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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 1980 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.

Keywords Co-citation analysis · PFNET · Cognitive neuroscience · Attention

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) Over that past three decades, a new mind-brain science, cognitive neuroscience, has 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

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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 generally 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 simplify networks, but retain structural information, thus facilitating visualization (Börner et al. 2003; Chen and Paul 2001). In addition, they simplify the mapping process for co-citation data (White 2003).

The author co-citation analyses and PFNETS presented here differ from those typically found in the literature in several respects. 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; Börner et al. 2003). In contrast, this study attempts to trace the dynamic development of a new discipline from its beginnings, 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 and their published work represents the proto-literature of the cognitive neuroscience of attention. This study traces how the structure of the proto-literature changed from a loosely linked set of precursor literatures into a literature that served as the basis for the cognitive neuroscience of attention.

Second, the analyses presented here make explicit use of co-citation networks as valued, rather than binary graphs. In bibliometric studies, author centrality is usually based on degree, betweeness, or closeness centrality, but these measures are defined only for binary graphs (Dearholt and Schvaneveldt 1990; White 2003). Flow betweeness centrality (Freeman et al. 1991) is a centrality measures defined for weighted graphs, such as PFNETS, that provides a more suitable measure for these data. In addition, the PFNET algorithm made makes explicit use of the weight of the co-citation relation between two nodes to construct the net. The 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 and 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, this study makes explicit use of a property of PFNETs (∞, n − 1). 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 literature are $r = \infty$, $q = n - 1$ nets, where n is the number of nodes in the network. In a PFNET (∞, n − 1) only two types of edges appear, 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 property, along with attention to co-citation weights, 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 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 to have increasingly 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 25-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. 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.

Hirst (1986) wrote the review of attention research from the psychological perspective. Robinson and Petersen (1986) wrote the review from the neurobiological perspective. The Hirst review cites 93 distinct authors; the Robinson and Petersen review 135 distinct authors. (These author counts include all authors on multi-authored papers.) In each review, numerous authors were cited multiple times. I define 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% of all authors cited in the reviews, account for approximately 45% of the author citations in the two reviews.

Table 1 The 28 core attention authors and citation counts from Hirst (1986) and Robinson and Petersen (1986)

Psychology	Neurobiology
A. Treisman (12)	D.L. Robinson (25)
D.A. Norman (10)	M.E. Goldberg (15)
W. Hirst (10)	S.A. Hillyard (13)
U. Neisser (10)	K.M. Heilman (11)
R.A. Shiffrin (9)	R.H. Wurtz (10)
C.D. Wickens (9)	M.C. Bushnell (9)
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)	R. Galambos (6)
	R. Naatanen (6)
	R.T. Watson (6)
	R.A. Andersen (5)
	C.W. Mohler (5)
	E.A. Weinstein (5)

Separate co-citation searches for the core authors were done for the years 1980, 1985, 1988, 1990, 1995, 2000, and 2005. For 1980 and 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 (www.geocities.com/) which generated the PFNETs (∞, n $-$ 1). Nets were drawn using the Pajak graph visualization software (De Nooy et al. 2005) and edited using Inkscape. (www.inkscape.org) Normalized flow betweeness centrality was computed for each author in the PFNETs using the UCINET algorithm. (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 appearing in both the Hirst and Robinson–Petersen reviews) remains fixed in the net's center. Author nodes are scaled by their normalized flow betweeness centrality in each net. 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 triangle termini 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. Only the nodes included in the PFNET at the point where the last cross-disciplinary secondary edge is added are shown.

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 four 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 and 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 summarizes the co-citation data by sample year for the core authors. The number of author co-citations increased 4.4-fold between 1980 and the peak year of 2000, whereas the co-citations of neuroscientists with psychologists increased 20-fold, representing 40% of all co-citations by 2005. The percentage of non-zero cells in the entire co-citation matrix increased from 44% in 1980 to 64% in 1990 and remained over 60% thereafter, an increase of between 15 and 21%. Confining attention to neuroscientist-psychologist author pairs, the percentage of non-zero cells in these sectors of the co-citation matrices increased from 25% in 1980 to 62% in 1995 and remained over 50% thereafter, an increase of between 25 and 37%. These data indicate that the scientific community increased co-citation of attention core authors between 1980 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 four 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, save 1980 when he the second ranked author. (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. Of particular interest, as will be seen in the discussion of the individual nets, is the increased centrality of Richard Andersen and Steven Petersen starting in 1990. These two authors do not even appear in the 1980 PFNET and have zero flow betweeness centrality in 1985, and yet become the second and third most central authors by 2000.

