) and one containing only the topic word *schizophrenia*, which in turn connects to 1-core words

referring to memory, emotion, and other words descriptive of research on learning and affect. The two most common and highly connected topic words in previous maps, *visual* and *cortex*, are now part of the 1-core with connections to only two and four other topic words respectively. If we imagine the 3-core removed from the map, we are left with four independent branches of the map. One of the four branches is again a methods branch relating to TMS. The three remaining branches are research subject branches containing words connoting affective processing, studies on sleep, visual attention and studies on prefrontal cortex.

Over the twenty year period, the topic maps change from being dominated by research areas with little mention of method, to being dominated by topic words referring to methods of brain imaging and recording. Overall the number of method words appearing in the maps increases and the number of experimental organisms decreases, to include only human studies. Research topic words, like *visual* and *cortex*, move from the peak of the maps to the base and decrease in their connectivity with other topic words. Brain imaging and recording come to occupy the highest ground in the maps and increase in their connectivity. This change in the topic maps is consistent with a change we noted in the journal citation maps: *Neuroimage* emerged in the 2007 map as the second ranked journal in number of publications and as a pure authority for three other journals in the map. Cognitive neuroscience appears to have changed from a

collection of diverse research subjects to a field dominated, if not defined, by imaging technologies.

The change in the experimental organism from a variety of non-human animals to solely human also reflects a significant change in cognitive neuroscience research. The intent of most cognitive neuroscientists from the outset has been to understand human cognition, relying on animal models where needed, appropriate, or the only alternative. As Gazzaniga and Miller described the new field, its intent was to describe the biological foundations of human cognition. At the outset, in the early to mid-1980s, the methods for studying human cognition (with the exception of electroencephalography) were confined to behavioral studies using unimpaired (cognitive psychology) or impaired (neuropsychology) participant groups. Animal models provided the means for conducting invasive studies. Brain imaging technologies, particularly the development of PET and later fMRI and TMS, coupled with paradigms from cognitive psychology, allowed cognitive neuroscientists to map cognitive functions onto neural structures in normal human participants. It became possible to study, at one level at least, the biological foundations of human cognition in humans. From this perspective, the journal citation and topic maps reflect the development of the field over two decades into the discipline Gazzaniga and Miller envisioned over the martinis.

Conclusion

The CN volumes used in this study seem to reflect nicely the emergence of cognitive neuroscience over the past two decades. Although the samples used here are small, there is much more of scientific and historical interest that could be gleaned just from the contributions to these, now, four volumes. It would be presumptuous to state any strong conclusions based on the data and methods used here. So, rather than offering conclusions, I will formulate two conjectures which the data imply that others might test and debate. First, a positive conjecture: Non-invasive imaging and recording technologies have allowed cognitive neuroscience to develop into a science of the biological foundations of human cognition.

Second, a cautionary conjecture: Cognitive neuroscience not only has become co-extensive with imaging studies, but also has become a variety of neuroscience, with psychology very much in the background. Might the full exploitation of advances in imaging technology require the constant infusion of better understandings of behavior, tasks, and task demands, along with better cognitive models?

In 1988, Michael Posner, Steve Petersen, Peter Fox, and Marcus Raichle (1988) articulated what I call the working hypothesis of cognitive neuroscience: “The human brain localizes mental operations of the kind posited by cognitive theories.” (p.1627) Imaging technology made this a viable and highly successful working hypothesis. This is consonant with my positive conjecture. In 1994, Posner and Raichle also stated “The

challenge for the future is to understand at a deeper level the actual mental operations assigned to the various areas of [brain] activation. Before this goal can be achieved, the experimental strategies used in PET studies must be refined so that more detailed components of the process can be isolated." (1994, p. 98). This statement would seem to suggest the importance of the continuous infusion of cognitive psychological ideas and results into cognitive neuroscience. This is consonant with my cautionary conjecture.

