Bain on Neural Networks

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In his book *Mind and body* (1873), Bain set out an account in which he related the processes of associative memory to the distribution of activity in neural groupings—or neural networks as they are now termed. In the course of this account, Bain anticipated certain aspects of connectionist ideas that are normally attributed to 20th-century authors—most notably Hebb (1949). In this paper we reproduce Bain’s arguments relating neural activity to the workings of associative memory which include an early version of the principles enshrined in Hebb’s neurophysiological postulate. Nonetheless, despite their prescience, these specific contributions to the connectionist case have been almost entirely ignored. Eventually, Bain came to doubt the practicality of his own arguments and, in so doing, he seems to have ensured that his ideas concerning neural groupings exerted little or no influence on the subsequent course of theorizing in this area.

Recently published histories of neural nets either ignore Bain’s contributions to this area completely (e.g., Dierig, 1994) or make only cursory reference to him (e.g., Valentine, 1989). Thus, Dierig reproduced a figure taken from Exner (1894) which is presented as constituting “the earliest representation of a neural network” (p. 450). The network in question had arisen out of Exner’s investigations into the characteristics of the motion aftereffect, (see Wade, 1994), but, some 20 years previously, Bain (1873) had reproduced a version of a neural network whose properties were specifically designed to support the processes of learning and associative memory.

More general histories of connectionism also pay scant regard to Bain (see Jones, 1993; Quinlan, 1991; Walker, 1990) and take the work of Hebb as their principal focus when setting out the properties of neural networks. Quinlan expresses the received view when he states: “it remains true that many of the ideas fundamental to connectionism were set out by Hebb” (Quinlan, 1991, p. 6) although, in this case also, we will argue that certain
of these fundamental ideas had already been stated by Bain some 70 years earlier.

Alexander Bain (1818–1903), see Fig. 1, is best known for his textbooks *The senses and the intellect* (1855) and *The emotions and the will* (1859), in which he offered an interpretation of mental phenomena within an associationist framework (for further biographical detail, see Hearnshaw, 1964). Specifically, he tried to match quantitative estimates of the associations held in memory to the neural structure of the brain. It was this exercise that first drew Bain into confronting the potential properties of neural groupings or networks. In the course of thinking about these issues, he was led to speculate on how the internal structure of neural groupings could *physically grow* to reflect the contingencies of experience and how this same internal structure could come to support the variety of associative links typically found in memory.

In the relevant section of *Mind and body*, Bain described how, after reading a paper by Beale (1864), his attention was drawn to
the manner of connexion of the nerve-fibres with the cell, and with one another through the cell [which was] conjectured and figured by Dr. Beale in a plan that facilitates our conception of the physical growths underlying memory and acquisition. (1873, p. 118)

The ensuing discussion introduces a series of arguments that draw upon principles similar to those now taken as critical for distinguishing connectionist modeling from other approaches to mental processing.

The more to appreciate the insights informing Bain’s arguments, we will look briefly at earlier arguments relating the phenomenology of thought to the structure of the brain as set out by Hartley. Then we will reproduce what Bain himself had to say in some detail. Finally, we will try to explain why Bain’s ideas, despite their precocity, have remained on the sidelines of history.

**FROM HARTLEY TO BAIN**

In the 18th century, David Hartley (1705–1757) realized that the principles set forth in Newton’s *Principia* could serve not only as a framework for interpreting physical events, but also for explaining the neurophysiological basis of thought. Hartley proposed that sensations enter into the nervous system as vibrations (matter in motion) which give rise to localized vibrations in the brain. Since these vibrations can persist after the external object has been removed, they can function as the physical substrate for our ideas. In his *Observations on man* (1749), Hartley outlined his basic argument which assumed that memory images could be conceived as smaller scale vibrations (vibratuncles) in the same regions of the brain as the original sensory experience. Since these vibrations can become associated by contiguity, they can link up to represent compound ideas and, in this manner, they can act as a material basis for the stream of consciousness.

At the time, Hartley could do little more than ground the material basis for thought and memory in the vibratory motions of brain particles. However, when Bain started to address these same issues he was in the position to argue that

\[ \ldots \text{many of the striking discoveries of Physiologists relative to the nervous system should find a recognised place in the Science of Mind. (1855, p. v)} \]

**BAIN’S “NEURAL GROUPINGS”**

Bain raised the issue of the material basis of cognitive states in his book *Mind and body. The theories of their relation* (1873). Here, he embarked on a detailed argument in which he contrasted the traditional concept of prestored memories against an alternative, constructive mode of storage capable of putting together what was required. Like Hartley, Bain believed that an act
of recollection implicates the neural connections involved in the original experience:

