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HS 120: Language, Culture and Cognition

Discuss the uniqueness of the human brain in comparison with other animals, in light of the latest scientific facts.

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Introduction

Charles Darwin had the opinion that humans are actually "**big-brained apes**" [1]. This view was also largely held by the scientific community until the late 1980s. However, with the scientific advancements and new histological techniques, neurologists began to realize the extreme complexity of the human brain. In 1999, studies made by Preuss and Coleman [2] found that the nerve cells in the human visual cortex were arranged in a mesh-like fashion unlike the simpler vertical arrays in other primates. In another interesting research, we observed that the human minicolumns left, planum temporale, are far wider than chimpanzees and monkeys. This area is primarily concerned with language and rhythm, which thus implied that humans were far from being just big-brained apes.

However, cognitive studies have also found several abilities in animals that were previously thought to be unique only to humans. But cognitive research has never kept pace with its neurological counterpart, and the papers claiming that animals are 'precursors' to human language are mostly not supported by valid computational models. So, it has become debatable if the particular line of research is a dead-end.

In this report, we will discuss how human language has developed a hierarchical structure and syntactic complexity by taking into consideration the ***dendrophilia hypothesis*** *[3]. We will then discuss how human phonology and regular level sequential processing is similar to other animals, called the* ***phonological continuity hypothesis*** *[4]. Finally, we will look at how processes like counting and rhythm recognition are not uniquely human, thus concluding that human cognition can be traced back to animals.*

The dendrophilia hypothesis

The dendrophilia hypothesis, **"suggests that human syntactic abilities rely on our supra-regular computational abilities, implemented via an auxiliary memory store (a 'stack') centered on Broca's region via its connections with other cortical areas."**

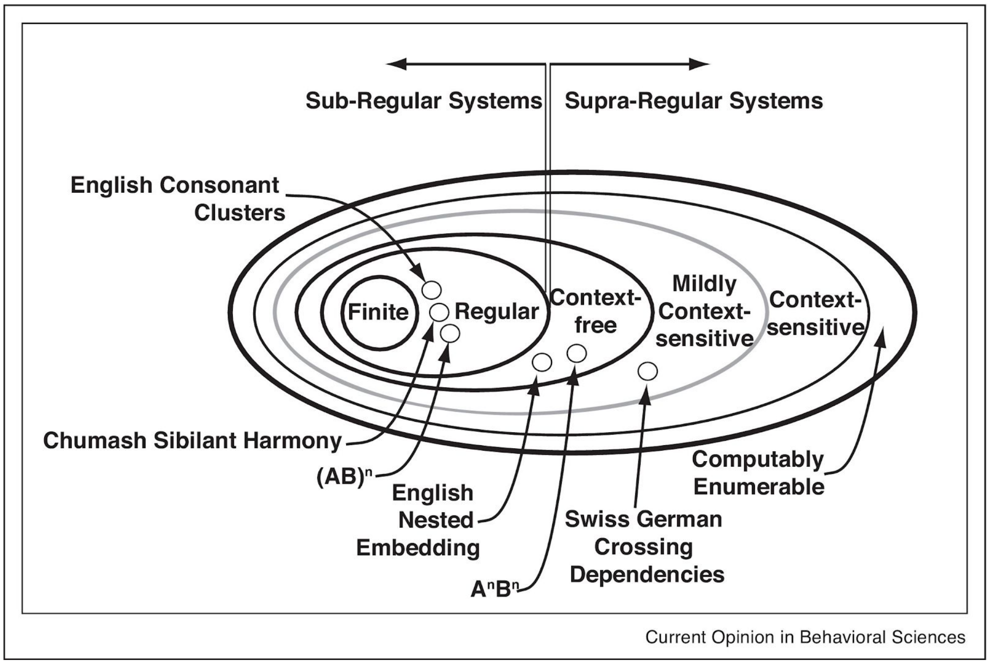
Since that might be too much information to digest at first glance, let's slowly understand what the hypothesis actually means. There are 2 things to keep in mind here - human phonology and phrasal syntax. While the former includes concatenation and sequencing abilities present in (non-human) animals, the latter serves as a key distinction between ours and other species.

Phrasal syntax (or simply syntax) refers to the arrangement of words into higher-order groupings such as phrases or sentences. One important term here is the hierarchical structure which refers to a nested grouping of words, often represented by a tree [5]. Modern linguists agree that hierarchical structure and not a sequential structure is the basis for phrasal syntax. For example, let's look at the sentence:

"Bill, having finished his work with Amanda, returned home early."

Just reading the sentence once will tell you that it was 'Bill' and not 'Amanda', who returned home early. This is because the two words are hierarchically adjacent, though not sequentially consistent as 'Amanda', and the action 'returned home' is actually positioned next to each other.

