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Formal Models at the Core ¹

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1. The Rise and (Apparent) Fall of the Grammatical Paradigm

At the height of the cognitive revolution, formal grammar was a model for entire areas of cognitive science (Mehler & Bever 1968). Its primary methodological tenet was that theories were axiomatic-like systems stated within formal language theory and, later, model theory (Partee 2011). Competing axiomatic theories made numerous predictions that had to be tested quickly and economically, hence a secondary tenet: data originated from the systematic construction of minimal pairs assessed introspectively (e.g., Chomsky's acceptability contrast between *Colorless green ideas sleep furiously* and **Furiously sleep ideas green colorless*). This two-pronged method—henceforth the 'grammatical paradigm'—yielded numerous empirical generalizations and theories in all areas of formal linguistics, be they Chomskyan or non/anti-Chomskyan (phonology, syntax, semantics, and pragmatics).

Coreference relations offer a classic illustration. In **He_i proofread Obama_i's book*, *he* cannot refer to Obama. While linear order might seem crucial ('A pronoun shouldn't corefer with a name it precedes'), the formal approach revealed a more accurate analysis based on constituent structure ('A pronoun shouldn't corefer with a name contained within its structural sister', e.g. Büring 2005). The grammatical paradigm helped discover and explain multiple additional facts—including why a more deeply embedded pronoun escaped the constraint (e.g., *The person he_i hired proofread Obama_i's book*). Such structure-based generalizations emerged from formal models, and were shown to hold true for many speakers across many languages thanks to the introspective method.

The grammatical paradigm was the backbone of phonology, syntax, semantics and pragmatics. However, it now looks decidedly *passé*: Formal theories are considered an optional luxury; they are eschewed entirely, or replaced with blackbox models that aim for near-perfect simulations. Introspective judgments are deemed unscientific, and replaced by larger experiments or corpus data (see e.g. Ferreira 2005, Gibson & Fedorenko 2013).

But impressions are deceptive. As we will argue, (i) the grammatical paradigm continues to be extraordinarily efficient because of the combination of formal models and quick ways to test them; (ii) its fruitfulness is established by its extensions beyond spoken language linguistics; but (iii) it needs to be integrated in new ways to contemporary cognitive science.

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2. The Efficiency of the Grammatical Paradigm

The core tenet of the grammatical paradigm lies in the construction of formal models. These have three virtues. First, they are explicit and thus unambiguous. Second, they automatically make numerous predictions. Critical ones establish their validity from multiple angles and help discover new facts, which constrain later investigations, irrespective of one's theoretical proclivities. Third, formal models typically involve different modules or levels of representation (Jackendoff 2017), and thus help explain and connect data from introspection, processing, acquisition, language impairment, and neuroimaging.

Because competing formal models make numerous critical predictions, these must be tested efficiently. A single article in formal linguistics can easily contain more than a hundred datapoints. Each can be seen as an abstract experimental condition. Setting up full experiments is usually impractical; for work on understudied or endangered languages, it may be impossible. The introspective method (typically with a small number of consultants) offers an efficient solution (see Mahowald et al. 2016 for quantitative results). This would all come to naught if the data were worth nothing. But the opposite is usually true: Sprouse & Almeida (2012, 2013) subject classic linguistic judgments to systematic quantitative assessments and conclude that they are reliable (but see, e.g., Gibson et al. 2011 for counterarguments). This needn't be surprising, as many results can be replicated or invalidated through the judgments of additional native speakers who come in contact with the research (possibly limiting the risks of a replication crisis, Sönning & Werner 2021, Strickland & De Cruz 2021). Costlier methods may be employed when needed (just like meta-analyses sometimes become necessary); oftentimes, they are versions of the introspective method, with non-experts and at a larger scale.

