DOCUMENT SUMMARY

This paper by Taylor, Fernandes, and Wraight introduces **Complementary Cognition**, a new theory of human cognitive evolution. It posits that humans evolved to have individual neurocognitive specializations in different "search" strategies (exploration vs. exploitation), leading to a system of cooperative, group-level cognition. This collective cognitive search, the authors argue, was a response to highly variable environments and is fundamental to understanding our species' exceptional adaptability, cumulative cultural evolution, and the emergence of language.

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Taylor_Fernandes_&_Wraight_2021_The_Evolution_of_Complementary_Cognition_Humans_Cooperatively_Adapt_and_Evolve_through_a_System_of_Collective_Cognitive_Search

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We propose a new theory of human cognitive evolution, which we term **Complementary Cognition**. We build on evidence for individual neurocognitive specialization regarding search abilities in the modern population, and propose that our species cooperatively searches and adapts through a system of group-level cognition. This paper sets out a coherent theory to explain why **Complementary Cognition** evolved and the conditions responsible for its emergence. Using the framework of **search**, we show that **Complementary Cognition** can be contextualized as part of a hierarchy of systems including **genetic search** and **cognitive search**. We propose that,

just as **genetic search** drives phenotypic adaptation and evolution, complementary **cognitive search** is central to understanding how our species adapts and evolves through culture. **Complementary Cognition** has far-reaching implications since it may help to explain the emergence of behavioural modernity and provides a new explanatory framework for why language and many aspects of cooperation evolved. We believe that **Complementary Cognition** underpins our species' success and has important implications for how modern-day systems are designed.

Introduction

In this article we propose a new theory of human cognitive evolution, which we argue lies at the core of explaining the exceptional adaptiveness of our species. In particular, we propose that members of our species are individually specialized in different but complementary neurocognitive **search** strategies and that consequently we regulate **search** for adaptive information at the group level, adapting cooperatively. The theory is grounded in Complex Systems theory (e.g. Mitchell 2011) and the framework of **Search** (e.g. (Hills et al. 2015). We call this emergent system of collective cognitive **search** **Complementary Cognition**.

Cross-cultural patterns that occur in human cognition suggest specialization in cognitive **search**, with large portions of the population having noticeable cognitive **search** biases. Looking at these complementary patterns of specialization comprehensively, we begin to see that they belong to a greater complex adaptive system (Taylor & Lockett forthcoming).

To reveal the significance of **Complementary Cognition**, we begin by defining **search** and show that **Complementary Cognition** can be contextualized as part of a hierarchy of systems of **search**, at the level of the genome; cognition; and collective cognition. These systems of **search** are significant: results of adaptive **search** can be inherited and so evolve over time.

Neurocognitive specialization in **search** predicts that our species evolved in a highly variable environment, since uncertainty is a key driver in the selection of **search** capability, and variability makes **search** optimization at the individual level difficult. We outline how such conditions prevailed during the evolutionary history of our ancestors (Potts 1998) and must have created strong selection pressures for efficiency and capability in **search**.

We propose that such selection pressures, coupled with fundamental constraints in individual cognition, induced division and specialization in neurocognitive capabilities; that is, selection pressures acting at the individual level resulted in the evolution of individual hominins with different but complementary neurocognitive **search** strategies, resulting in the emergence of a new system of **search** at the collective level.

Specialization in **search** would only be possible in the context of appropriate means of collaboration. We propose that **Complementary Cognition** co-evolved in a positively reinforcing feedback loop with aspects of communication and cooperation. This has implications for an evolutionary theory of language, providing two key reasons for its evolution: first, as a mechanism to facilitate collaborative **search** between cognitively specialized individuals; secondly, as a new inheritance channel to share the results of cognitive **search**. Particular features of human language conform with this theory. For example, the integration of information from different **search** strategies creates information of unbounded complexity, and so communicating the results of complementary cognitive **search** requires an open system, a key feature of human language.