Table 2 Changes in occurrence and distribution of core author co-citations 1980–2005

Year	Author co-citations	Neuro-psych co-citations (%)	% Non-zero cells	% Non-zero neuro-psych cells
1980	853	73 (8)	44	25
1985	1291	123 (10)	49	25
1989	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 3 Top four authors in each sample year ranked by normed flow betweeness centrality

1980	Neisser 63.5	Posner 41.5	Robinson 33.1	Galambos 27.0
1985	Posner 65.8	Wurtz 57.8	Robinson 40.1	Mountcastle 33.7
1988	Posner 88.2	Wurtz 44.0	Mountcastle 21.4	Hillyard 21.2
1990	Posner 86.0	Mountcastle 44.5	Broadbent 27.6	Hillyard 21.2
1995	Posner 85.1	Andersen 29.0	Hillyard 20.5	Petersen 19.4
2000	Posner 78.6	Petersen 44.7	Andersen 32.2	Hillyard 19.7
2005	Posner 85.5	Petersen 40.9	Andersen 34.7	Hillyard 15.7

The PFNETS: 1980–2005

In interpreting the PFNETS, three features are of primary interest: (1) the number of specialty clusters that form and the order in which they form during net construction; (2) the presence of secondary edges linking neuroscience clusters with psychology clusters and when they appear in net construction; (3) the presence of primary edges linking a neuroscientist with a psychologist and when they appear in net construction. In all these nets, the links are scaled to the percentage of co-citations represented by the link. Given how the PFNET algorithm operates, 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.

In the 1980 net, a cognitive psychology cluster and a neuroscience cluster form early and simultaneously in net construction. An evoked response potential cluster forms later in net construction. Here Heilman and Watson (black–white striped nodes) are shown as part of a general neuroscience cluster (Fig. 1). However these scientists are best characterized as clinical neuropsychologists. They are distinguished here because their relation to the

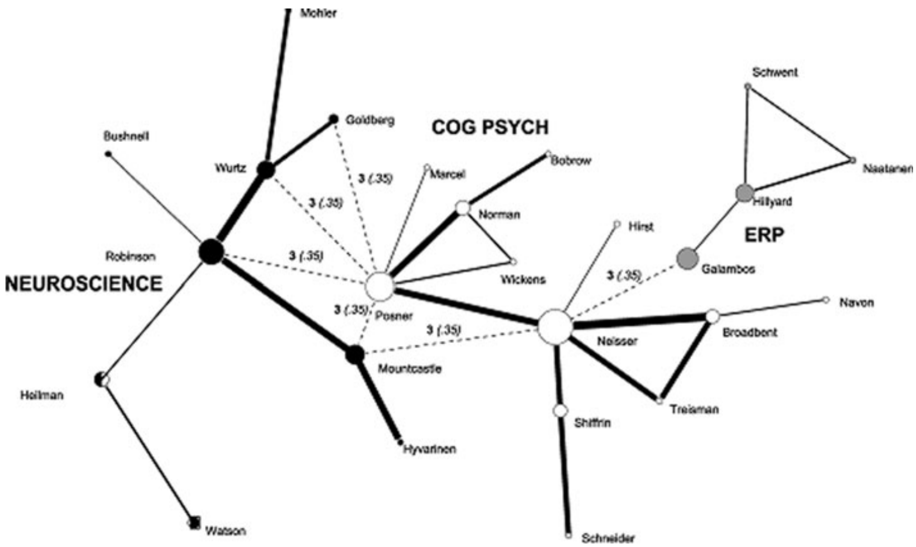

Fig. 1 In the 1980 net, neuroscience (*black* nodes and *black–white* nodes) and cognitive psychology (*white* nodes) develop as clusters with high internal co-citation rates. ERP (*grey* nodes) develops later in net construction. These clusters are connected by secondary edges at very low levels of co-citation

