Can We Talk? How the Cognitive Neuroscience of Attention Emerged from Neurobiology and Psychology, 1980-2005

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Abstract
This study uses author co-citation analysis to trace prospectively the development of the cognitive neuroscience of attention between 1985 and 2005 from its precursor disciplines: cognitive psychology, single cell neurophysiology, neuropsychology, and evoked potential research. The author set consists of 28 authors highly active in attentional research in the mid-1980s. PFNETS are used to present the co-citation networks. Authors are clustered via the single-link clustering intrinsic to the PFNET algorithm. By 1990 a distinct cognitive neuroscience specialty cluster emerges, dominated by authors engaged in brain imaging research.

Introduction

In 1986, Joseph LeDoux and William Hirst (1986) co-edited *Mind and Brain: Dialogues in cognitive neuroscience.* In the preface, they state: "Researchers in both the brain and cognitive sciences are attempting to understand the mind. Neuroscientists and cognitive psychologists should be natural allies, but tend to work in isolation of one another. *Mind and Brain* represents a pioneering attempt to bring these two fields closer together. The editors' objective was to force scientists who are working on the same problem but from different perspectives to address each other." (p. i). Since the publication of LeDoux and Hirst's book, a new mind-brain science, cognitive neuroscience, had emerged from this initially forced dialogue. Cognitive neuroscience is now a vigorous, expanding, and highly institutionalized discipline.

The present study examines how cognitive neuroscience developed from those initial, forced exchanges. It will concentrate on one research area within cognitive neuroscience, research on attentional systems. Attentional systems enable us to select, voluntarily or involuntarily, from the vast stream of stimuli impinging on our senses, those stimuli that require in-depth processing. (See Hirst, 1986 for further explanation.) Attention is a mental construct that must be inferred from behavioral and other experimental data. Thus, research on attention should provide an interesting initial case study of how scientists integrated ideas and methods of neurobiology, largely dominated by behaviorist principles, with those of cognitive psychology, the science of the mental, to create a cognitive neuroscience of attention.

This paper uses author co-citation analysis to study the development of the dialogue. The analysis follows White (2003) in using raw author co-citation data to construct pathfinder associative networks, PFNETs. (Dearholt and Schvaneveldt, 1990) PFNETs simplify, or prune, co-citation networks, in such a way that the distance matrix for the original network is preserved. PFNETs have become popular in bibliometric studies for several reasons. PFNETs simplify networks, but retain structural information, thus facilitating visualization. (Borner, 2003; Chen, 2001) In addition, they simplify the mapping process for co-citation data (White 2003)

In four respects, the author co-citation analysis and PFNETS used here differ from those typically found in the literature. First, most author co-citation analyses begin by generating a comprehensive set of authors publishing in a discipline and use co-citations to map the intellectual structure of the discipline. (McCain, 1990: Borner, Chen, & Boyack, 2003) In contrast, this study attempts to trace the dynamic development of a new discipline

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prospectively, using a relatively small set of authors: 28 neuroscientists and psychologists, whose work figured prominently in LeDoux and Hirst's initial forced dialogue. These authors were the pioneering researchers in this nascent field. Their published work represents the proto-literature of the cognitive neuroscience of attention. This study traces how the structure of the proto-literatures changed from a loosely linked set of precursor literatures into a literature that served as the basis for the cognitive neuroscience of attention. Later studies will examine how this proto-literature, its authors, their students, and co-authors contributed to the further development of the field.

Second, most uses of PFNETs in the bibliometric literature present the finished PFNETs as binary graphs; that is, edges in the graph have weight zero or one. However, co-citation networks are valued graphs, wherein edge weights are co-citation counts. Here edge weights are put to interpretative use. Typically, bibliometricians use centrality measures to identify important authors in co-citation networks. Author centrality is usually based on degree, betweeness, or closeness centrality, but these measures are defined only for binary graphs. (Dearholt & Schvaneveldt, 1990; White, 2003) Flow betweeness centrality (Freeman, Boragatti, & White, 1991) is a centrality measures defined for weighted graphs that proves more suitable for these data.

Third, seldom do bibliometric studies exploit the information used to construction the PFNET. The PFNET algorithm begins with a set of unconnected nodes and adds edges to the net in decreasing order of edge weight. At any stage in net construction, nodes are either isolated or belong to a cluster containing at least two nodes. PFNET construction is an agglomerative clustering procedure equivalent to single link clustering. (Dearholt & Schvaneveldt, 1990) However, unlike a dendrogram, the PFNET contains an explicit representation of the links between author pairs that are responsible for the merging of clusters. Observing changes in PFNET structure, its clusters, and the order in which clusters merge, reveal how the publishing scientific community changes its judgment of the pair-wise salience of the cited authors' work, how these changes give rise to new specialty clusters, and how the salience of specialty clusters change over time.