We suggest that the evolution of **Complementary Cognition** can be characterized as a **Major Transition** (Maynard Smith & Szathmáry 1995) and represents a significant transition in evolvability, enabling substantially greater capacity, speed and flexibility to adapt than adaptation at evolutionary or cognitive scales.

We propose that the emergence of **Complementary Cognition** plays a central role in explaining our species' remarkable adaptiveness. Humans have come to thrive in nearly every terrestrial environment on the planet. From tropical rainforests, savannah to tundra, our phenotypic adaptations are almost identical. Adaptation to such a range of habitats has primarily been achieved through extra-somatic or cultural adaptations—including behavioural and technological adaptations (Binford 1962; Richerson & Boyd 2005). The evolution of these cultural adaptations is open-ended and cumulative. We propose that the reason for this adaptive capability is **Complementary Cognition** and that it lies at the heart of explaining our cumulative cultural evolution.

Definition of Complementary Cognition

Complementary Cognition is the theory that our species cooperatively adapts and evolves through a system of collective cognitive search.

It is proposed that Complementary Cognition emerged as a consequence of individual neurocognitive specialization in search and co-evolution with language and aspects of cooperation.

Cooperative search between specialized individuals enables the co-creation of adaptations of higher fitness value. It does not imply that individuals carry out exploratory or exploitative activities exclusively, but rather are specialized so that they differ with regard to the neurocognitive capabilities that support search, and how information search is balanced. Complementary Cognition can be contextualized as part of a hierarchy of systems through which our species adapts and evolves which includes genetic evolution.

Complementary Cognition evolved due to high environmental variability during our species' evolution, which created strong selection pressures for cognitive search capacity and efficiency.

Complementary Cognition contributes to our understanding of behavioural modernity and the emergence of cumulative cultural evolution.

Search, adaptation and evolution

Although many systems of adaptation exist within an organism (McGlade & Allen 1986), the adaptive systems of **genetic search** and **cognitive search** differ in that the results can be stored, inherited and updated through further **search**. This leads to evolution of adaptations over time. Complementary cognitive **search** also has this property.

What do we mean by search?

Living systems need to acquire and update adaptive information: information that is of most adaptive value will vary over time and space, for example as predators or prey move, or as resources are depleted or change with seasons and environmental variability, creating uncertainty that necessitates **search** (Hills et al. 2015). **Search** in some form is thus fundamental to adaptation across species.

The optimal **search** strategy will involve a mixture of **exploration** and **exploitation**. This can be viewed as a continuum. At extremes, all resources are fully allocated to either **exploration** or **exploitation** of existing information. Consider a simple **search** for food in physical space. An organism can exploit the known area where it stands, exploiting a known patch of resources, or it could **search** more globally, exploring unknown areas for new patches of resources, or mix these behaviours.

Search is not restricted to physical domains. Abstract **search** can involve information domains, such as the social domain or abstract design ideas, or searching memories for a relevant piece of information. Abstract searches occur over information landscapes instead of physical ones.

Navigating this ubiquitous **'exploration-exploitation' trade-off** is a **search** optimization problem (Črepinšek et al. 2013). Organisms continuously face the dilemma of whether to pursue actions that exploit existing but possibly suboptimal information, or explore uncertain but potentially more profitable solutions. While **exploration** may lead to better resources, exploring to the exclusion of **exploitation** might result in too many undeveloped new ideas and a lack of refined skills and expertise. By contrast, focusing too much on **exploitation** risks being trapped in a local optimum or failure to adapt to environmental change (March 1991).

Genetic search

Darwin's theory of evolution through natural selection can be interpreted as a **search** process (e.g. see Watson & Szathmáry 2016) by which successful adaptations are inherited and updated over time. Every organism's genotype can be regarded as a balance between inherited information that existed in the previous generation and variation arising for example from mutation or recombination.