other neuroscientists versus cognitive psychologists will change in subsequent maps. The neuroscience cluster splits into a clinical neuropsychology cluster and a single cell neurophysiology cluster. Five cross-disciplinary secondary edges (dashed lined) link cognitive psychology to neuroscience and one cross-disciplinary secondary edge links cognitive psychology to ERP. These links occur at very low levels of co-citation (3) and are the 24th through 31st edges of 33 total edges added in net construction. ERP researchers are incorporated into the net via their links to various psychologists, not to other neuroscientists. Weinstein joins the net with the 32nd edge and is the single "tail node" omitted from the figure. In this PFNet, there are no primary edges linking neuroscientists with psychologists. In 1980, neither Andersen nor Petersen were co-cited with the other core authors and thus do not appear in the net at all.

In the 1985 net (Fig. 2), a cognitive psychology cluster and a neuroscience cluster again form simultaneously and early in net construction. There are two sets of secondary edges linking neuroscience specialty clusters with psychology clusters. 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 ten co-citations (.9%). This cross-disciplinary secondary edge is the 21st of 41 edges added to form the complete net. This ERP cluster is joined to the larger neuroscience-cognitive psychology cluster at a low co-citation level of 3 (.2%) with a set of six tied edges that are among the last (40th) to be added to the net. Weinstein is again the single "tail node" omitted from the figure. In this PFNET, there are no primary edges linking neuroscientists with psychologists.

The complete 1988 PFNET (Fig. 3) contains 32 edges. Here neuropsychology and single-cell neurophysiology have split. The ERP cluster (gray nodes) consisting of Hillyard and Naatanen develops simultaneously in net construction with the other specialty clusters,

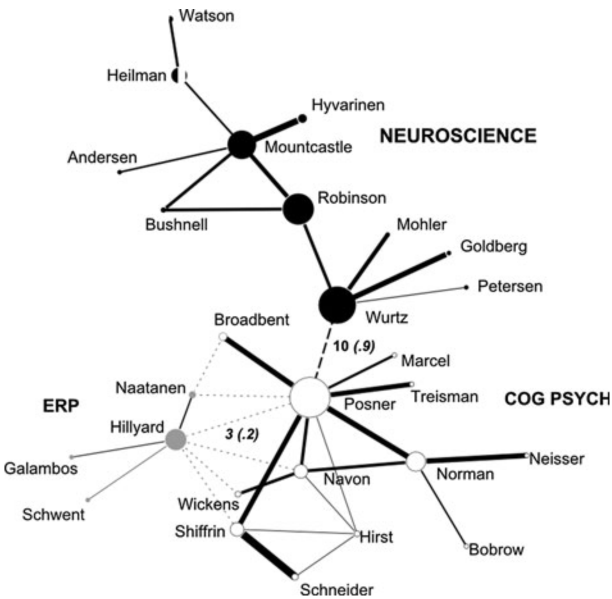

Fig. 2 The 1985 PFNET three clusters form. Neuroscience (*black* nodes and *black–white* nodes) and ERP research (*gray* nodes) are connected to cognitive psychology (*white* nodes) by secondary edges (*dashed lines*) at relatively low levels of co-citation, ERP more distantly than neuroscience