Finally, PFNETs are defined by two parameters r, the dimension of the Minkowski metric used in the net, and q, the length of the path over which a triangle inequality defined from the metric must be observed. Most PFNETs appearing in the bibliometric literature are $r = \infty$, $q = n - 1$ nets, where n is the number of nodes in the network. This parameter choice results in the greatest pruning of a citation network. A PFNET (∞, n-1) has the property that only two kinds of edges appear in it, primary edges and secondary edges. A *primary* edge connects an isolated node to another node (isolated or not). A *secondary* edge connects two nodes that are already included in separate, but previously unconnected clusters; that is, secondary edges join pre-existing node clusters. This feature allows one to state a hypothesis about the development of the cognitive neuroscience of attention explicitly in terms of the types of edges appearing in the PFNETS (∞, 27) below. If LeDoux and Hirst were correct in their description of the dialogue between mind and brain scientists in 1986, one would expect to see a PFNET wherein brain scientists and mind scientists belong to distinct specialty clusters that are connected, if at all, only by secondary edges having low co-citation weight. As the dialogue matures, one would expect to see the specialty clusters connected by secondary edges having higher co-citation weights. Eventually one might expect to see mixed clusters of neuroscientists and psychologists, where neuroscientists and psychologists are joined by primary edges at relatively high levels of co-citation; that is, one would expect to see the emergence of a cognitive neuroscience specialty cluster relatively early in the construction of the PFNET. This hypothesis is examined using PFNETs for 28 highly-cited attention authors, based on citation data over a 20 year period, from 1985 through 2005.

Methods

Citation analysts rely on journals in the field, textbooks, comprehensive reviews or comprehensive, on-line literature searches to identify an appropriate set of authors for study. Such studies allow one to map the intellectual structure of the research discipline in which the authors are engaged. In the early 1980s, there were no cognitive neuroscience journals or textbooks, no comprehensive reviews of a non-existent or nascent field, and no authors readily identifiable as cognitive neuroscientists. The chapters in LeDoux and Hirst (1986), however, provide useful surrogates for review articles in a non-existent research area. LeDoux and Hirst engaged neuroscientists and cognitive psychologists in dialogues on four research themes common to neurobiology and cognitive psychology in the mid-1980s: attention, perception, memory, and emotion. For each research theme, a neuroscientist and a cognitive psychologist wrote a review from their disciplinary perspective. Each author also commented on the review of their theme written from the other scientific perspective. The reviews and exchange of commentaries attempted to highlight similarities and differences between the neurobiological and psychological approaches to the research theme, with an emphasis on finding common, or at least neighboring, ground. Thus, these reviews cite what could be considered the proto-literature for cognitive neuroscience. It is rare that we have an explicit attempt to identify independent, but potentially relevant, research that could provide the basis for a new interdisciplinary field. The co-citation analyses here exploit this unique opportunity trace the trajectory of cognitive neuroscience from forced dialogue to new research front.

Hirst (1986) wrote the review of attention research from the psychological perspective. D. L. Robinson and S.E. Petersen (1986) wrote the review from the neurobiological perspective. The Hirst review cites 93 distinct authors; Robinson and Petersen cite 135 distinct authors in their review. (These author counts include all authors on multi-authored papers.) In each review, numerous authors were cited multiple times. To keep the number of co-citation searches manageable and to limit citation “noise”, I defined a core author as an author cited five more time in one of the two reviews. Using this threshold there were 12 core authors representing the psychological perspective and 16 representing the neurobiological perspective. (Table 1) These 28 authors, 10 percent of all authors cited in the reviews, account for approximately 45 percent of the author citations in the two reviews.

Table 1. The 28 core attention authors and citation counts in the two reviews. Posner is the only core author who is highly cited from both the psychological and neurobiological perspectives.

Psychology	Neurobiology	
A. Treisman (12)	D.L. Robinson (25)	R. Galambos (6)
D.A. Norman (10)	M.E. Goldberg (15)	R. Naatanen (6)
W. Hirst (10)	S.A. Hillyard (13)	R. T. Watson (6)
U. Neisser (10)	K.M. Heilman (11)	R.A. Andersen (5)
R.A Shiffrin (9)	R. H. Wurtz (10)	C.W. Mohler (5)
C.D. Wickens (9)	M.C. Bushnell (9)	E.A. Weinstein (5)
D.G. Bobrow (8)	J. Hyvarinen (8)	
M.I. Posner (8)	S.E. Petersen (8)	
W.E. Schneider (8)	V.B. Mountcastle (7)	
D.C. Broadbent (6)	**M.I. Posner (7)**	
A.J. Marcel (5)	V. Schwent	
D. Navon (5)		

Separate co-citation searches for the core authors were done for the years 1985, 1988, 1990, 1995, 2000, and 2005. For 1985 citation data was collected from *Science Citation Index* (SCI) and *Social Science Citation Index* (SSCI) on the Dialogweb© system. For the other years searches were done on the *Web of Science.* The year 1988 was included, because at the time of data collection, 1988 was the earliest year for which citation data was available on the *Web of Science*.