Pragmatics offers a good example of what the grammatical paradigm has achieved. Even after phonology, syntax and semantics became formal fields, pragmatics remained within the purview of informal theorizing because the role of reasoning and context made a formal approach difficult. A key notion, from Grice (1989), was that of an implicature: from *I'll invite Ann or Mary*, one typically reasons that I won't invite *both*, because otherwise I would have used the more informative word *and* rather than *or*. The formal approach considerably refined the analysis, but also showed, against initial hypotheses, that implicatures arise not just at the level of entire utterances, but also within constituents (Chierchia et al. 2012). Recently, Grice's ideas were radically expanded using Bayesian and game-theoretic tools (e.g. Goodman & Frank 2016). Formal models thus converted earlier intuitions into predictive theories, yielding unexpected results. They helped turn pragmatics from the 'wastebasket' of linguistics (Bar-Hillel 1971) into one of its most dynamic subfields. Models led to *more* experimental results on all fronts—processing, acquisition, cross-linguistic variation, special populations, neuroimaging; and to vibrant debates about the modular decomposition between meaning and reasoning.

3. The Fruitfulness of the Grammatical Paradigm

The vitality of the grammatical paradigm can be seen in its application beyond spoken language linguistics: to sign languages, gestures, emojis, and literature; and outside of linguistics, to pictures and comics, music and dance, concepts and reasoning, and even moral psychology.

Formal models and introspective methods are now routinely applied to sign languages (Sandler & Lillo-Martin 2006), a standard if understudied linguistic object. Within visual communication, they are increasingly applied to non-standard objects as well, such as gestures and even emojis (Schlenker 2018; Grosz et al., to appear). In literature, the grammatical paradigm helped analyze a literary style, 'Free Indirect Discourse', which mixes properties of direct and indirect discourse (Banfield 1982). With time, this produced a minor industry of semantic work, in English and cross-

linguistically (Eckardt 2014). Beyond language, Greenberg (2013) and Abusch (2020) develop a formal semantics for pictures/pictorial narratives, while discourse structures are investigated in Cohn's work on comics (e.g. 2013). Lerdahl and Jackendoff's (1983) work on musical syntax pioneered a long line of formal and empirical research, with experimental validations (Lerdahl & Krumhansl, 2007), and extensions to musical meaning (Schlenker 2017). Strikingly, just as in linguistics, Lerdahl's *formal* modeling reveals the need for multiple levels of structural analysis (grouping, meter, tonal space, scale structure, tonal attractions/expectations, and event hierarchies; Lerdahl, 2001). Essential musical generalizations cannot be stated without these. Following this lead, the grammatical paradigm is now also applied to the form and meaning of dance (Charnavel, to appear; Patel-Grosz et al., to appear). To different extents, the grammatical paradigm can also be recognized in further domains, from the study of concepts and reasoning (Gärdenfors 2014, Koralus and Mascarenhas 2013) to moral psychology (Rawls 1971, Mikhail 2011).

4. The Future of the Grammatical Paradigm

While efficient and fruitful, the grammatical paradigm must be adapted to contemporary cognitive science.

On the modeling side, formal tools keep being improved, and computational methods are often essential to extract quantitative predictions from discrete models. In particular, probabilistic approaches use numerical optimization methods to explore a continuous space of hypotheses, as in computational cognitive science. They routinely build on the grammatical paradigm, taking inspiration from its theories and seeking to account for its data, as in the case of Bayesian pragmatics, mentioned above. We see the relation as one of symbiosis, not opposition.

On the empirical side, the choice of method is a matter of cost and benefit. The key is that there is now a continuum of methods, with introspection at the less costly end, large-scale experiments at the costlier end, and an increasing number of options in between (e.g., small-scale surveys or online experiments). Quick and economical methods are optimal for theory construction and refinement. Costlier and more sophisticated methods are needed in two types of cases: when cheap methods yield insufficiently clear or reliable results in view of the stakes, or when other data types are needed to test predictions. For instance, acquisition and processing data helped buttress the modular decomposition of meaning proposed by implicature theory, mentioned above (Chemla & Singh, 2014). In neuroimaging, Pallier et al. (2011) and Ding et al. (2016) showed that constituent structure, which was crucial in stating the correct rule of coreference above, is tracked by cortical representations. In this case as in others, rich linking hypotheses allow connections between behavior and neural implementation to naturally emerge within the grammatical paradigm (Embick & Poeppel 2014). To generate such connections, formal models are crucial. They cannot be replaced by informal appeals to the relevance of context or the causal force of statistical contingencies—be it in neuroscience or elsewhere.

Better methods make better science. But their *raison d'être* is to build and test theories. The grammatical paradigm offers a simple, unifying and effective way to do so.

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