ENDNOTES

1. The isolated topic words deleted from the maps and their number of occurrences are:
for 1988, amnesia (11), cell (17), cortical (18), development (19), evidence (12), human (23), pattern (17), patient (15), potential (12), processing (16), response (14), studies (14), study (13), system (20) ; for 1995, attention (15), cell (22), cognitive (12), development (12), evidence (21), information (13), model (12), motion (13), multiple (11), primate (12), priming (11), processing (15), regulation (11), representation (20), role (17), selective (13), spatial (26), specific (11), task (17); for 2007, action (18), adult (11), behavioral (11), brain (40), effect (29), motion (16), movement (11), network (12), neuron (15), role (29), sensory (11), signal (11), and. temporal (26).

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Captions for Tables

Table 1. Summary of 1988, 1995, and 2007 data sets.

Table 2. Journals containing five 5 or more articles in each data set. P = psychology, N = Neuroscience, G = General, C = Clinical medicine.

Table 3. Hub-Authority journals with scores equaling the sum of their hub score and authority score.

Table 4. Pure hub journals with hub scores.

Table 1

Year	Authors	Articles	Title Words	Journals	Journals with ≥ 5 Articles	% Articles in Journals with \geq 5 Articles
1988	150	433	1531	144	26	57
1995	150	567	1870	159	33	64
2007	107	558	1713	146	27	66

Table 2

1988	1995	2007	
J Neurosci (N)	21 Invest Ophth Vis Sci (C)	26 J Neurosci (N)	48
B Psychonom Soc (P)	15 J Neurosci (N)	25 Neuroimage (N)	29
J Comp Neurol (N)	15 J Neurophysiol (N)	23 J Neurophysiol (N)	22
Nature (G)	13 P Natl Acad Sci USA (G)	20 Nat Neurosci (N)	21
Behav Brain Sci (P)	12 Nature (G)	19 Neuropsychologia (N)	20
Brain Res (N)	12 Neuropsychologia (N)	19 P Natl Acad Sci USA(G)	20
P Natl Acad Sci USA (G)	12 Brain Cognition (N)	15 Cereb Cortex (N)	18
Science (G)	12 J Cognitive Neurosci (N)	14 Neuron (N)	18
Exp Brain Res (N)	11 Behav Brain Sci (P)	13 Sleep (N)	15
J Clin Exp Neuropsych (P)	11 Eur J Neurosci (N)	12 J Cognitive Neurosci (N)	14
Psychopharmacology (N)	9 Neuroreport (N)	12 Biol Psychiat (C)	13
Trends Neurosci (N)	9 Science (G)	12 Perception (P)	13
Brain Cognition (N)	8 J Physiol-London (N)	11 Science (G)	13
Electroen Clin Neuro (C)	8 Neuron (N)	11 Trends in Cogn Sci (N)	12
J Exp Psychol-Learning (P)	8 J Comp Neurol (N)	10 Nature (G)	11
J Neurophysiol (N)	8 Trends Neurosci (N)	10 Brain Res (N)	10
Psychophysiology (P)	8 Cereb Cortex (N)	9 Neurosci Res (N)	9
Cognition (P)	7 J Exp Psychol Human (P)	8 Schizophrenia Bull (C)	9
Cog Neuropsych (P)	7 Neuroscience (N)	8 Brain and Language (P)	8
Epilepsia (N)	7 Behav Neurosci (N)	7 J Vision (C)	8
Neuropsychologia (N)	7 Behav Brain Res (N)	7 Movement Disord (N)	7
Prog Brain Res (N)	7 Brain Res (N)	7 Neurology (N)	6
J Physiol-London (N)	6 Exp Brain Res (N)	7 Psychophysiology (P)	6
Behav Brain Res (N)	5 Psychopharmacology (N)	7 Current Opin Neurobiol (N)	5
Devl Brain Res (N)	5 Biological Psychiatry (C)	6 Exp Brain Res (N)	5
Perception (P)	5 Current Opin Neurobiol (N)	6 Nat Rev Neurosci (N)	5
	Mol Brain Res (N)	6 Nervenarzt (C)	5
	Neurology (N)	6	
	Neuropsychology (N)	6	
	Pers Ind Diff (P)	6	
	J Exp Psychol Learn (P)	5	
	Psychological Science (P)	5	