The raw co-citation matrices served as input to the Knot software (available at www.geocities.com/interlinkinc/home.html) which generated the PFNETs (∞, 27). The nets were draw using with the Pajak graph visualization software (De Nooy, Mrvar, & Batagelj, 2005) and edited using Inkscape. (www.inkscape.org/download) Normalized flow betweeness centrality was computed for each author in the PFNETs using the algorithm available in UCINET. (www.analytictech.com) The author nodes are placed in the PFNETs using the Kawai-Kimura spring embedding algorithm, under the constraint that the node for Posner (the only core author from both the Hirst and Robinson-Petersen reviews) remains fixed in the net's center. Author nodes are scaled by their normalized flow betweeness centrality. Specialty clusters are coded by gray-scale and texture and are labeled in the respective nets. Connections between author nodes are scaled in each net by percentage of total co-citations for the given year. Given the importance of primary and secondary edges linking neuroscientists with psychologists in this study, cross-disciplinary primary edges are indicated by solid lines with hollow triangles at each end and cross-disciplinary secondary edges are indicated by dashed lines. Primary and secondary cross disciplinary edges are labeled by their co-citation weight (bold type) and the percentage of co-citations they represent (bold italic in parentheses.) As is well known, single link clustering can result in a long tail of single nodes attached to a single large graph component. To simplify visual presentation, these tail nodes do not appear in the nets. Nodes appearing in the figures are only those included in the PFNET at the point where the last cross-disciplinary secondary edge is added to the net.

Findings

Core Author and Co-citation Data

Of the 228 total authors cited in the Hirst and Robinson and Petersen reviews, the reviews cited only 4 common authors: M. I. Posner, R. H. Wurtz, C.W. Mohler, and B.T. Volpe. The two reviews cite only three common papers, (Posner, 1980) and (Wurtz & Mohler, 1976a, b). Posner was the only author that was highly cited in both the Hirst and the Petersen-Robinson reviews. Thus, based on these reviews, it would appear that in 1986, the common ground shared by the neurobiology and the cognitive psychology of attention was extremely limited.

Table 2. Changes in occurrence and distribution of core author co-citations 1985 – 2005.

Year	Author co-citations	Neuro-Psych co-citations (%)	% Non-zero Cells (n = 784)	% Non-zero Neuro-Psych Cells (n = 192)
1985	1291	123 (10)	49	25
1988	1259	281(22)	59	43
1990	2109	536 (25)	64	51
1995	2745	945 (34)	70	62
2000	3714	1458 (39)	69	55
2005	3317	1314 (40)	63	53

Table 2 summarizes the co-citation data by sample year for the 28 core authors. The number of author co-citations increased 2.6 fold between 1985 and in 2005, whereas the co-citation of between neuroscientists and psychologists, increased around 11-fold over this time period, representing 40 percent of all co-citations by 2005. The percentage of non-zero cells in the entire co-citation matrix increased from 49 percent in 1985 to 64 percent in 1990 and remained over 60 percent thereafter, an increase of between 15 and 21 percent. Confining attention to neuroscientist-psychologist author pairs, the percentage of non-zero cells in these sectors of the co-citation matrices increased from 25 percent in 1985 to 62 percent in 1995 and remained over 50 percent thereafter, an increase of between 25 and 37 percent. These data indicate that the scientific community increased co-citation of attention core authors between 1985 and 2005 and increased the percentage co-cited neuroscientist-psychologist pairs even more rapidly. It would appear that LeDoux and Hirst's forced dialogue of 1986 became more congenial over the course of the next two decades.

Author Centrality

Table 3 shows the top 5 authors in each PFNET based on normed flow betweeness centrality computed from their co-citation counts. Posner is the most central author in each year. (Posner is by far the most central author using any centrality measure, binary or weighted.) Other central authors tend to be neuroscientists, save Broadbent in 1990 and the emergence of Treisman as a highly central author in 2000 and 2005. Of particular interest, as will be seen below in the discussion of the individual nets, is the increased centrality of Richard Andersen and Steven Petersen between 1985 and 2005. These two authors had zero flow betweeness centrality in 1985 and became the second and third most central authors by 2000.

Table 3. Top five authors in each sample year ranked by normed flow betweeness centrality.