Variability, uncertainty and the evolution of cognitive search

Genetic search has obvious limitations. It does not enable an organism to adapt to environmental changes during its lifetime. If changes occur faster than can be adapted for genetically, adaptation must occur through other mechanisms for the organism to survive and reproduce. Many species have evolved the capacity for **cognitive search**, enabling behavioural adaptation during an organism's lifespan.

Cognitive search

Cognition is not generally viewed from the perspective of **search** in the field of cultural evolution. Emphasis has been on how cultural adaptations are inherited and maintained between generations, with importance placed on mechanisms such as social learning (Henrich 2017; Laland 2017; Richerson & Boyd 2005) as well as other aspects which support high fidelity and bandwidth of inheritance such as niche construction (Sterelny 2011). In other words, how past adaptive knowledge is exploited.

Hills et al. (2015) propose that cognition can be envisioned as a **search** process, characterized by the **exploration-exploitation trade-off**. **Search** can be used as a common framework for understanding cognitive behaviour and the function of cognitive control across domains (Hills et al. 2015). Regulating **search** is so central to adaptive success that optimally balancing **exploration** and **exploitation** is believed to be one of the most important selective forces operating in the evolution of cognition (Cohen et al. 2007; Hills et al. 2015).

Variability and uncertainty in hominin evolution

It is well established that hominin evolution occurred in the context of extremely high levels of variability and thus uncertainty. Environmental evidence, such as oxygen isotope measurements, reveals that the period of human evolutionary history over the past six million years corresponds with one of the most dramatic periods of climate oscillation of the past 65 million years (Potts 1998). Hominid evolution coincides with longer and even more extreme climatic oscillations (Potts 1998).

The evolution of complementary cognitive search

Division and specialization in cognitive search

While differences in human **search** behaviours have been observed (e.g. Hutchinson et al. 2012), the notion that the individual members of our species are neurocognitively specialized in complementary cognitive **search** strategies has not been previously proposed. Division and specialization are common throughout nature. In the context of an already cooperating group, within-species division and specialization are favoured when features that confer fitness benefits are functionally incompatible (Rueffler et al. 2012) or when efficiency benefits to reduction of task-switching costs or specialization reach a certain threshold (Cooper & West 2018; West et al. 2015).

Co-evolution with lowered coordination costs

Our species' unique ability to collaborate in complex ways at scale (Melis & Semmann 2010) has been difficult to explain from an evolutionary perspective. For example, there remains significant debate as to why language evolved (see Szathmáry 2010, fig. 1, for an overview of theories). **Complementary Cognition** provides a new explanatory framework for understanding why such sophisticated levels of cooperation and means of communication such as language evolved.

Specialization in cognitive search and co-evolution with language

Specialization will affect which cooperative traits are selected for. For example, in physical or perceptual space, forms of gestural communication such as pointing, or shared intentionality, may have been adequate for cooperative **search** towards shared goals. As capability and specialization evolved in other **search** domains, other forms of information sharing were probably required. It becomes almost impossible to **search** certain domains cooperatively, especially abstract domains, without means of sharing complex abstract information. Language enables such sharing. Human language differs qualitatively from that of other animal communication systems in the use of recursion, which endows human language with a uniquely open-ended capacity to communicate abstract concepts (Hauser et al. 2002) **Complementary Cognition** provides an explanatory framework for language by outlining the selection pressures that could have led to its evolution, and why a new channel of information transfer and inheritance with these properties was required.

Emergent benefits of Complementary Cognition

Navigating **search** at the group level confers a number of important benefits such as: significant efficiency savings; globally increased capacity in **search**; risk mitigation at the individual and group level; and recombination of different **search** strategies. Overall, the combination of these benefits significantly increases the robustness of the group to environmental variability. It can be regarded as a meta-adaptation which represents a substantial qualitative improvement in evolvability.