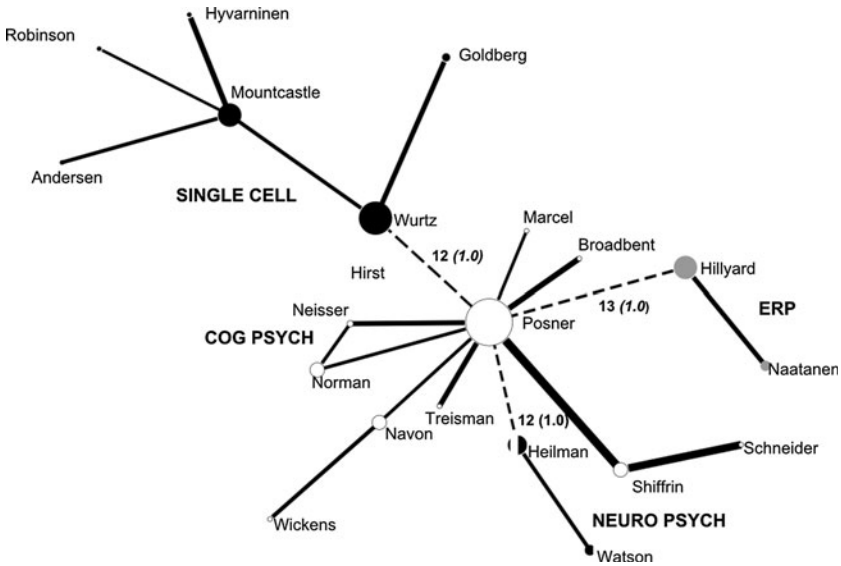

Fig. 3 In the 1988 PFNET neuropsychology becomes linked directly to cognitive psychology. All neuroscience clusters are connected to cognitive psychology at similar levels of co-citation

rather than developing much later in construction as it did in previous years. There are three cross-disciplinary secondary edges. Hillyard-Posner, the 18th edge, connects cognitive psychology and ERP. At the same point in net construction, at a level of 12 co-citations, the secondary edge Posner-Heilman (19th edge) links the neuropsychology (black–white nodes) directly to cognitive psychology (white nodes) and Posner-Wurtz connects psychology and single-cell neurophysiology. 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, the 22nd edge to added to the net (co-citation weight 10, 0.8% of 1988 co-citations).Changes in the weight of this edge will figure prominently in the emergence of a cognitive neuroscience cluster in subsequent years.

The complete 1990 PFNET (Fig. 4) contains 29 edges. There are now three clusters, single-cell neurophysiology, ERP, and a cognitive neuroscience cluster. The cognitive neuroscience cluster develops first, followed by the ERP and then the single cell neurophysiology cluster. There are two cross-disciplinary secondary edges, Posner-Hillyard (12th edge) and Posner-Mountcastle (17th edge). The major development is the appearance of two cross-disciplinary primary edges (edge termini marked with open triangles) very early in net construction. Posner-Petersen with citation weight 56 (2.6% of 1990 co-citations) is the second edge added in the 1990 net construction; it was the 21st edge added to the 1988 net. The second cross-disciplinary primary edge is Posner-Heilman (6th edge) with co-citation weight 42 representing 2.0% of co-citations; it was the 19^{t}h 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. Eleven authors join this main cluster in the tail via primary edges subsequent to the addition of the Posner-Mountcastle edge.

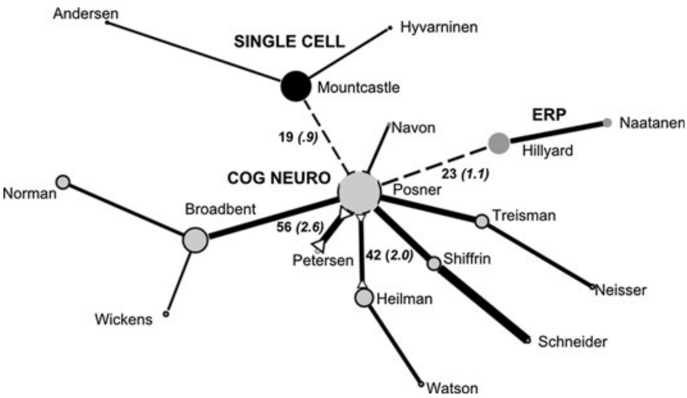

Fig. 4 In the 1990 PFNET a neuroscientist and a neuropsychologist are linked to a cognitive psychologist via primary edges (*solid lines*, *open triangles*) in a cognitive neuroscience cluster

The complete 1995 PFNET (Fig. 5) contains 33 edges and reveals further consolidation of the cognitive neuroscience cluster. Again there are three specialty clusters, cognitive neuroscience, single cell neurophysiology, and ERP. A distinct cognitive psychology cluster composed of Schneider and Shiffrin also appears. There are three sets of secondary edges. Posner-Hillyard (5th edge) connects cognitive neuroscience with ERP. Posner-Schneider and Posner-Shiffrin (the 10th and 11th edges) connect cognitive neuroscience with cognitive psychology. Three tied cross-specialty secondary edges (17th in net construction) link Posner and Petersen to single-cell neurophysiology. The primary cross-specialty edge of Posner-Petersen (co-citation weight 197, 7.2% of the 1995 co-citations) is, in fact, the first edge that appears in net construction. Posner-Heilman (co-citation weight 60, 2.2% of co-citations) is the fourth edge used in net construction. With the