If we suppose the sound of a bell striking the ear, and then ceasing, there is a certain continuing impression of a feeble kind, the idea or memory of the note of the bell; and it would take some very good reason to deter us from the obvious inference that the continuing impression is the persisting (although reduced) nerve currents aroused by the original shock. And it may be so with ideas resuscitated from the past—the remembrance of the former sound of the bell. (1873, p. 90)

This proposal is then elaborated by identifying the mechanisms of retention and recall with the internal structure of the neural groupings involved. This means that

for every act of memory, every exercise of bodily aptitude, every habit, recollection, train of ideas, there is a specific grouping, or co-ordination, of sensations and movements, by virtue of specific growths in cell junctions. (p. 91, italics added)

In her historical account, Valentine cited the italicized portion of the quotation (Valentine, 1989, p. 349) but then proceeded to concentrate on other, later sources. In fact, at this point, Bain has barely started on setting out his ideas concerning the manner in which associations between ideas can be grounded in the internal activity of neural groupings and their modifications with experience.

In his subsequent discussion, Bain raised two fundamental questions about how “nerve groupings” (neural networks) could come to sustain the known flexibilities associated with human thought. He first asked how the internal organization of a neural network could come to support different responses under different conditions of stimulation. He then asked how it is that such an internal organization could arise in the first place. We will consider each point in turn.

**Neural Groupings**

On the first issue, Bain described how a neural grouping or network could provide the computational flexibility that is required if multiple associations are to be stored. The wording may be archaic but the meaning is clear:

If each set of sensory fibres had one definite connection with motory or outcarrying fibres, we should have always the same movement answering to the stimulation of the same nerves, as in the reflex system; the fibre \( a \) could do nothing but affect the movement \( x \). It is necessary to the variety and flexibility of our acquirements, that the fibre \( a \) should at one time take part in stimulating \( x \), and at another time take part in stimulating \( y \), the circumstances being different. The stroke of the clock will stimulate us at one time to set in one direction, and at another time in another direction, according to the ideas that it co-operates with. (p. 109, original italics)

Bain maintained that this flexibility resides in the way in which nerve fibers can be connected together so that, on different occasions, stimulation can
be channeled to different parts of the network. He also pointed out how the degree of stimulation present in the network can serve as an additional factor bearing on the input–output function:

...the degree of stimulation of the same fibres will determine not merely a greater energy of the same response, as would happen in reflex stimulation; but a totally different response: \( a \), weak, determines movement \( x \); \( a \), strong, determines \( y \). (p. 109, original italics)

Hence, within the scope of a few tentative hypotheses, Bain has managed to capture a number of the computational properties of neural networks as now understood. He conceived of individual nerve cells carrying excitatory links to selected other cells within a grouping, that each nerve cell is summat- ing the degree of stimulation it receives from other parts of the network, and further that one and the same network can be involved in computing different outputs depending on its internal connections.

As a concrete example of what he had in mind, Bain instances the ‘‘network’’ shown in Fig. 2.\(^1\) Here, the joint stimulation of \( a \) with \( b \) gives \( X \), that of \( b \) with \( c \) gives \( Y \), and that of \( a \) with \( c \) gives \( Z \). There have been claims other than that made by Dierig (1994) in identifying the first neural network to have appeared in print but none of these contenders provides the degree of explicit commentary as evidenced above and subsequently.\(^2\)

Given the complex neurological structure of the brain, Bain realized that, in principle, such networks could be scaled up; a critical point if anything like the degree of flexibility required for handling human cognition was to be approached:

...the number of fibres and cells brought into action, before the grouping can converge upon some one set of cells definitely connected with an out-going motor arrangement, or with some other internal grouping,—must be very great indeed; and but for the vast number of fibres and cells, demonstrably present in the brain, the separate embodiment of every separate impression and idea would seem impractical. (p. 113)

Further levels of flexibility would also arise given the manner in which neutral groupings would respond to ‘‘unequal intensities of stimulation of the same nerves.’’ In this respect, Bain remarked how

\(^{1}\) In his text, Bain described how ‘‘a branch of \( a \) may unite with a branch of \( c \) from which crossing \( Y \) emerges.’’ This slip has been corrected in the legend to the figure. That it was a slip is evident from the later commentary.