Implications for cultural evolution

Neurocognitive specialization in **search** has not previously been considered, nor has its potential effect on cultural evolution. With regard to inheritance of adaptive knowledge (i.e. the results of previous searches), one aspect to consider is that individuals with different cognitive specializations may be more reliable sources for different kinds of socially learned information. For example, specialists with an exploitative bias may be better at faithfully copying and recalling detailed or procedural information passed down through generations, such as the correct sequence and way of making a tool. Conversely, those with an explorative **search** will be better able to identify global patterns in inherited information, enabling generalizations and predictions about unknown or ambiguous situations.

Discussion: relation to existing research and areas for future research

Alignment with variability selection

Complementary Cognition aligns strongly with Potts' **'Variability Selection'** hypothesis, which proposes that, rather than being adapted to a particular environment, humans are adaptive with respect to environmental variability, that is, inconsistency of selective conditions (Potts 1998; Potts & Faith 2015; Potts et al. 2018). **Complementary Cognition** enables precisely this—significantly, it increases the capacity to adapt not to a particular environment, but to any kind of environmental context—any information landscape.

Cultural evolution

Cultural innovation and transmission have long been seen as analogous to genetic mutation and transmission (Boyd & Richerson 1985; Cavalli-Sforza & Feldman 1981). The framework of **search** highlights the similarity between these processes. **Genetic search** drives phenotypic adaptation and **cognitive search** drives behavioural adaptation. In a similar manner, we propose that **Complementary Cognition** (cooperative cognitive **search**) lies at the heart of explaining the exceptional level of cultural adaptation in our species.

Apparent gap between behaviourally and anatomically modern humans

Complementary Cognition could contribute to understanding the apparent delay of around 100,000 years between anatomically modern humans and typically modern human cultural behaviour (Sterelny 2011).

Evolutionary theory of language and cooperation

Several different theories have be proposed to explain the evolution of language (Hauser et al. 2014; Szathmáry 2010, fig. 1). **Complementary Cognition** provides a new theory of how language evolved as a means of enabling cooperative **search** and as an inheritance mechanism for the more complex adaptive information that resulted.

Major transition

We propose that the evolution of **Complementary Cognition** can be characterized as a **major transition** (Taylor & Fernandes forthcoming). These rare evolutionary events occur when evolution favours cooperation, division of labour, specialization and interdependence to such a degree that there is a loss of individuality (Maynard Smith & Szathmáry 1995; West et al. 2015).

Implications and significance

Summary of Complementary Cognition

We have proposed that humans primarily adapt and evolve via a hitherto unrecognized system of complementary cognitive **search**, which we call **Complementary Cognition**.

Complementary Cognition within a hierarchy of evolutionary systems

Complementary Cognition can be contextualized as part of a hierarchy of self-similar systems, each of which contributes to the adaptation and evolution of our species. This hierarchy includes phenotypic adaptation and evolution, which is driven by **genetic search** and natural selection and behavioural adaptation, driven by **cognitive search** (Fig. 1).

Figure 1. Hierarchy of Search.

*This figure depicts a three-tiered hierarchy of adaptation and evolution. At the bottom is **Genetic Search**, leading to phenotypic adaptation. The middle tier is **Cognitive Search** at the individual level, leading to extra-somatic adaptation. At the top is **Complementary Cognitive Search**, described as group-level cognitive search among neurocognitively specialized individuals, leading to co-created extra-somatic adaptations.*

Limitations

It is important to not over-simplify our discussion regarding **Complementary Cognition**. Whilst grounded in the theory of complex adaptive systems, this article should be seen as an overview to contextualize further development and publication of specific forthcoming research.

Closing remarks

> The fact is that no species has ever had such wholesale control over everything on earth, living or dead, as we now have. That lays upon us, whether we like it or not, an awesome responsibility. In our hands now lies not only our own future, but that of all other living creatures with whom we share the earth. (Attenborough 1979, 308)

Our species' evolutionary history was shaped by climate change and substantial environmental variability. We are now facing a period of dramatic climate change, in which our environment will vary at a rate hitherto unforeseen in human history. However, this time, human activity is the cause of variability. We have in a sense come full circle. This may be more connected than we realize.

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