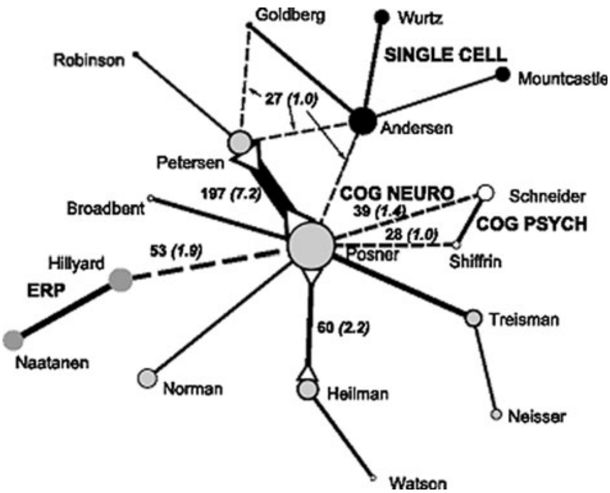

Fig. 5 The strongest link in the 1995 net is a primary edge linking Posner and Petersen. ERP and single cell neurophysiology are linked to cognitive neuroscience cluster by secondary edges

addition of this fourth edge, the cognitive neuroscience cluster (light gray nodes) contains Posner, Petersen, Treisman, and Heilman. The main component of the net contains 17 authors. Eleven authors fall into the tail of single-link clustering regime.

The 2000 PFNET (Fig. 6a) contains only two specialty clusters, cognitive neuroscience (light gray nodes) and single cell neurophysiology (black nodes). There is one cross-specialty secondary edge, Anderson-Petersen, the 9th of 28 edges in the complete net, which links a cognitive neuroscience cluster of seven core authors to a single-cell neurophysiology cluster containing three core authors. The cognitive neuroscience cluster is formed around the cross-specialty primary edge Posner-Petersen (co-citation weight 336, 9.0% of 2000 co-citations), the first edge added in the construction of the PFNET. The third edge added to the net is also a cross-specialty primary edge, Posner-Hillyard (co-citation weight 106, 2.8% of co-citations). This edge links Hillyard to a cluster containing Posner, Petersen, and Treisman; ERP research disappears from the net as a separate cluster to become part of the cognitive neuroscience cluster. The final cross-disciplinary primary edge is the fifth edge added to the net, Posner-Heilman (co-citation weight 71, 1.9% of the co-citations). Naatanen and Schneider complete the cognitive neuroscience cluster. The remaining 18 authors accrete to this large cluster, via primary edges none of which are cross-disciplinary.

The 2005 PFNET (Fig. 6b) 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 the same with slight differences in ordering. (The Spearman rank correlation between the nine edges is 0.90, $p < 0.01$) We might interpret the similarity between the 2000 and 2005 nets as an indication that the co-citation relationships among the core authors, and the "proto-literature" they generated, have stabilized to provide the historic background, or conceptual foundation, for the cognitive neuroscience of attention.