1985		1988		1990	
Posner	65.8	Posner	88.3	Posner	86.0
Wurtz	57.8	Wurtz	44.0	Mountcastle	44.5
Robinson	40.1	Mountcastle	21.4	Broadbent	27.6
Mountcastle	34.0	Hillyard	21.2	Hillyard	21.2
Hillyard	8.0	Heilman	14.4	Heilman	14.5
1995		**2000**		**2005**	
Posner	83.6	Posner	85.4	Posner	82.6
Andersen	49.0	Petersen	47.0	Petersen	36.3
Hillyard	20.5	Andersen	33.6	Andersen	34.6
Petersen	15.1	Hillyard	20.5	Heilman	14.5
Heilman	14.5	Treisman	16.8	Treisman	13.6
Naatanen	14.5			Hillyard	13.6

The PFNETS: 1985 – 2005

The 1985 PFNET is shown in Figure 1. In all these nets, the links are scaled to the percentage of co-citations represented by the link. Given how the PFNET algorithm operates in net construction, edges are added to the net by decreasing number (or percentage) of co-citations. In the figure, thicker edges are added to the net before thinner edges. Thus, one can see that in the 1985 net, a cognitive psychology cluster and a neuroscience cluster form simultaneously in net construction. In this PFNET, there are no primary edges linking neuroscientists with psychologists. However, there are two secondary edges linking neuroscience specialty clusters with psychology clusters; hence, three specialty clusters are present. The edge Wurtz-Posner (dashed line) joins a cluster of ten psychologists (white nodes, except Hirst and Bobrow, who join the net with the addition of subsequent edges) to a cluster of ten neuroscientists (black nodes, all except Petersen and Weinstein) at the level of 10 co-citations (.9 percent). Toward the end of net construction, a cluster of evoked response potential researchers (gray nodes) forms around Hillyard. This cluster is joined to the larger neuroscience-cognitive psychology cluster at a co-citation level of 3 (.2 percent) with a set of six tied edges that are among the last to be added to the net. ERP researchers are incorporated into the net via their links to various psychologists, not to other neuroscientists. After the ERP cluster is joined to the net, all core authors except Weinstein are in the net. Weinstein is the single "tail node" omitted from the figure. In this figure, Heilman and Weinstein (black-white striped nodes) are shown as part of the neuroscience cluster. However, these scientists are best characterized as clinical neuropsychologists. They are distinguished here because their relation to neuroscience versus cognitive psychology will change in subsequent maps.

The four specialty clusters that emerge during net construction represent research areas that were actively pursuing research on attentional systems in the mid-1980s. Cognitive psychology, single-cell neurophysiology, neuropsychology, and ERP were among the founding disciplines of cognitive neuroscience, the independent research fronts which LeDoux and Hirst engaged in the early cross-disciplinary dialogue. Cognitive psychologists employ behavioral studies on normal participant populations to identify cognitive functions and to develop cognitive models of human behavior. The neuroscientists in the cluster joined to psychology are primarily single-cell neurophysiologists. Single-cell neurophysiologists use electrodes implanted in the brains of primates to record neural activity associated with behavioral tasks. Neuropsychologists use behavioral methods to study the effects of brain injury on behavior. ERP researchers record electrical fields generated by neural activity at the surface of the skull, while human participants are engaged in a sensory or cognitive task.

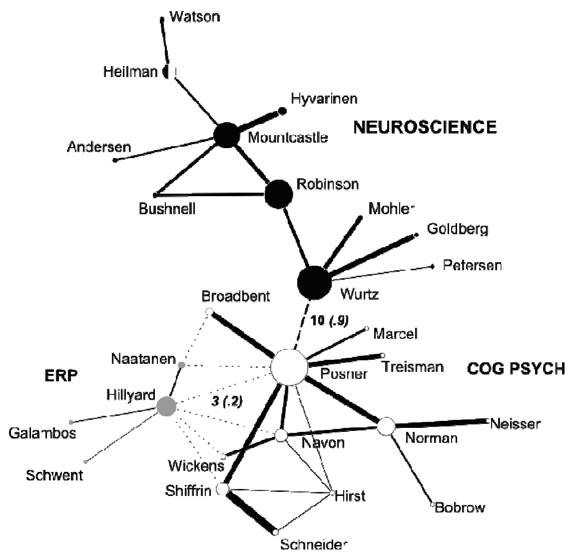

Figure 1. The 1985 PFNET shows the four precursor disciplines of cognitive Neuroscience and ERP research are connected to cognitive psychology by secondary edges (dashed lines) at relatively low levels of co-citation, ERP more distantly than neuroscience.

