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INVITED ARTICLE

Neurocognitive models of sense-making

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Abstract
Sense-making is a temporally extended inference task involving multiple cycles of information foraging, evaluation, and judgment. Recent advances in neural simulations of sense-making are opening new venues to explore core issues on modeling complex cognition in the brain. Decision making is a basis element in complex cognition, and despite decades of study, it continues to draw interest from diverse fields. Through the construction and validation of neurocognitive models, the neural origins of complex cognition can be investigated and simulated to explain decision making behavior. We describe the broad landscape of inquiry, interdisciplinary motivation, and specific applications for building neurocognitive models that simulate the complex cognitive processes underlying sense-making.

Introduction

The study of cognition, over thousands of years, has undergone a transformation from being driven by philosophers pondering the nature of the mind to biologists investigating the functions of neurons (Boden, 2006). Today, cognitive science is a major field of research, but defining cognition remains challenging in and by itself. In some ways, cognition picks up where simple perception leaves off. Recently, growing interest in neural computation began to penetrate cognitive science. While certain aspects of cognition appear amenable to computer simulations, a full understanding of complex cognitive phenomena remains elusive. Most efforts to date have largely focused on laboratory studies of isolated cognitive processes that are unlike the highly interleaved, temporally extended suite of cognitive functions humans perform in the real world. A host of questions arise when addressing a real world problem, such as investing in a good stock or treating a disease: How and when do

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we learn to use these processes in different contexts? How are these operations carried out in the brain? Do they bias each other? In such real world circumstances, it is often decision making bias that surfaces as the topic of interest (Kahneman, 2011; Kahneman, Slovic, & Tversky, 1982; Klein, Orasanu, Calderwood, & Zsambok, 1993). In this article, we introduce sense-making as framework for studying cognition and biases, and briefly review the trade space of selected cognitive modeling efforts and complexity in the brain. We examine a tool in applied sense-making to mitigate bias and its mapping to neurocognitive processes, and discuss learning systems in the brain that adapt and perform them.

Complex cognition and sense-making

Whether the domain is law enforcement, medical diagnosis, organizational management, scientific research, or intelligence analysis, successful sense-making in the real world requires several cognitive capabilities and operations (Croskerry, 2009; Heuer, 1999; Pirolli & Card, 2005; Weick, 1995). Neural systems can reduce the uncertainty and complexity of their operational space by attending to subsets of information, evaluating it, storing it, and reusing it. Learning is key in each of these four operations, and complex cognition requires goal driven behavior in each one. Cognitive control involves a number of interacting neural circuits to determine when to switch between goals (Botvinick, Cohen, & Carter, 2004; Braver, 2012; D'Ardenne and Eshel, 2012; Kerns, Cohen, & MacDonald, 2004). Although goal driven behavior and cognitive control are widely studied in both animal and human models (Chatham, Herd, & Brant, 2011; Herd, Krueger, Kriete, & Huang, 2013; O'Reilly et al., 2010; Wiecki & Frank, 2011), in the real world goals are not necessarily predefined, discrete, or even stationary. Instead, goals often have to be self-generated, are inter-related (e.g., hierarchical), and change in time or with context. The interplay between explicit and implicit learning in these capabilities provides powerful heuristics for dealing with uncertainty and complexity at the expense of cognitive biases. A rich framework that encompasses these cognitive processes can be found in the fields of applied (Klein, Moon, & Hoffman, 2006a,b) and organizational psychology (Weick, 1995) in the form of ''sense-making'' theory. As described by Louis (1980):

> ''Sense-making can be viewed as a recurring cycle [...]. The cycle begins as individuals form unconscious and conscious anticipations and assumptions, which serve as predictions about future events. Subsequently, individuals experience events that may be discrepant from predictions. Discrepant events, or surprises, trigger a need for explanation, or post-diction, [...] for a process through which interpretations of discrepancies are developed [...].''

This definition highlights the potential of sense-making as a useful conceptual scaffold for understanding bias in the broader context of complex cognition as well as to address relevant processes — such as spatial and numerical estimation, decision making, affective cognition (e.g. reward, risk, and loss), attention, and memory - in the context of sense-making. The data-frame theory of sense-making describes these processes in complex cognition in terms of hypothesis formulation, information foraging, evaluation, and inference (Klein et al., 2006a,b). It is an extension of frames as a data structure for cognition that was first applied in the context of perception (Minsky, 1975).

Sense-making has also been described as the cognitive function that structures the unknown by inter-relating mental content (including external stimuli and internally generated representations) so as to allow comprehension, prediction, and action (Weick, 1995). A challenging aspect of this process is the necessity to continuously adapt the existing interpretation to a dynamic and ever-changing environment. This observation provides a links to the viewpoint that sense-making arises from autonomous agency in the context of experience with the external world (Froese & Ziemke, 2009). An in depth discussion of all facts of sense-making, however, is beyond the scope of this article.

Sense-making in the brain: Complexity at multiple scales

As intimated above, sense-making inherently involves a complex interaction among specialized systems sub-serving episodic, working and semantic memory, perception and attention, language, executive control, and other functions. As a consequence, efforts to model cognitive operations related to sense-making have generally involved systems with a high degree of internal differentiation and interactivity. The earliest efforts along these lines were in artificial intelligence (AI), and that field remains active in this regard. Most recently, for example, machine learning applications have been proposed to model the content of text corpora (Landauer, McNamara, Dennis, & Kintsch, 2007). In such models, as in earlier AI approaches, a key factor turns out to be the background knowledge the system brings to bear in making interpretations or decisions. This may take the form of the rich semantic knowledge (referred to as schemas in AI and frames in sense-making theory) or the prior distributions that inform inference in recent Bayesian models (Griffiths, Chater, Kemp, Perfors, & Tenenbaum, 2010; Lee, 2008; Tenenbaum, Griffiths, & Kemp, 2006). A different approach to analyzing the meaning of language and words involves the use of cognitive maps based on semantic relations such as synonymy and antonymy (Samsonovich & Ascoli, 2010), which revealed universal dimensions of affect such as valence (good vs. bad) and arousal (calming vs. exciting). An extension of this kind of analysis was recently introduced based on the ''is-a'' relation of hypernymy-hyponymy, leading to the definition of a new metric of ''abstractness'' or, more properly, ontological generality (Samsonovich & Ascoli, 2013). The ability to measure how general a given concept is (e.g. your neighbor's beagle vs. a dog vs. living entity) is particularly relevant to sense-making because the gist of a situation or mental state can usually be identified at a particular position in the hierarchy of semantic meaning. For the same reason, ''knowledge engineers'' are actively engaged in the construction of appropriate ontologies in many domains of knowledge. For curated ontologies with rigorous inheritance of logical hierarchy, ontological generality can