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Characterization of reasoning in terms of perceptual simulation

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Abstract

Although characterizing reasoning and natural language semantics in traditional logic captures their complexity and productivity, accounting for the grounding of logical reasoning in perception raises several challenges. These include difficulties in explaining the integration of reasoning and perceptual processing, and in accounting for the evolution of human reasoning from sensorimotor origins. Central to these problems is the fact that traditional logic includes elements such as quantifiers and negation that do not obviously occur in perceptual representations. We propose a formal framework in terms of perceptual simulation that bridges this gap. We demonstrate that perceptual simulations have the power to explain crucial elements of logical human reasoning and also allow us to provide the first unified linguistic analysis of noun phrases, negative polarity items and branching quantifiers within a single cognitively motivated formal framework.

Keywords: Reasoning; Perceptual simulation; Quantifiers; NP semantics; NPI; Branching quantifiers

1. Introduction

Logical languages such as first-order predicate logic are commonly used to represent natural language semantics and to characterize human reasoning (cf. Gamut, 1991).[1] Such a logical approach reflects the compositionality and productivity of natural language semantics. Human reasoning also shares productivity and at least some deductive properties with logical inference.[2] On the other hand, a major problem with the use of logic for enabling natural language semantics and reasoning is the grounding of the semantic information in perception (cf. Harnad, 1990).

The problem is that if we assume that a first-order logic (FOL) or its equivalent enables human reasoning, then it means that the ingredients of reasoning involve abstract elements such as quantifiers, the negation operator '¬' and the disjunction connective '∨'. In contrast, it is not immediately obvious how such abstract elements could be included in perceptual representations such as visual images.[3] This makes it harder to account for how reasoning and perception integrate. As a result, cognitive theories

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[1] We assume that humans reason with natural language semantic representations. Although this is not an absolute necessity for our account, most semantic theories (Carpenter, 1997; Gamut, 1991; Heim & Kratzer 1998) assume this. Also, since a crucial motivation for the formal language that we propose is the efficient data exchange between different computational methods that are used for formulating human-level intelligence, it makes little sense to multiply the number of knowledge representations discussed in this paper.

[2] Some researchers (Oaksford & Chater, 2006; Spivey, 2007) argue that human reasoning is not logical. However, even if human reasoning is not exactly like classical logic inference, a theory of reasoning somehow needs to explain those aspects of human reasoning that have motivated logical formalisms.

[3] In fact, it is not easy to represent quantifiers and propositional negations in terms of visual images. See Uchida, Cassimatis, and Scally (2012) for details.

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become fragmented and significant inefficiencies or inadequacies are introduced into computational systems attempting to combine reasoning and perception.

Admittedly, it is debatable whether human reasoning and perception should be integrated in the theory of human-level intelligence. However, as Barsalou (1999) pointed out and as our own earlier work (Uchida et al., 2012) also discussed, the view that reasoning occurs using representations similar to perceptual representations has several theoretical merits. It helps explain how cognition and perception are connected, how child cognition develops and how human cognition evolved from the cognition of animals with primarily perceptual and motor abilities. Further, an increasing amount of psychological and neurological data (Barsalou, Pecher, Zeelenberg, Simmons, & Hamann, 2005) is consistent with this theory.

In natural language interpretation, perceptual information such as visual images can continually interact with the semantics of natural language expressions.[4] Similarly, perceptual information can be integrated into general reasoning at any time (cf. Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). For example, when a car driver perceives another car running too close to his car, he may drive away from that car, according to a general reasoning rule such as, 'If one's car is too close to a large object, one drives ones' car away from that object'. We may represent this rule by a first-order formula in (1).[5]

(1) $\forall x \forall y \forall z((\mathrm{Car}(x) \& \mathrm{Drive}(y,x) \& \mathrm{BigObject}(z) \& x \neq z \& \mathrm{Near}(x,z)) \rightarrow \mathrm{DriveAwayFrom}(y,x,z))$

However, in the above example, the perceptual system recognizes a particular car, say, John's car that John is driving, getting too close to another particular car, i.e., the car that John is seeing next to his car. Thus, if we account for human cognition by using first-order logic as in (1), there will be non-trivial inference steps in order to match the concrete perceived information with the rule stated by the abstract logical form in (1) so that John can conclude, 'John drives John's car away from the car running next to his car.'