The 1988 PFNET (Figure 2) shows the same four precursor specialty clusters as appeared in 1985. The major change is that the neuropsychology cluster (black-white nodes) is now connected directly to cognitive psychology (white nodes), via the secondary edge Posner-

Heilman. A second development is that the ERP cluster (gray nodes) consisting of Hillyard and Naatanen develops simultaneously in net construction with the other three specialty clusters, rather than developing much later in construction as it did in 1985. Finally the secondary edges (dashed lines), joining the brain science clusters to cognitive psychology, are added to the net at approximately the same point in net construction, at citation weights of 12 and 13 representing 1.0 percent of 1988 co-citations. There are no primary edges linking brain scientists with psychologists. Eight authors join this main component in the tail of the clustering, via primary edges. However, among these "tail" edges is a cross-disciplinary primary edge linking Petersen and Posner (co-citation weight 10, .8 percent of 1988 co-citations).Changes in the weight of this edge figure will figure prominently in the emergence of a cognitive neuroscience cluster in subsequent years.

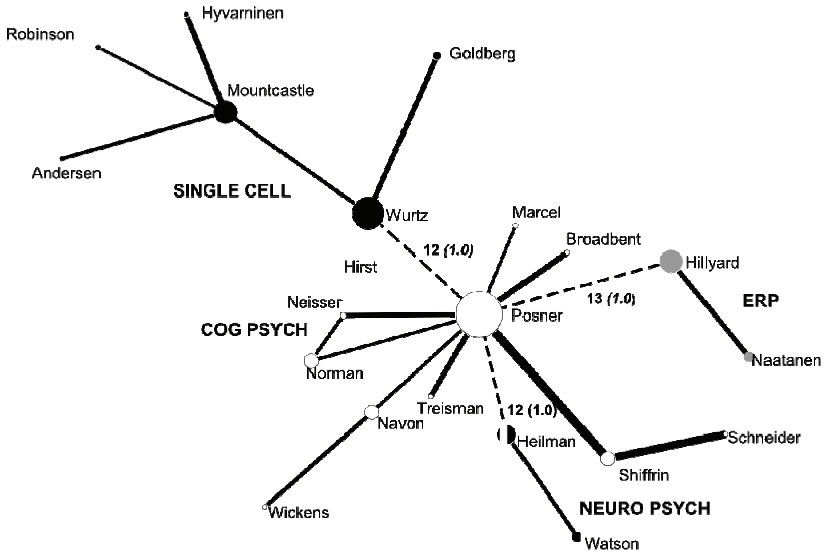

Figure 2. In the 1988 PFNET neuropsychology becomes linked directly to cognitive psychology. All neuroscience clusters are connected to cognitive psychology at similar levels of co-citation.

In the 1990 PFNET (Figure 3), the major development is the appearance of two cross-disciplinary primary edges (edge termini marked with open triangles) very early in net construction. The first of these is the edge Posner-Petersen with citation weight 56 (2.6 percent of 1990 co-citations). This edge is the second edge added in the construction of the 1990 PFNET; it was the 21st edge added to the 1988 net. The second cross-disciplinary primary edge is Posner-Heilman with co-citation weight 42 (2.0 percent of co-citations). This is the sixth edge added to the 1990 net; whereas it was the 19th edge added in 1988. With the addition of this edge, the distinct neuropsychology cluster disappears and the neuropsychologists are incorporated into an interdisciplinary cluster (light gray nodes) containing 11 core authors: a single cell neurophysiologist, two neuropsychologists, and eight cognitive psychologists. Given this cluster's interdisciplinary character, one can label it as a cognitive neuroscience cluster. Subsequent cross-disciplinary secondary edges, Posner-Hillyard (co-citation weight 23, 1.1. percent of co-citations) and Posner-Mountcastle (co-citation weight 19, .9 percent of co-citations) now connect the ERP and single-cell neurophysiology clusters to the cognitive neuroscience cluster. These two precursor disciplines join the net at approximately the same stage in net construction, and at the same percentages of annual co-citations at which they jjoined the cognitive psychology cluster in 1988. Eleven authors join this main cluster in the tail via primary edges subsequent to the addition of the Posner-Mountcastle edge.

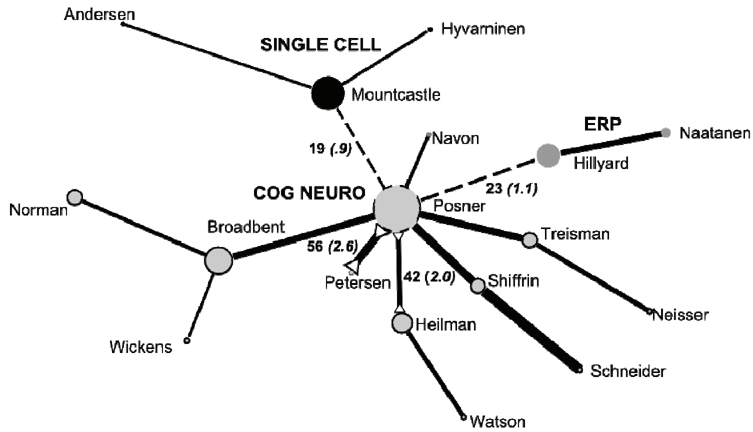

Figure 3. In the 1990 PFNET a neuroscientist and a neuropsychologist are linked to a cognitive psychologist via primary edges (solid lines, open triangles) in a cognitive neuroscience cluster.