Table 3

1988		1995		2007	
		Journal of			
Journal of Comparative Neurology	1.19	Neuroscience	0.80	Journal of Neuroscience	0.89
Brain Research	0.82	Brain Research	0.52	Neuron	0.74
Experimental Brain Research	0.50	Neuron	0.50	Nature Neuroscience	0.60
Journal of Neurophysiology	0.45	Nature	0.47	Journal of Neurophysiology	0.48
Journal of Physiology-London	0.31	Journal of Neurophysiology	0.46	Nature	0.44
		Journal of Comparative Neurology	0.45	Science	0.43
		Science	0.42	PNAS	0.33
		PNAS	0.34		
		Neuroscience	0.31		
		Experimental Brain Research	0.23		
		Journal of Physiology-London	0.20		

Table 4

1988		1995		2007	
Developmental Brain Research	0.37	European Journal of Neuroscience	0.39	Current Opinion in Neurobiology	0.50
Journ. of Neuroscience	0.31	Cerebral Cortex	0.30	Cerebral Cortex	0.34
Behavioural Brain Research	0.25	Molecular Brain Research	0.28	Nature Reviews Neuroscience	0.32
Trends in Neurosciences	0.20	Neuroreport	0.28		
		Psychopharmacology	0.28		
		Trends in Neurosciences	0.28		
		Current Opinion in Neurobiology	0.27		

Captions for Figures

Figure 1. 1988 journal citation map. Hub-authority journals are black nodes, authority journals dark grey nodes, hub journals light grey nodes. Nodes are proportional to hub scores, authority scores, and hub + authority score for the black nodes.

Figure 2a – c. The neuroscience (black nodes) and general science (white nodes) strong components of the 1988(a), 1995(b), and 2007(c) journal citation maps. Citations flow from neuroscience to general science strong component.

Figure 3. 1995 journal citation map. Hub-authority journals are black nodes, authority journals dark grey nodes, hub journals light grey nodes. Nodes are proportional to hub scores for light gray nodes, authority scores for dark gray, and hub + authority score for the black nodes.

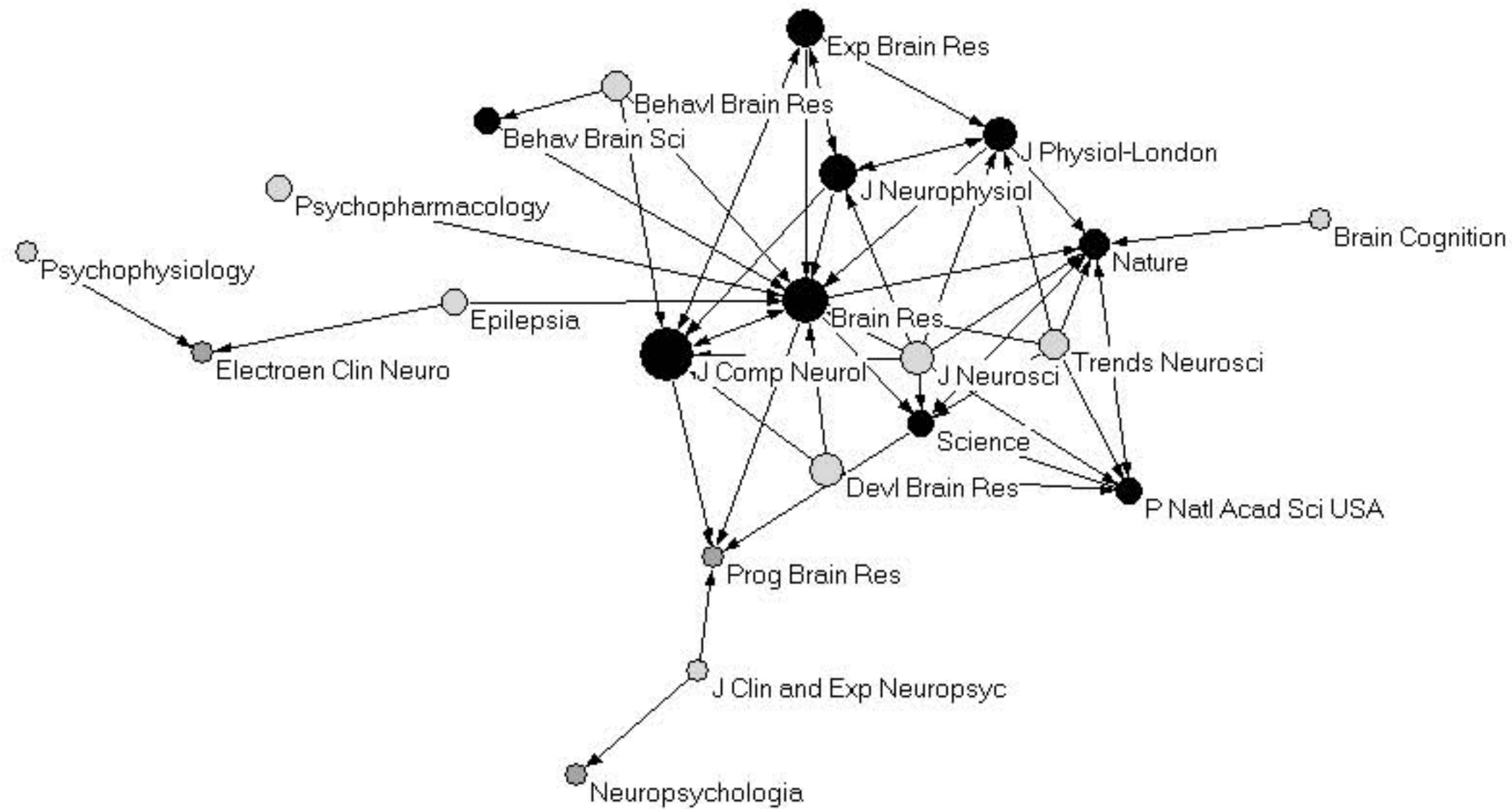
Figure 4. 2007 journal citation. Hub-authority journals are black nodes, authority journals dark grey nodes, hub journals light grey nodes. Nodes are proportional to hub scores, authority scores, and hub + authority score for the black nodes.