To address these problems, we present an account of human reasoning in terms of simulations with perceptual mechanisms and propose a language that represents such simulations. Since the ingredients of this language have corresponding elements in perceptual representations such as visual images (see Section 2), our theory will be able to account for the integration between reasoning and perception as above, or the grounding of linguistic information in perception, in a more efficient manner.

In this paper, we compare our simulation language with first-order logic (FOL) before considering higher-order logics in future work. This is partly because, although the analysis of reasoning with first-order logic has the above mentioned grounding problem with regard to perception, an analysis using higher-order logic (cf. Gamut, 1991) is even worse in this regard.[6] Similarly, most established automated implementations of reasoning use first-order logic (cf. Fitting, 1996), which indicates that a theory of reasoning using higher-order logic still has a non-trivial hurdle to clear, since no proper scientific theory should require the supervision of the theorist to deal with new data. On the other hand, an analysis of natural language semantics and reasoning using higher-order logic (cf. Barwise & Cooper, 1981; Carpenter, 1997; Gamut, 1991) has several merits, such as the compositionality of interpretation and its ability to represent finer-grained entailment relations. In this regard, we hope that our future research can show that perceptual simulations can capture these merits of higher-order logic without sharing its demerits.[7]

As mentioned above, we characterize human reasoning in terms of simulations with perceptual mechanisms. Several cognitive scientists (Barsalou, 2009; Goldman, 2002; Gordon, 1995; Gordon & Cruz, 2002) also formulate human reasoning in terms of simulations. In addition to the efficient integration of perceptual information into reasoning, simulation theory naturally explains how the ability of reasoning (and the use of natural language associated with it) has evolved from the perceptual abilities shared by humans and their primate ancestors (Barsalou, 1999; Cassimatis, Murugesan, & Bignoli, 2009a). A theory that formulates reasoning and natural language interpretation in terms of a

[4] Humans often omit language expressions whose meanings are perceptually recoverable in the context, exemplified with fragmental utterances such as "Look" and "Which book?" – "The red one". There has been discussion whether such utterances are elliptical (Merchant, 2004) or truly sub-sentential (Stainton, 2004). On either view it is uncontroversial that inference is involved in fleshing out what was meant.

[5] For readability, we simplify logical formulas by omitting the details such as tense, modality and location. We use intuitive English expressions for predicates, such as 'BigObject' and 'DriveAwayFrom', ignoring the internal structures of the semantics of the corresponding English expressions for convenience.

[6] One can conclude this from the fact that the interpretation models for higher-order logics include functions that map sets of individuals to functions from sets of individuals to truth values (e.g., denotations of *every* and *some*), etc., whereas the interpretation models for first-order logic include only concrete individuals and the first-order sets that have either those individuals or ordered pairs of those individuals as members. In this regard, notice that each first-order interpretation model does not explicitly represent abstract notions such as quantifiers and negations.

[7] Sorted first-order logic can capture many elements of higher-order logic (cf. Fox & Lappin, 2004; Gamut, 1991). Thus, in order to formulate higher-order reasoning in our framework, we can aim to characterize the corresponding sorted first-order reasoning in terms of simulations. The so-called 'proportional' quantifiers, such as *most linguists*, are commonly taken to exceed the power of first-order logic. In this regard, we can introduce probabilistic elements to simulations, or posit certain internal structures for individual objects (Uchida & Cassimatis, 2010), extending the plural-individual structures in Link (1983) with our characterization of quantification in terms of simulations. We leave further details for another paper.