On the structure of the mind

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Abstract

The focus of any attempt to create an artificial brain and mind should reside in the dynamic model of the network of information. The study of biological networks has progressed enormously in recent years. It is an intriguing possibility that the architecture of representation and exchange of information at high level closely resembles that of neurons. Taking this hypothesis into account, we designed an experiment, concerning the way ideas are organised according to human perception. The experiment is divided into two parts: a visual task and a verbal task. A network of ideas was constructed using the results of the experiment. Statistical analysis showed that the verbally invoked network has the same topological structure as the visually invoked one, but the two networks are distinct.

1 Introduction

The key to reproducing intelligence and consciousness lies in the understanding and modelling of the organisation of functional areas, the privileged pathways of communication and exchange of information, and their more likely evolution and growth, as in Aleksander (2005). The heart of a biomimetic robot is the pump that sustains the blood-flow of information. The information comes from a number of functional parts which do not necessarily need to be bioinspired: it is possible to produce depth maps without knowing how the visual system produces them. What is important to know is how the depth map is used for navigation and in how many other different tasks it is used. The organisation and evolution of the information, as well as the fusion of pieces of information of varied degrees of uncertainity, are characteristics of a living being and this is what needs to be emulated directly from a biological system.

The Project of the Human Genome Consortium (2003) culminated with the completion of the full human genome sequence in April 2003. Now the research moves forwards, after having named and counted genes. Understanding the organisation and interaction of genes is the new frontier of biotechnology. This endeavour is helped by the development by Barabasi (2002) of a new science of networks, which sheds light into the complexity of organisation of living and artificial mechanisms alike.

The focus of this century will be the brain. Many researchers have already moved to the race for mapping the human brain neurons and understanding their functionalities, for example in Koslow and Hyman (2000). However, neurons are just one element. What about that special products of the human brain, the ideas? Is it possible to gain insight into the world of the ideas? Is it possible to count them? Are ideas organised in a recognisable way?

In the article by Macer (2002) the Behaviourome project was first proposed. In analogy with the genome project aimed at mapping the human genome, here the aim was to count ideas and to find out whether the number of ideas is finite, uncountable or infinite. One of the proposed means of obtaining the final goal was to provide a mental mapping of ideas and their interrelationships.

The organisation of information may be modelled in mathematical terms as a dynamic network. We are intrigued by the possibility that from the lowest possible level of information sources, namely the neurons, to the highest possible level of information products, the ideas, the same structural network may be underling the architectural building of their organisation. Networks have been used for a long time to represent complex systems. They have been popularised recently by Barabasi (2002), who studied self-organising networks. Self-organising networks may be random or scale-free. There is evidence that the organising architecture of a scale-free network underpins the structure and evolution of biological systems (like cells), social systems (like one's circle of friends) and artificial networks (like the Internet).

We designed an experiment in order to study how higher level information invoked by different stimuli, namely visual and verbal, is organised in the mind. The importance of such a speculative attempt lies in the fact that if a symmetry between lower and higher levels is found, then the same mathematical model may be used to bridge the gap between top-down and bottom-up approaches to create artificial brains and minds.

2 Ideas and networks

In order to proceed in our experiment we need to focus on two elements: ideas and networks. Ideas (and their relationships) are the subject of this research. We need to define them and to highlight some elements of the disciplines that study their relationships.

According to Macer (2002) ideas are mental conceptualisations of things, including physical objects, actions or sensory experiences, that may or may not be linguistically expressible.

Self-organising networks, occurring in the natural world and as a development of human activities, may be modelled as being random or scale-free. Both scale-free networks and random networks are *small world networks*, which means that, although the networks may contain billions of nodes, it takes only a few intermediate nodes to move from one node to any other. Let us indicate by k the number of incoming or outgoing links from any node in the network. The difference between a random and a scale-free network is quantified by the probability density function $P(k)$ of a node having k incoming or outgoing links. In the case of a random network, $P(k)$ has a Poisson distribution, $P_1(k) \sim \exp(-k)$. In the case of a scale-free network, the probability may be modelled by a power function, $P_2(k) \sim k^{-c}$, where c is a positive constant.