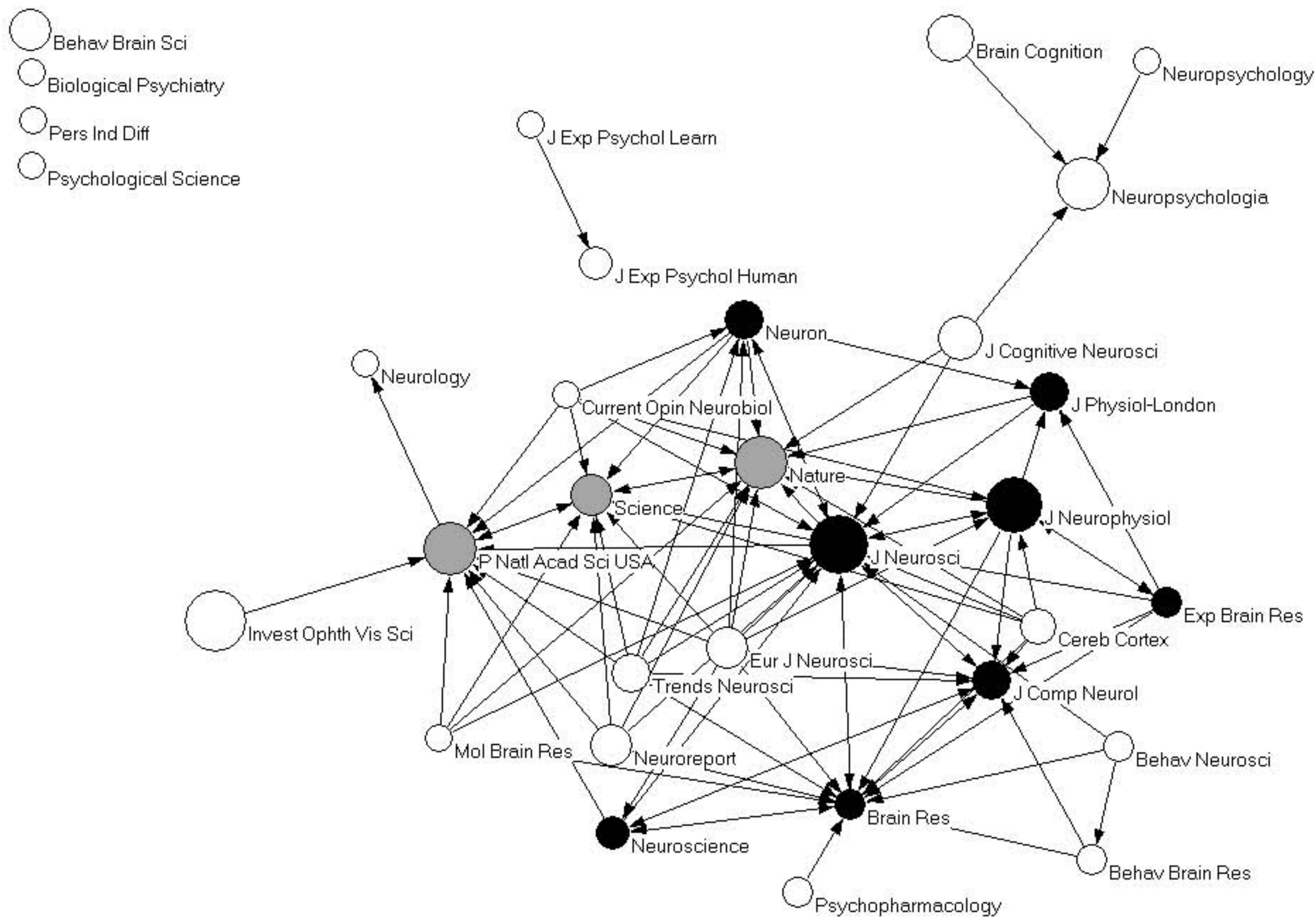
Figure 5. 1988 cognitive neuroscience topic map. Black nodes are in the 2-core and grey nodes in the 1-core. Node size proportional to log of word occurrences.