The 1995 PFNET (Figure 4A) reveals further consolidation of a cognitive neuroscience cluster. There are two cross-specialty primary edges (solid lines, open triangle termini). Posner-Petersen (co-citation weight 197, 7.2 percent of the 1995 co-citations) is, in fact, the first edge that appears in net construction. Posner-Heilman (co-citation weight 60, 2.2 percent of co-citations) is the fourth edge used in net construction. With the addition of this fourth edge, there are two clusters in the net, a cognitive neuroscience cluster (light gray nodes) containing Posner, Petersen, Treisman, and Heilman and an ERP cluster containing Naatanen and Hillyard (dark grey nodes). The fifth edge placed in the net is the first cross-specialty secondary edge, Posner-Hillyard (co-citation weight 53, 1.9 percent of co-citations), which links cognitive neuroscience with ERP. Three cognitive psychologists (Schneider, Shiffrin, and Norman, the white nodes) are joined to this cognitive neuroscience - ERP cluster. The final cross-disciplinary secondary edges are three tied edges, all with co-citation weights 27 (1.0 percent of co-citations) which link Posner with Andersen and Petersen with Andersen and Goldberg, merging the cognitive neuroscience plus ERP plus cognitive psychology cluster with single-cell neurophysiology (black nodes). At this point the main component of the net contains 17 authors. Eleven authors fall into the tail of single-link clustering regime. What is interesting in the 1995 net is that the first cluster to form is the cognitive neuroscience cluster to which ERP is now the most salient of the precursor clusters. Some cognitive psychologists, distinct from those in the cognitive neuroscience cluster, then join the main component of the graph. Single cell neurophysiology is now the last cluster to be added to the PFNET. The salience of ERP research to cognitive neuroscience, as measured by percentage of co-citations, has nearly doubled since 1990, but the salience of single cell neurophysiology remains constant at around 1 percent of co-citations.

The 2000 PFNET (Figure 4B) contains only two specialty clusters, cognitive neuroscience (light gray nodes) and single cell neurophysiology (black nodes). The cognitive neuroscience cluster is formed around the cross-specialty primary edge Posner-Petersen (co-citation weight 336, 9.0 percent of 2000 co-citations), the first edge added in the construction of the PFNET. The third added to the net is also a cross-specialty primary edge, Posner-Hillyard (co-citation weight 106, 2.8 percent of co-citations). This edge links Hillyard to a cluster containing Posner, Petersen, and Treisman. ERP research disappears from the net as a separate precursor cluster to become part of the cognitive neuroscience cluster. The final cross-disciplinary primary edge is Posner-Heilman (co-citation weight 71, 1.9 percent of the co-citations).

Naatanen and Schneider complete the cognitive neuroscience cluster. The single cross-specialty secondary edge, Andersen-Petersen (co-citation weight 59, 1.6 percent of the co-citations), joins the cognitive neuroscience cluster to a single-cell neurophysiology cluster containing Andersen, Goldberg, and Wurtz. The remaining 18 authors accrete to this large cluster, via primary edges none of which are cross-disciplinary.