\(^{2}\) Walker (1990) reproduces an apparently earlier example of a neural network from the second edition of Herbert Spencer’s *Principles of psychology* (1870, p. 527), which is one of several possible models he considers for connections between afferent and efferent nerves. However, these models were specifically concerned with the genesis of neural connections within the nervous system and not with the way in which they might serve as the material basis for memory and thought.
FIG. 2. Bain’s diagram illustrating the way in which the connections in a neural network can channel activation in different directions:

It requires us to assume, not merely fibres multiplying by ramification through the cell junctions, but also an extensive arrangement of cross connections. We can typify it in this way. Suppose $a$ enters a cell junction, and is replaced by several branches, $a', a''$ etc; $b$ in like manner, is multiplied into $b', b''$ etc. Let one of the branches of $a$ or $a'$, pass into some second cell, and a branch of $b$, or $b'$, pass into the same, and let one of the emerging branches be $X$, we have then a means of connecting united $a$ and $b$ with $X$, and in some other crossing, a branch of $b$ may unite with a branch of $c$, from which crossing $Y$ emerges and so on. . . . By this plan we comply with the primary condition of assigning a separate outcome to every different combination of sensory impressions.

The diagram shows the arrangement. The fibre $a$ branches into two $a', a''$; the fibre $b$ into $b', b''$; $c', c''$. One of the branches of $a$ unites with one of the branches of $b$, or $a'$, $b'$ in a cell $X$; $b'$, $c''$ unite in $Y$; $a'$, $c'$ in $Z$. (1873, pp. 110, 111)

. . . a more energetic current necessarily takes a more extended sweep, and affects a number of cells and fibres that are left quiescent under a feeble current. The cells being viewed as crossings—where a current in one circuit induces a current in an adjoining circuit—there is, at each crossing, a certain resistance to overcome, and the feeble current is sooner exhausted and stops short of the distance reached by the stronger. (pp. 113–114)

This state of affairs is depicted in Fig. 3, which is intended to explain how different outputs can arise as a function of unequal intensities of stimulation in an input unit, labeled (a) in the figure.

It is noteworthy that whereas Beale’s diagram, to which Bain referred, corresponded to the view as seen under a microscope, in Figs. 2 and 3 Bain has chosen a more abstract mode of representation that emphasized the interactions occurring within groupings of neural units.
FIG. 3. The effects of unequal intensities of stimulation on a network (1873, p. 115). Weak stimulation of \( a \) gives to a spread of activation summatting at the response unit, \( X \). Strong stimulation of \( a \) leads to a "wider sweep" through the network which now brings unit \( Y \) into its ambit. Bain’s commentary on this figure can be summarized as \( a^1 \) and \( a^2 \) give \( X \); \( a^3 \), \( a^4 \), and \( a^5 \) give \( Y \). The same network can be expected to support different responses as stimulation levels summate in different parts of the network.

ESTABLISHING NEURAL GROUPINGS

So far as the second question is concerned, dealing with the establishment of specific connections in a network, Bain pointed to the consequences that would arise when units were active together:

We know what are the conditions of making an acquirement, or of fixing two or more things together in memory. The separate impressions must be made together, or flow in close succession; and they must be held together for a certain length of time, either on one occasion or on repeated occasions. Now to each impression, each sensation or thought, there corresponds physically a group or series of nerve-currents; when two impressions concur, or closely succeed one another, the nerve currents find some bridge or place of continuity, better or worse, according to the abundance of nerve matter available for the transition. In the cells or corpuscles where the currents meet and join, there is, in consequence of the meeting, a strengthened connexion or diminished obstruction—a preference track for that line over lines where no continuity has been established. (p. 117, italics added)
In short, as experiences recur, we can expect the relevant neural groupings
to come to reflect the mutual dependencies between their component parts
and *pari passu* so too for the ideas that they sustain.

HEBB’S NEUROPHYSIOLOGICAL POSTULATE

We can compare the italicized excerpt above with the content of Hebb’s
neurophysiological postulate, which states

> When an axon of cell A is near enough to excite a cell B and repeatedly or persistently
takes part in firing it, some growth process or metabolic change takes place in one
or both cells such that A’s efficiency, as one of the cells firing B, is increased. (Hebb,
1949, p. 62)

There is much in common between the two statements, although it is proba-
bly too late to relabel the postulate as Bain’s rather than Hebb’s. Indeed,
perhaps a more remarkable correspondence can be found in the following
statement by Bain:

> I can suppose that, at first, each one of the circuits would affect all others indiscrimi-
nately; but that, in consequence of two of them being independently made active at
the same moment (which is the fact in acquisition), a strengthened connexion or
diminished obstruction would arise between these two, by a change wrought in the
intervening cell-substance; and that, afterwards, the induction from one of these cir-
cuits would not be indiscriminate, but select; being comparatively strong towards
one, and weaker towards the rest. (1873, p. 119)

In addressing at one and the same time both the computational properties
of neural networks and their internal modifications as the network’s links
are altered through experience, Bain emerges as the first theorist to move
beyond generalized statements toward providing detailed examples of the
ways in which neural networks could sustain cognitive activity in general.
He recognized that variety in computation can still be derived from a given
pattern of cross connections within a network and he explains how neural
units that are coactive together would be capable of establishing the connec-
tion strengths needed for the networks to function as required.