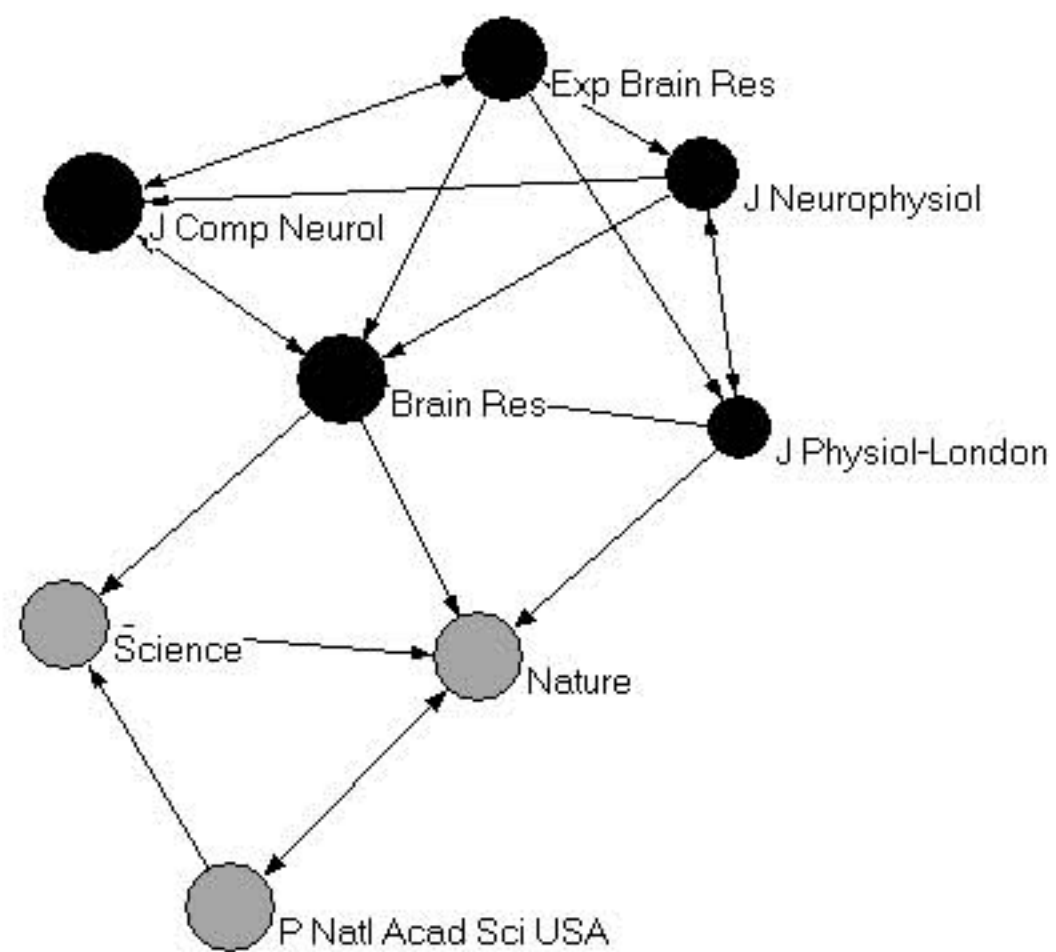
Figure 6. 1995 cognitive neuroscience topic map. White nodes are in the 3-core, black nodes in the 2-core, grey nodes in the 1-core. Node size proportional to log of word occurrences.