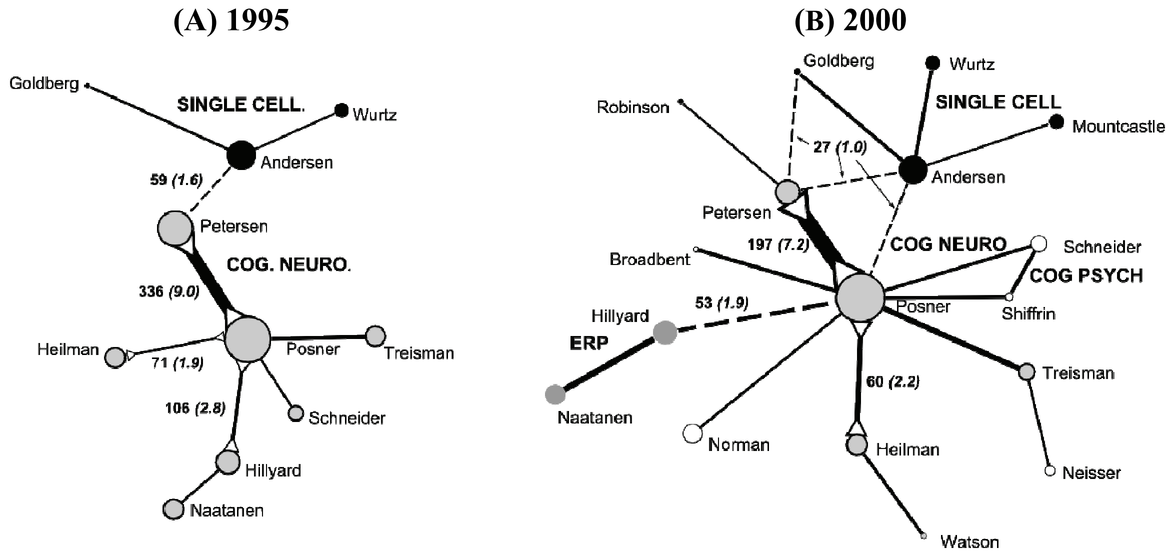

Figure 4. (A) The strongest link in the 1995 net is a primary edge linking Posner and Petersen. ERP and single cell neurophysiology are linked to cognitive neuroscience cluster by secondary edges. (B) In 2000, a cognitive neuroscience cluster containing scientists from all precursor disciplines emerges early in net construction, linked to Posner by primary edges. Single cell neurophysiology remains as an independent precursor cluster. The 2005 PFNET is nearly identical to the 2000 PFNET.

The 2005 PFNET (not shown) is nearly identical in structure and composition to the 2000 net. The only difference is that the psychologist Norman is included in the cognitive neuroscience cluster as a fourth cognitive psychologist in addition to Posner, Treisman, and Schneider. If one were to remove the Posner-Norman edge from the 2005 PFNET, the first nine edges of the 2000 and 2005 PFNETs are be identical and the Spearman rank correlation between the nine edges would be .90 ($p < .01$) We might interpret the similarity between the 2000 and 2005 PFNETs as an indication that the co-citation relationships among the core authors, and the "proto-literature" they generated, has stabilized to provide the historic background, or conceptual foundation, for the cognitive neuroscience of attention.

Discussion and Conclusions

My goal was to assess the development of a two-decade dialogue between brain scientists and psychologists engaged in research on attentional systems, a dialogue that culminated in the cognitive neuroscience of attention. Author co-citation analyses of 28 core authors for six separate years between 1985 and 2000 were analyzed using PFNETs. These analyses exploited edge weights, the single hierarchical clustering implicit in PFNETs, and the role of primary and secondary edges in interpreting the nets. I hypothesized that if a cognitive neuroscience of attention did emerge from the initial, limited dialogue between neuroscientists and psychologists, one should initially see distinct, separate specialty clusters of neuroscientists and psychologists, see changes in salience among these clusters, observe these clusters increasingly earlier in the construction of the PFNETS over subsequent years, and eventually see the emergence of a cognitive neuroscience cluster, including

neuroscientists and psychologists, linked by primary edges at increasingly earlier stages in net construction. The analyses support this hypothesis.
Analysis of the co-citation data shows that while co-citations of the 28 core authors grew 2.6-fold between 1985 and 2005, co-citations of neuroscientists with cognitive psychologists grew 11-fold. The initially forced cross-disciplinary dialogue became more congenial.

Based on flow betweeness centrality (or any other centrality measure one might choose) Posner has the highest centrality in each of the PFNETs. The centrality of his work to the development of the cognitive neuroscience of attention becomes even more evident when one notices that after 1985 all the primary and secondary edges connecting neuroscience with psychology involve Posner. By 2000 the most central authors are all members of the cognitive neuroscience cluster, with the exception of Andersen who provides a link to the remaining, independent precursor cluster of single cell neurophysiology.

Turning to the PFNETS, the 1985 net was composed of three specialty clusters: cognitive psychology, single-cell neurophysiology/neuropsychology, and evoked response potential (ERP) studies. The ERP cluster developed late in net construction and was only weakly tied to cognitive psychology. This net also supports LeDoux and Hirst's (1986) claim that dialogue between these precursor clusters was extremely limited. The strongest connection was between cognitive psychology and single-cell neurophysiology, as represented by the secondary edge linking Posner and Wurtz (.9 percent of 1985 co-citations). The 1985 PFNET attests to the quality of the Hirst and Robinson-Petersen reviews. Recall that the only author highly cited in both reviews was Posner and that of the three other jointly cited authors, two were Wurtz and Mohler, Mohler being a member of the Wurtz laboratory. It would appear that the description of the literature presented in the reviews captures very well the view of all authors who were citing the literature of the precursor fields in the mid-1980s.