THE NUMERICAL NEMESIS OF BAIN’S NETS

Most of the material for *Mind and body* was prepared 10 years before its
publication and it was presented as three talks to the Philosophical Society
in Aberdeen (see Bain, 1904). It was subsequently produced as a book in
the *International Scientific Series* following an encounter at a meeting of the
British Association for the Advancement of Science at Edinburgh in 1871;
Herbert Spencer facilitated the alliance. The book was produced with great
despatch. In his *Autobiography* Bain stated that

> the whole subject had been simmering for a number of years. More particularly was
the attempt made to deal with the connexion of mind and brain by numerical esti-
mates; namely by taking, on the one hand, the number of psychical situations, and, on the other hand, the nervous groupings rendered possible by the approximately assignable number of nerve cells and fibres. . . . The chief novelty consisted in the treatment of the intellect upon the method of innumeration just referred to. (1904, pp. 312, 313)

The numerical estimates of “psychical situations” were derived from tasks such as learning arithmetic tables, musical scores, foreign languages, and facial features. These estimates were then related to estimates of the numbers of nerve cells and fibres in the brain—these were given as one- and five-thousand million, respectively. Adopting these values, Bain speculated that

with a total 200,000 Acquisitions of the assumed types, which would certainly include the most retentive and most richly-endowed minds, there would be for each nerve grouping 5000 cells and 25,000 fibres. (1873, p. 107)

As we have seen above, Bain then went on to enquire as to how the nerves might be grouped to provide the necessary mapping onto associative memory. However, 10 years later he was having second thoughts about his excursion into psychical inumeration. In an article in *Mind* he referred to two factors he had failed to take properly into account. The first concerned the size of the population of partially formed associations

... which are not devoid of value, seeing that a comparatively small amount of farther repetition can at any time raise them to full efficiency; and, moreover, in cooperation with other weak links, they may attain the full power of resuscitation. I can form no estimate of these imperfect associations, farther than they must enormously exceed the number of the perfect class” (1883, p. 409).

The second obstacle derived from the operations of what is now termed “elaborative rehearsal”—the facilitation of learning and recall by adding information to the association as it is being acquired. Partially formed associations and elaborative rehearsal must each make their own additional demands on the neural resources of the brain, and for Bain by this point it seemed the estimates were getting completely out of hand. Thus, the reason Bain failed to pursue his ideas further was not that he doubted the logic of his approach but that he doubted the arithmetic:

The hypothesis was a legitimate one; but subsequent reflection led to the belief that the number of psychical elements, although run up to hundreds of thousands, was still inadequate. (1904, p. 313)

THE HISTORICAL NEMESIS OF BAIN’S NETS

Although Bain withdrew his ideas from the center stage of his own reasoning—thus relinquishing his role as a proponent of the connectionist case—his arguments and examples remained in the public domain. The paradox is why, having apparently proceeded so far, these same ideas failed to influence those who followed. For example, David Ferrier studied under Bain at Aber-
deen, and although Mind and body is cited in his classic work The Functions of the Brain (1876), none of the above detail is mentioned at all.

Could this have been a consequence of the uncertainty concerning the detailed structure of the nervous system that prevailed at this time? The ‘‘neuron doctrine’’ eventually replaced the alternative view that the nervous system consisted of ‘‘one huge reticulum’’ (see Finger, 1994) but it was not the received view at the time Bain was writing. In Mind and body he notes that

\[ \ldots \text{nerve-fibres proceed from the nerve-centres to the extremities of the body without a break, and without uniting or fusing with one another; so that each unfailingly delivers its separate message. \ldots Every nerve ends in a corpuscle; and from the same corpuscle arises some other fibre or fibres either proceeding back to the body direct, or proceeding to other corpuscles, whence new fibres arise, with the same alternative.} \] (pp. 30, 31)

In proposing the concept of neural growth, Bain seems to have anticipated the ‘‘idea that grew out of neuron doctrine \ldots that dendritic or axonal branches could grow to enhance or block communication at the synapse’’ (Finger, 1994, p. 339). In fact, as was pointed out earlier, Bain’s diagrams of neural groupings are essentially schematic representations more attuned to the structure of mental associations than to the microscopic detail of the nervous system. Their neuro-psychological significance would become much clearer once the neuron doctrine had been widely accepted. Hebb, unlike Bain, was able to drawn upon a conception of the nervous system comprising individual neurons terminating in synaptic junctions.

REFERENCES