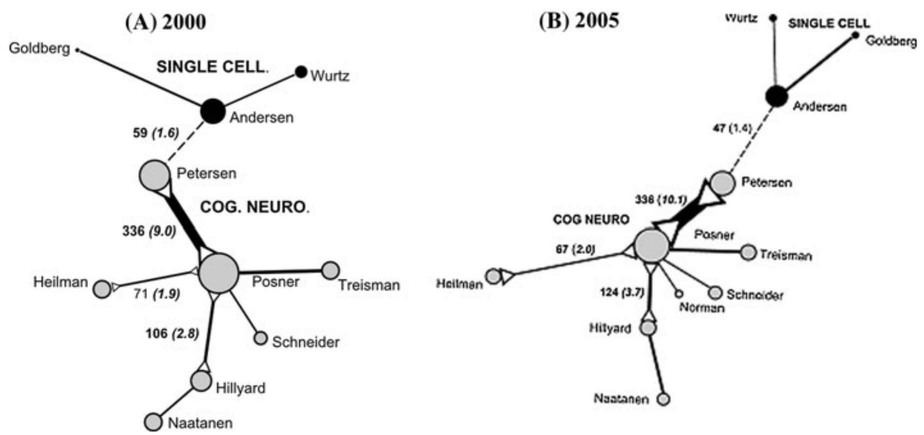

Fig. 6 **a** In 2000, a cognitive neuroscience cluster containing scientists from all precursor disciplines emerges early in net construction, linked to Posner by primary edges. Single cell neurophysiology remains as an independent precursor cluster. **b** The 2005 net is nearly identical to the 2000 net

Discussion and conclusions

My goal was to assess the development of a 25-year 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 seven separate years between 1980 and 2005 were analyzed using PFNETs. These analyses exploited edge weights in the nets, the single hierarchical clustering implicit in the PFNET algorithm, and the role of primary and secondary edges in interpreting a PFNET (∞, n $-$ 1). 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 forming increasingly earlier in the construction of the PFNETS over subsequent years, and eventually see the emergence of a cognitive neuroscience cluster which includes 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 increase by a factor of 4.4 between 1980 and 2005, co-citations of neuroscientists with cognitive psychologists grew by a factor of 20. 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 single cell neurophysiology cluster.

Turning to the PFNETS, the 1980 net was composed of three specialty clusters: cognitive psychology, neuroscience (composed of both single-cell neurophysiologist and neuropsychologists), and evoked response potential (ERP) studies. The cognitive psychology and neuroscience clusters developed simultaneously and independently in net construction. The ERP cluster developed late in net construction. The two brain science clusters were both linked to cognitive psychology at a very low co-citation rate, a rate that might be deemed "noise" in most citation studies.

It is interesting to note that Posner (1980), the only article author highly cited in both Hirst (1986) and Robinson and Petersen (1986), appears in all of the links between cognitive psychology and neuroscience in the 1980 net. In the 1985 net, the strongest connection between cognitive psychology and neuroscience is represented by the secondary edge linking Posner and Wurtz (0.9% of 1985 co-citations). Recall that Wurtz and Mohler, Mohler being a member of the Wurtz laboratory, were among the four authors who were jointly cited by Hirst (1986) and Robinson and Petersen (1986). These two nets support LeDoux and Hirst's (1986) claim that dialogue between these precursor clusters was extremely limited. The 1980 and 1985 nets also attest to the quality of the Hirst and Robinson-Petersen reviews. The reviews suggested the Posner and Wurtz were among the few authors occupying common, or bordering, ground in the mid-1980s. 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 at the time the reviews were written.

The four specialty clusters that emerge during net construction in the early to mig-1980s represent research areas that were actively pursuing research on attentional systems. Cognitive psychology, single-cell neurophysiology, neuropsychology, and ERP were among the founding disciplines of cognitive neuroscience. One might call them the precursor disciplines of the cognitive neuroscience of attention. These were the independent research fronts which LeDoux and Hirst attempted to engage in the early cross-disciplinary dialogue. These specialties are most clearly characterized by their methods. Cognitive psychologists employ behavioral studies on normal participant populations to identify cognitive functions and to develop cognitive models of human behavior. 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. The development of the cognitive neuroscience of attention can be seen in how the mutual salience of research in these precursor clusters changed between 1980 and 2005.

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% from 1990 through 2005. The link between Posner and ERP increased from 0.2% of the co-citations in 1985 to 3.74% 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% of co-citations, increasing to 1.6% in 2000 and 1.4% 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, 0.8% of co-citations). The strength of the 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% 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 positron emission tomography (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 et al. 1988; Posner et al. 1988; and Posner and 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. PET and functional magnetic resonance imaging (fMRI) provided the technology required to localize cognitive function in the brain, making imaging studies the focal point of the entire cognitive neuroscience enterprise (Bruer 2009).

This study also 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 is both appropriate and intriguing. This resulting author set provided the basis for a 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 includes 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 yet 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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