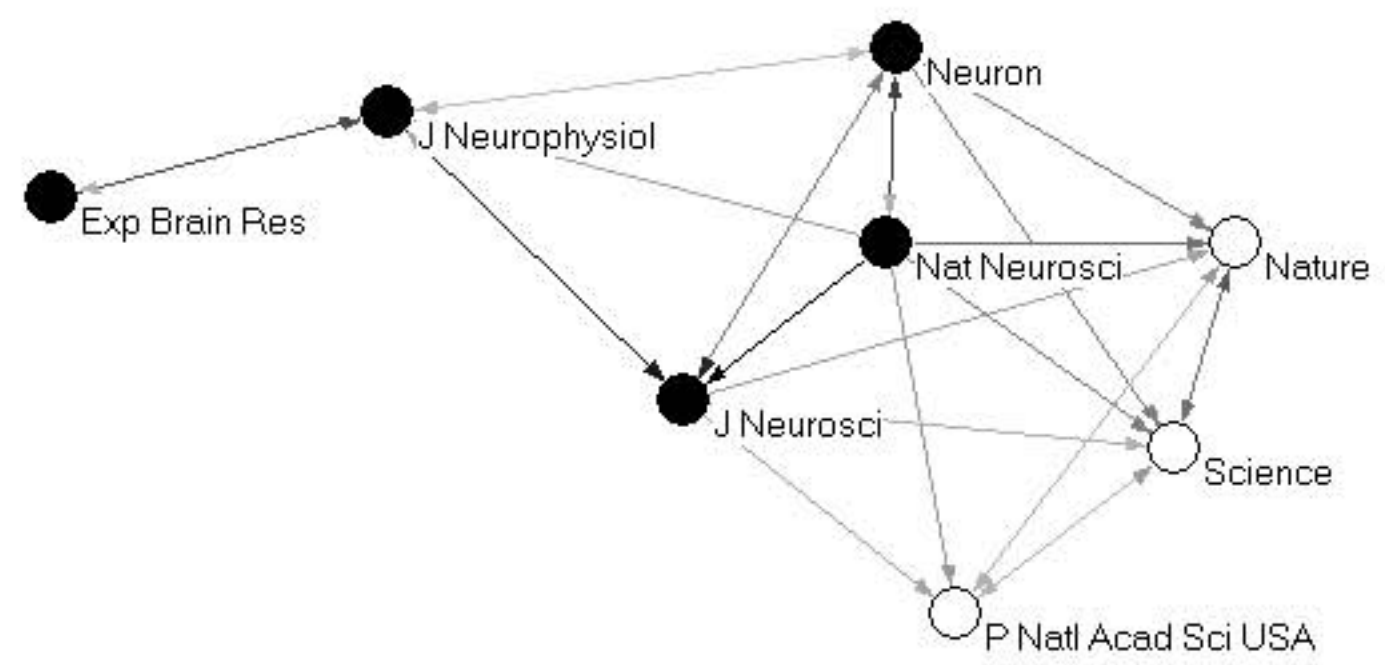
Figure 7. 2007 cognitive neuroscience topic map. White nodes are in the 3-core, black nodes in the 2-core, grey nodes in the 1-core. Node size proportional to log of word occurrences.