3 Experimental methodology

We often see something which triggers some thought, which triggers another thought and so on. We colloquially refer to this as a flow of thoughts. We may try to stimulate such a trail of thoughts by showing an image or mentioning a word to a person. Each person will generate their own path of linked thoughts. The collection of ideas that have been thought may be visualised as a network of ideas and analysed as such. So the questions we would like to answer are:

1. How many ideas on average exist between any two randomly chosen ideas?
2. Does this number depend on whether the stimuli for these ideas are presented to a person in a visual or in a linguistic way?
3. If a network of ideas can be generated, which is its topology?

There are serious difficulties in the design of an experiment in order to answer the above questions. The most important difficulties are:

1. How does one define an idea?
2. How does one deal with the enormous number of different ideas?
3. How can one expose a subject to a collection of ideas?
4. How does one count the intermediate ideas between any two ideas?

The brief answers to the above questions are as follows.

1. Since we wish to show the ideas in the form of an image in the visual experiment, we need to restrict ourselves to an idea being an object, e.g. umbrella, flower, car, sun, etc.
2. It is obvious that we need to restrict ourselves to a finite number of ideas. We decided to use 100 nouns. There were various reasons for that, mainly practical, related to the way the stimuli had to be presented to the subjects. The nouns had to be chosen in an objective way, so as not to reflect any prejudices or associations of the investigators. We chose them to be words uniformly spread in the pages of a dictionary.
3. We showed to each subject the full collection of ideas as a matrix of 10×10 images arranged in an $A0$ size poster. Each noun was represented by a clip-art from the collection of Microsoft Office. This ensured that effort had gone into the design of the images so that they were most expressive for the particular object they were supposed to depict. Before use, each image was converted into grey and it was modified so that the average grey value of all images was the same. This ensured that no image would be picked out because of its excessive brightness or darkness.
4. A picture from the collection was picked at random and then the subject was asked to pick the next most similar one, and then the next most similar one and so on. Every time an object was picked after another one, a link was recorded between these two objects.

We conducted the experiments on a sample of 20 subjects. The sequence of actions that constituted the visual experiment are listed below.

- Allow the subject at the beginning to see the whole table of objects for several minutes, to familiarise themselves with what is included in the restricted world.
- Pick up one of the objects at random and highlight it by putting a frame around it. Ask the subject which of the remaining objects is most similar to this. Once the subject has made their choice, cover the highlighted object, highlight the object they had picked and ask them to pick the next most relevant object. Stop when half of the objects are still visible. This ensures that the subject has still plenty of choice when they make their choice of the last object. The subject may be allowed to say that an object has no relation to any other object in the table. Then the particular experiment may stop. Another experiment may follow starting with a different initial object.
- The position of the objects should not be changed during the experiment, as we wish the person to know what is included in the restricted world in which they have to make their choice.

The verbal experiment was aimed at identifying how many intermediate ideas exist between any two ideas presented in a verbal form. This experiment took place several weeks after the visual experiment. The same subjects took part in both experiments. Each subject was presented with a table containing 100 words corresponding to the 100 pictures presented in the visual experiment. The experiment followed these steps:

- Allow the subject at the beginning to see the whole table of words for several minutes, to familiarise themselves with what is included in the restricted world.
- Pick up one of the words at random and highlight it by putting a frame around it. Ask the subject which of the remaining words is most similar to this. Once the subject has made their choice, cover the highlighted word and ask them to pick the next most relevant word. Stop when half of the words are still available. The subject may be allowed to say that a word has no relation to any other word in the table. Then the particular experiment may stop. Another experiment may follow starting with a different initial word.
- The position of the words should not be changed during the experiment, as we wish the person to know what is included in the restricted world in which they have to make their choice.