In the following years, the dialogue leading to the cognitive neuroscience of attention can be characterized as one where neuropsychology and ERP research became increasingly salient to cognitive psychology, in particular to the work of Posner. The strength of the link between Posner and neuropsychology as a percentage of co-citation increased from 0 to around 2 percent from 1990 through 2005. The link between Posner and ERP increased from .2 percent of the co-citations in 1985 to 3.74 percent in 2005. These two precursor clusters were amalgamated into a cognitive neuroscience cluster, neuropsychology in 1988 and ERP in 2000. The relationship of single cell neurophysiology to first cognitive psychology, then cognitive neuroscience, remained relatively stable between 1985 and 1995 at around 1 percent of co-citations, increasing to 1.6 percent in 2000 and 1.4 percent in 2005. Cognitive psychology participated in this dialogue by providing a small group of the original 12 cognitive psychologists who became part of the cognitive neuroscience cluster. By 2005 this core included Posner, Treisman, Schneider, and Norman. From the perspective of the published work of the 28 pioneering attention researchers, by 2000 this proto-literature had coalesced into a PFNET consisting of a large cognitive neuroscience cluster containing at least one representative of each of the precursor disciplines connected by a secondary edge to a smaller cluster of three single-cell neurophysiologists, where Andersen was the most salient neurophysiologist.

However, the central development in this dialogue and in the emergence of the cognitive neuroscience of attention is the relationship between Posner and Petersen. In 1985 Petersen was linked to Wurtz. In 1988 Posner and Petersen were the first brain science-mind science pair to be linked by a primary edge (co-citation weight 10, .8 percent of co-citations). The strength of connection between these authors grew dramatically in subsequent years and by 1995 they were the most strongly linked authors. Their percentage of co-citations increased from 2.6 percent in 1990, to 7.2 in 1995, to 9.0 in 2000, and 10.1 in 2005.

Petersen's rise in prominence can be attributed to several factors. In the mid-1980s, at the time Robinson and Petersen (1986) wrote their review, both Petersen and Robinson held positions at the National Eye Institute, National Institutes of Health in the laboratory of Robert Wurtz. Wurtz was the strongest link between the neuroscience and psychology of attention in the 1985 net. Second, in 1985, Petersen moved to Washington University in St. Louis to work with Michael Posner and others in a PET imaging group. Posner and Petersen co-authored three seminal papers on PET studies of attention and single word reading in 1988 and 1990 (Petersen, Fox, Posner et al., 1988; Posner, Petersen, Fox, et al. 1988; and Posner & Petersen, 1990). (In fact, in the set of 28 core authors, Posner and Petersen is the only psychologist-neuroscientist pair to co-author a publication.) The 1990 paper on the attention system of the human brain, as of late 2008, had been cited over 2,100 times. All these papers addressed the importance and promise of brain imaging technology to advance our understanding of the mind-brain. Posner, Petersen, Fox et al. (1988) stated what was to become the working hypothesis of cognitive neuroscience: "The human brain localizes mental operations of the kind posited by cognitive theories."(p. 1627) PET and fMRI provided the technology required to localize those functions, making imaging studies the focal point of the cognitive neuroscience enterprise. (Bruer, In press.)

This study illustrates the utility of interpreting PFNETS as weighted rather than binary graphs. If one were to interpret the nets as binary graphs, one would see Posner as the central core author in the dialogue and observe changes in Posner's ego net over a twenty year period. With sufficient background knowledge, or use of some other clustering technique, one could recognize that the authors in Posner's ego net came from different precursor research specialties. What one might miss is emergence of cross-disciplinary secondary edges and their growth into primary edges that signal the development of a new specialty cluster. One would not see the dynamic of the increased co-citation relation between Posner and Petersen that signals the creation of this interdisciplinary cluster and marks the emergence of a technology and methodology that now defines cognitive neuroscience.

Finally, the method used here of relying on two review articles to generate a set of core authors for co-citation analysis is admittedly non-standard and merits further scrutiny. In the current case, where the attempt was to study the development of a cross-disciplinary dialogue, using reviews intended to initiate that dialogue are both appropriate and intriguing. This resulting author set provided the basis for plausible, defensible interpretation. If instead, one had used all authors publishing on attention in neuroscience and psychology journals in, say, 1985, the top 50% of the 173 publishing authors would have had to be included in the analysis before any neurophysiology authors appeared in the sample. Attention research was so dominated by psychologists that the initial exchanges between psychology and neurophysiology would have been below thresholds commonly used in citation studies. However, generating a similar sample for 1990 attention authors, would show that the top 10% of these 764 authors include 11 of my core authors and that these core authors are among the most central of the authors in a 1990 co-citation PFNET. (Bruer, Unpublished. The nets are posted at www.jsmf.org.) The non-standard method used here to generate core authors thus has the advantages of being more sensitive to the progress of the dialogue early and converging with results based on more standard methods as the dialogue matures. Of course, only further research comparing methods of data generation and analysis for the study of emerging fields can yield definitive answers.

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