- B Psychonom Soc
- Cognition
- Cognitive Neuropsychology
- J Exp Psychol-Learning
- Perception

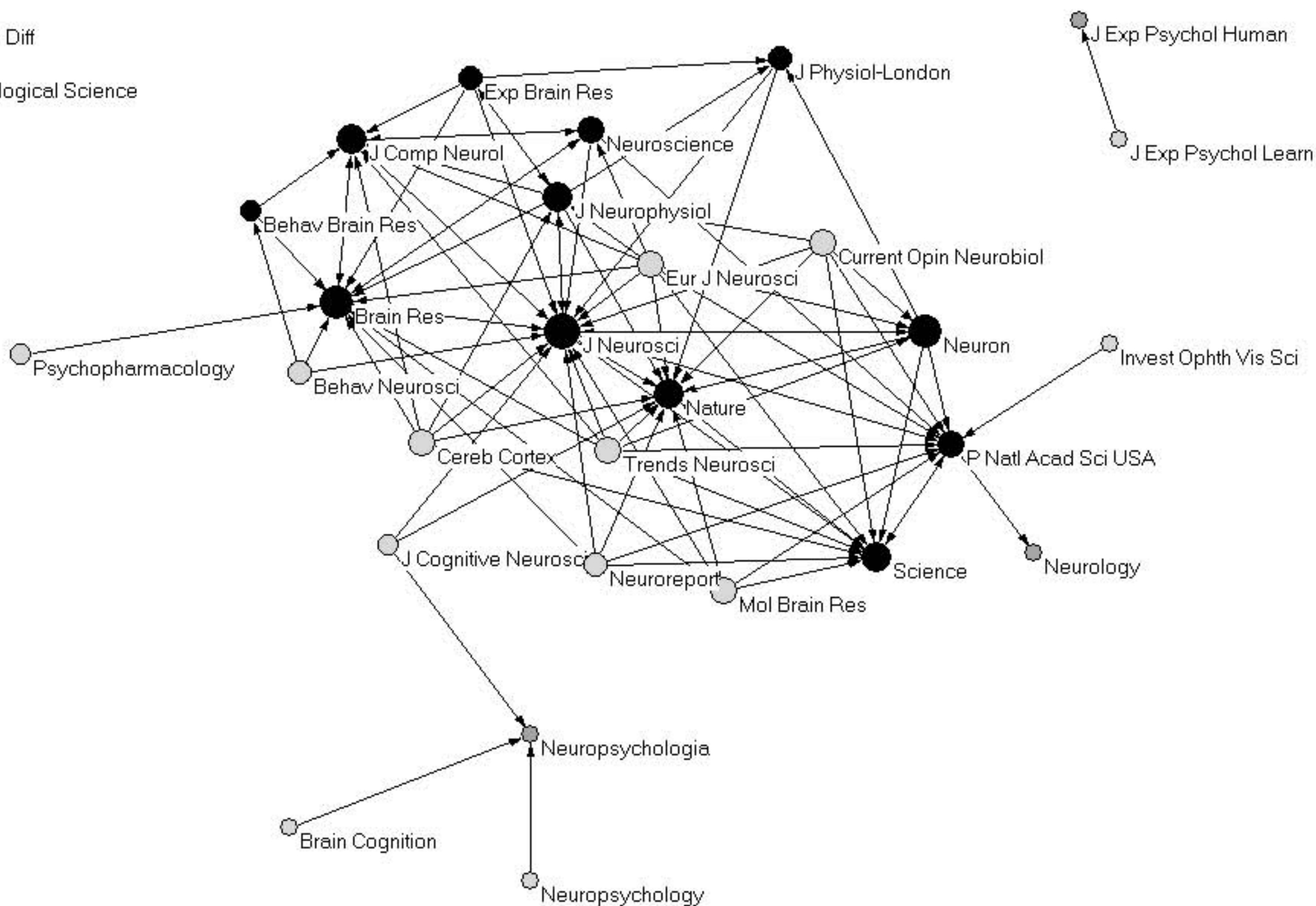








- Behav Brain Sci
- Biological Psychiatry
- Pers Ind Diff
- Psychological Science



- Sleep
- Schizophrenia Bull