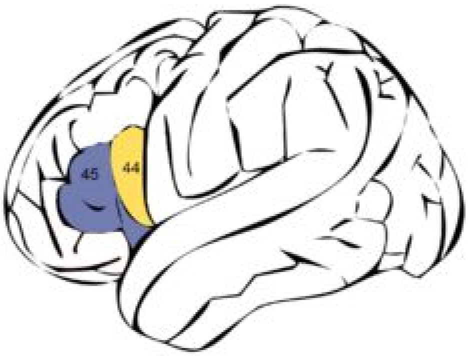
More formally, for a flexible hierarchical structure processing, we better need computational abilities than are needed for regular computational processing, more often termed as a **finite state automata (FSA)** [6]. FSA can process sequences with a single grouping level but does not extend to multiple nesting levels as we observe in the case of human language. We term the processing above the regular-level as **supra-regular** in the dendrophilia hypothesis. What is more important to note is that at the core of every supra-regular computational system is a regular computational system. The primary lacuna for the FSA is an additional memory (a stack or queue or a counter) that stores the results of each level of processing of information.



The extended formal language hierarchy. Image from Research Paper [7]

In the 2010s, neurologists studied the animals to try and observe if they possess any ability to process supra-regular expressions [8]. While some were in favor, most of the results pointed at the fact that there was no good evidence that any non-human species successfully processes supra-regular grammars. This forms the first computational component for the dendrophilia hypothesis, which draws inspiration from the bottom line that supra-regular grammar is one pivotal aspect to distinguish humans and animals in terms of language and cognition.

Now that we know and understand the basic idea behind the hypothesis, the next thing to worry about is - how are such capabilities implemented in the human brain? The answer comes from decades of work around the Broca's area. Studies have shown the following about Broca's area:



Broca's area is made up of Brodmann areas 44 (pars opercularis) and 45 (pars triangularis)

- ❖ When the size of hierarchical chunks being processed by participants in an fMRI experiment is systematically varied, independent of semantics, increased chunk size leads to a steady increase in the activation of Broca's area [9].
- ❖ When syntactic complexity is increased for German sentences, Broca's area is preferentially activated for Broca's area.
- ❖ Broca's area is much more developed in humans as compared to other animals like chimpanzees both in terms of cortical surface area as well as in terms of connections to other cortical regions. In the latter case, a dorsal pathway linking Broca's region to parietal, occipital, and temporal regions is uniquely strongly developed in humans as compared to a simpler ventral pathway for other primates [10].

From all this information, we can come to the conclusion that - the accessory memory (stack or equivalent) required for supra-regular processing of hierarchical structure is implemented in the neural circuit centered on Broca's region. This forms the second aspect of the dendrophilia hypothesis. To summarise, we can say that the dendrophilia hypothesis "**provides both an explicit computational characterization about how the abilities underlying human hierarchical organization and phrasal syntax differ from the animal sequence-processing abilities and a specific implementational model of how this difference is implemented in the human brain".**

The phonological continuity hypothesis

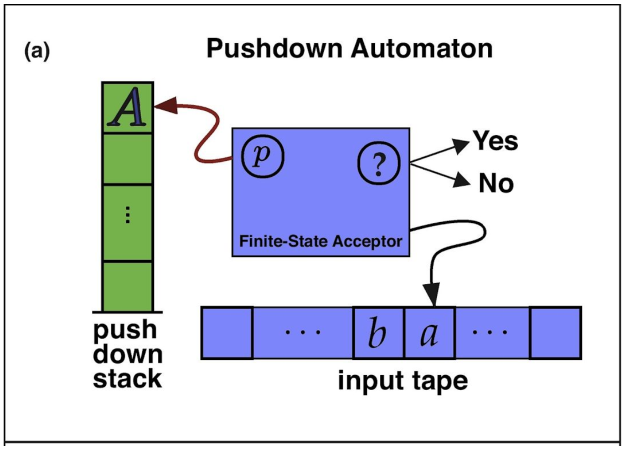
The phonological continuity hypothesis, “**suggests that humans share the processing capabilities required to deal with regular-level sequential processing, and thus phonology, with other animals, and these shared capabilities are implemented in homologous neural processing algorithms and circuitry.**”

While discussing the dendrophilia hypothesis we had focussed on the supra-regular computational abilities of non-human animals. However, the question that arises is - since humans and other animals are both able to deal with simple sequencing and grouping, how far are these abilities related? Evolutionary aspects suggest that there should be a relation between them, and they must rely on similar or more precisely a homologous neural circuitry.