4 Experimental results

The first point to investigate is whether there are ideas that are selected more frequently than others, i.e. whether there are ideas that are more popular or spring into mind more often, or all ideas are generally selected with the same frequency.

ID	Idea	Frequency	# Connections
42	graduate	16	15
29	doctor	12	11
99	wedding	14	11
2	airport	12	9
33	electricity-mast	14	9
96	tree	14	9
90	teacher	16	8

Table 1: Ideas that manifest a *hub* behaviour in the visual network.

From sociological studies reported by Gladwell (2000), we know that such nodes act as *hubs* and play an important role in a network. We found that only 7% of the ideas are both very frequent and very well connected. This 7% of ideas are connected to 60% of the remaining ideas for the visual experiment, presented in table 1, and to 50% of the remaining ideas for the verbal experiment, presented in table 2. These numbers show evidence of a small world behaviour for the networks of ideas we have built.

ID	Idea	Frequency	# Connections
7	bicycle	8	10
22	circus	7	12
48	house	10	12
69	rain	7	11
71	road	7	9
83	shopping	7	9
99	wedding	8	11

Table 2: Ideas that manifest a *hub* behaviour in the verbal network.

The number of intermediate ideas between any two given ones may be investigated using two measures. The first measure is the *average path*, defined as the average length of the path between any two nodes, if such a path exists. To calculate it, one has first to calculate the *average* distance between any two given nodes and then average all these distances over the whole network. We denote this measure by $\bar{a}$. The second measure is called *mean path*. First, one has to find the *shortest path* between any two given nodes, if there is any. Then the shortest paths are averaged over the entire network. We denote this measure by $\bar{m}$.

The second research question was to discover whether the number of intermediate ideas between any two given ones depends on the way the stimuli are presented to the subject. In table 3 we list the path length characteristics for the two experiments. Taking into consideration the standard deviations of these measures, one notices that the path lengths are statistically the same, irrespective of the method used for hint giving.

Experiment	$\bar{a}$	σ_a	$\bar{m}$	σ_m
Visual experiment	13.3	1.9	11.5	3.5
Verbal experiment	13.9	1.7	12.6	4.2

Table 3: Summary of path length measures.

However, the ideas which act as hubs in the two cases are different, as one may see by comparing tables 1 and 2. This strongly indicates that the ideas are organised in two different networks, one verbal and one visual, which, however, exhibit similar topologies.

To further examine this topology we use the degree density $P(k)$, as this is a measure that characterises a network independently from the number of its nodes. We test here for the following null hypotheses:

- H_1: The data have been drawn from a population with Poisson distribution $P_1(k)$.
- H_2: The data have been drawn from a population with power law distribution $P_2(k)$.

Our analysis showed that we may reject the H_1 null hypothesis at 95% confidence level of rejection, while hypothesis H_2 is compatible with our data.

5 Conclusions

The results show:

- a small world behaviour of the networks obtained both by visual and verbal cues, indicated by the low mean path and low clustering coefficient values;
- a correspondence between the visual and verbal network in the value of the mean path and the value of the possible number of hubs;
- a correspondence in the topology of the networks, the two networks being statistically equivalent in topology;
- a difference between the visual and verbal networks indicated by the concepts that acted as hubs in the two networks;
- evidence that the networks are organised as scale-free ones.

If the mind organises itself in the form of networks, it appears that these networks are strongly influenced by the hardware on which the mind resides, i.e. the brain, otherwise we should not have a different network for the flow of ideas when visual stimuli are used, from that created when verbal stimuli are used. It is possible, therefore, to hypothesise the existence of a hierarchy of organisation of information which flows from the lowest level of electro-chemical information of the neurons, to the highest conceptual abstractions of ideas. The hierarchy is supported by the same underling network framework, which is one of scale-free topology. The network represents the hardware of the organisation, dictating which dynamical modification is plausible in the evolution of the information. What we should look for, in order to create a link between top-down and bottom-up approaches, is a mapping between neural structures and their higher level correlates.

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