Two important limitations for this hypothesis are an absence of a solid methodology to prove/support this hypothesis, and also defining what exactly ‘homology’ means with respect to the above hypothesis. But this hypothesis does have a basis when considered in the context of evolution and has several significant consequences.

In phonology, the fundamental operation is concatenation over strings, defined as serial sequences of items. The syntactic focus is more of a higher dimension to phonology. Extending this to a neural direction means that the capability to interpret and use supra-regular grammar is an improvement over the power to understand regular or sequential computations. This means that during the process of evolution, the human brain evolution ‘hijacked’ preexisting primate sequencing capabilities and simple sequential grouping capabilities already present in our common ancestor with chimpanzees, and modified them to implement hierarchical multi-level grouping. This is done via the important process of duplication-with-differentiation, something quite key to molecular-evolution [11].

This in a sense handles the doubts regarding homology. It means if humans are able to process the basic sequential information in the same way as animals, it is possible that we make use of similar neural processing algorithms for the same. It's important to note that this is not necessarily true, since the same end result can be obtained by implementing a variety of algorithms, but considering that the superior human brain has evolved in the differentiation after duplication procedure, it's less likely to be so.

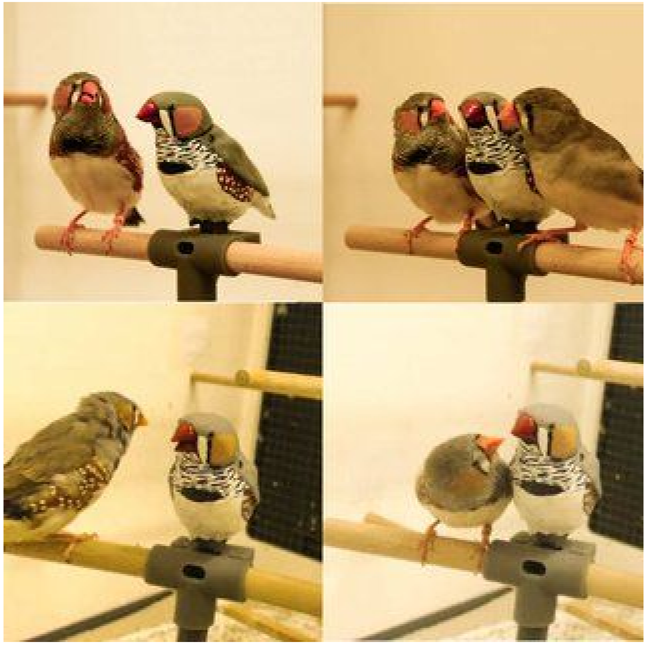


The components of a pushdown automaton, the simplest supra-regular computational model.[12]

The key processing distinction between phonology and syntax is about the regular versus supra-regular computations, rather than the atoms that are combined by these operations. This is because every supra-regular pushdown automaton has, at its heart, a regular FSA. So, PCH specifically suggests that both phonological processing and the regular aspects of syntactic processing should be shared between humans and animals, and remains agnostic about whether the items being combined are syllables or morphemes or indeed musical notes or visual icons. PCH thus opens up an array of new research opportunities, like the one we'll see next.

Understanding the roots of rhythm

As we have already seen in the last topic of discussion, we know that the PCH is not concerned about the items being combined to generate the regular FSA. In the case of musical notes, this takes the form of rhythm. Rhythm is one fundamental aspect of human language. For modeling this, we study Zebra Finches, a species of bird, that has an unusual precision and capability in understanding musical notes.



Young zebra finches interacting with RoboFinch inside a cage[13]

In the case of zebra finches, male species learn music from tutors! Experiments have shown that zebra finches might have an understanding of isochronous rhythm. In one such experiment, a robotic zebra finch was used to produce music, and various parameters were varied to see the response of other finches [13].

❖ Individual birds were housed with a robotic zebra finch that emitted an isochronous call pattern. Within ample minutes the zebra finches adjusted their call rate to create a regular back-and-forth exchange with the robotic finch.

❖ The robot was then set to emit “jamming” calls that were produced at the moment when the zebra finch was most likely to respond. All zebra finches adjusted their call pattern to avoid the jamming calls, either by calling earlier, later, or both earlier and later.

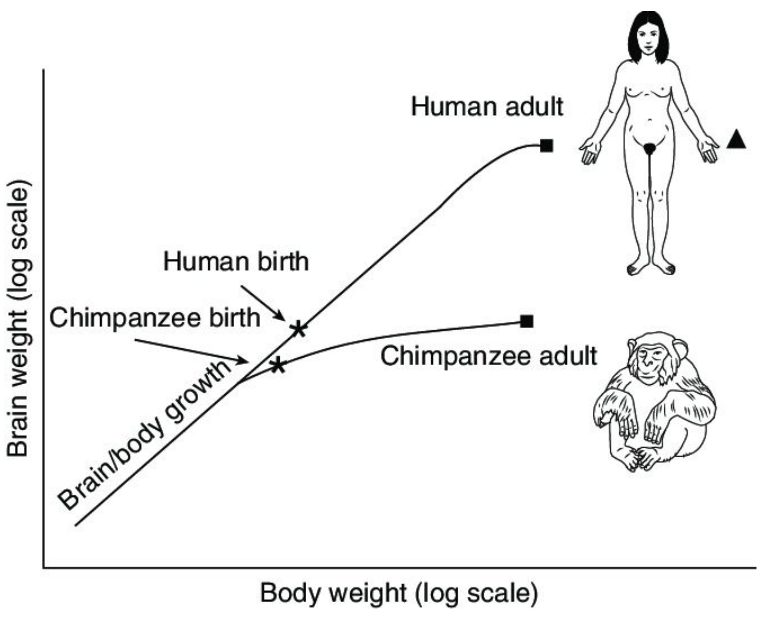
❖ Furthermore, when the robotic finch produced a pattern of alternating single and paired calls, the zebra finches timed their calls differently for the single compared to the paired calls, indicating they apparently detected the alternating pattern of the robot calls and used this to anticipate whether the next call would be single or paired.

This shows that the Zebra finches might have an understanding of rhythm as we know it. However, how far that understanding goes is debatable. This is because humans are quickly and easily able to reveal patterns in sound and discuss several aspects right from regularity, pitch, pattern etc. Recent studies have shown that it’s possible that Zebra finches distinguish and discriminate the different notes based on their specific inter-pulse-interval durations, i.e, local features, without attending to or learning about the global pattern of regularity-irregularity of the strings [14]. However, even in this case, there is a continuum with some birds performing considerably better than the rest.

In any case, Zebra Finches provide a solid example to suggest that animal cognition is a good candidate to be a precursor to the evolution of complex human evolution.

Grouping, Patterns and Numbers

The hierarchical organization of information that we have seen in the case of supra-regular grammar also extends to other use cases, such as in grouping, number system, and recognizing patterns. Experiments with chimpanzees on grouping, also work pretty fine [15]. For instance, chimpanzees sort apple, grape, etc., into one bin, bread, cupcake, etc., into another, thus recognizing categories, and category is a precursor of hierarchical information, there is no evidence that they recognize class-inclusion, which is another precursor of the hierarchical organization of information. Class inclusion for example means the chimpanzee should be able to realize that ‘an orange is a fruit, but a fruit is not an orange’. One interesting thing to note is children below the age of ~3 years are not able to do such class inclusion. A good rule of thumb is concepts acquired by children after 3 years of age are never acquired by chimpanzees (look at the graph) [16] and that goes a long way to support the PCH, and also the idea that our cognition has some roots in other primates.



Brain Weight vs Body Weight for chimpanzees and humans[17]

Similarly, for patterns and numbers, chimpanzees, and other animals have a more crude understanding. It’s like the perception of a few objects, rather than exactly 5 objects. Research and historical evidence has shown that numbers apparently also did not exist back when we had hunters and gatherers. The transformation to having exact numbers is more motivated by social and economic factors.

Conclusion

Indeed these are exciting times in neurobiology, given the astounding power of modern methods to fuel an increase in research work about neural implementation, algorithms, and activity. We are discovering new and amazing facts about the power of the human brain every day, and this means we should also take huge strides in understanding the evolutionary beauty of language and cognition as we know it today. At the same time, it’s essential to note that conducting studies about animals and their communication will help us simplify the process of understanding more about the human language.

The hypothesis we discussed, the examples and experiments, all point out clearly, that this an exciting topic for research, and quietly aptly justify the goal we wanted to achieve in the introduction, i.e. human brain, language, and understanding is complex no doubt, but certainly has its relatively simpler counterparts in animals.

Contributions:

Both Anjali and I have worked together, reading 3 of the 6 research papers (uploaded on teams) which seemed relevant to our argument. We made conclusions and wrote them on another doc and finally made a fair doc, the PDF of which is attached here. To assess individual contributions will be tough but roughly,

a. **Anjali Soni**: Read "Human and animal cognition: Continuity and discontinuity", analyzed the idea, and wrote about the introduction, grouping, patterns, and numbers, and also read about the topic of Zebra Finches.
b. **AB Satyaprakash**: Read "What animals can teach us about human language: the phonological continuity hypothesis", comprising the dendrophilia hypothesis, phonetic continuity hypothesis, and also discussed the Robotic Finch experiment. Additionally, I wrote these topics on the PDF.

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