

Modal semantic universals optimize the simplicity/informativeness trade-off*

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Abstract The meanings expressed by the world’s languages have been argued to support efficient communication. Evidence for this hypothesis has drawn on cross-linguistic analyses of vocabulary in semantic domains of both content words (e.g. kinship terms (Kemp & Regier 2012); color terms (Regier, Kay & Khetarpal 2007; Zaslavsky, Kemp, Regier & Tishby 2018)) and function words (e.g. quantifiers (Steinert-Threlkeld 2021); indefinite pronouns (Denić, Steinert-Threlkeld & Szymanik 2022)) approaching the hypothesis concretely in terms of a trade-off between simplicity and informativeness. We apply the analysis to *modals* (e.g. *can*, *ought*, *might*). Two proposed universals in this domain from Nauze (2008) and Vander Klok (2013) are used for generating many artificial languages with varying degrees of quasi-naturalness as a proxy for natural data. A computational experiment shows that most of the optimal solutions to the trade-off problem are predicted by Vander Klok; meanwhile, as languages more robustly satisfy Nauze’s universal, they also become more optimal. This suggests that efficient communication is a leading explanation for constraints on modal semantic variation.

Keywords: modals; efficient communication; simplicity; informativeness; semantic universals; variable force

1 Introduction

The languages of the world exhibit *constrained variation*: while there is considerable cross-linguistic variation, there are also many unattested languages and considerable shared structure amongst the languages. Put differently, only a small subset of the mathematically possible languages have ever been spoken by any linguistic community. One goal of theoretical linguistics consists in accurately characterizing and explaining this subset —identifying the ‘humanly possible’ languages. Such expla-

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nations can occur at every level of linguistic analysis. In the domain of semantics, we can ask: which meanings are attested cross-linguistically, and why?

In many domains, strong / robust constraints on the meanings expressed in the languages of the world—*semantic universals*—have been discovered (Barwise & Cooper 1981; von Stechow & Matthewson 2008). When such universals are discovered, it is natural to want to explain them as well. A hypothesis going back to Zipf (1949) holds that the meanings observed across languages are shaped by a pressure for efficient communication.

This paper develops this hypothesis concretely in terms of a trade-off between cognitive simplicity and communicative informativeness (Kemp, Xu & Regier 2018), in the domain of *modals*. A modal is typically considered to be a semantic operator that qualifies the truth of an expression. In English, this can be expressed by auxiliaries including *might*, *may*, *must*, *could* and adverbs like *probably*, *necessarily* among a variety of other constructions. Cross-linguistically, these meanings are expressed by diverse lexical categories and strategies.¹

Modality exemplifies the property that Hockett (1960) named displacement: the phenomenon of talking about beyond the actual here and now. Modality also displays context-sensitivity: the kind of possibilities discussed in conversation is often underspecified. This work approaches contextual underspecification in modality as a potential target of explanation for communicative efficiency. Specifically, we explore the question: given that many modal semantic systems can be constructed, are the natural language modal inventories optimized for a trade-off between simplicity and informativeness?

To answer these questions, we explore two proposed modal semantic universals from Nauze (2008) and Vander Klok (2013) in a computational experiment. The former universal is a lexeme-level one: it says that all modals have a certain property. The latter is a lexicon-level one: it says that *modal systems* as a whole are structured in a particular way. Our findings show that (i) as languages become more optimized for trading off simplicity and informativeness, they have more modals satisfying Nauze’s property, that (ii) most of the optimal languages satisfy Vander Klok’s lexicon-level property, and (iii) languages satisfying Vander Klok’s property are significantly more optimal than the population as a whole.

The paper is structured as follows. We first provide an overview of cross-linguistic semantic variation for modals and our framework (Section 2). We then introduce the simplicity/informativeness trade-off (Section 4) and describe in detail how to measure these properties in the modal domain (Section 4.2). The main

¹ Not every language has a small set of lexical items used to express every modal category: Urdu/Hindi expresses modality via a specific set of morpho-syntactic constructions (Bhatt, Boğel, Butt, Hautli & Sulger 2011). Additionally, Tlingit has few grammatical strategies to express modality, and instead uses various pragmatic strategies to communicate about its modal categories (Cable 2017).

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computational experiment and results are presented in Section 5. A discussion of modeling decisions and areas for future work is found in Section 6. We conclude in Section 7.

2 Modal Semantics and Framework

Modals are expressions that are used to talk about alternative ways the world could be, over and above the way the world actually is. Paradigms are certain English auxiliaries like *may* and *must*. Since at least Kratzer (1981), the semantics of modals have been explicated in terms of two axes of variation: force and flavor. These axes can be illustrated with the following examples.

- (1) a. (Context: a friend walks in and shakes off a wet umbrella. You say:)
It *must* be raining.
- b. (Context: you are reading the specifications of a homework assignment. It partially reads:)
You *must* upload your homework as a PDF.
- (2) a. (Context: a friend is leaving and grabs an umbrella on the way out, saying:)
It *may* be raining.
- b. (Context: a mother offers a treat to a child for finishing an assignment:)
You *may* have a cookie.

The *must* examples exhibit strong (i.e. universal) force, but differ in flavor. For example, (1a) can be glossed as saying: all of the worlds compatible with my evidence are worlds in which it is raining. The universal quantification represents the force, and the domain of worlds (those compatible with my evidence) the flavor, in this case epistemic. (1b) exhibits universal force with deontic flavor, roughly saying that all the worlds in which you follow the rules are ones in which you upload a PDF. The examples with *may* in (2) exhibit weak (i.e. possibility) force: their meaning says that some world satisfies the prejacent. (2a) and (2b) again differ in flavor, with the former being epistemic and the latter being deontic.

In addition to epistemic and deontic flavors, many others have been identified: bouletic (worlds in which desire are fulfilled), teleological (worlds in which goals are satisfied), et cetera. Similarly, there are arguably more forces than just weak and strong: for instance, there are weak necessity modals (e.g. *should*, *ought*) which intuitively express universal quantification over a smaller domain of worlds (von Stechow & Iatridou 2008). See Matthewson (2019) and references therein for further discussion of these two axes.

The examples above show that English modals lexically specify modal force (each modal has a fixed quantificational force) but exhibit variability across flavors

(the modals can express more than one flavor). We note that such variability does not require that all modals in English can express all flavors: for instance, *might* arguably can only be used epistemically. Kratzerian semantics for modals capture this by hard-coding quantificational force into the meaning of a modal but relying on context to determine the flavor.²

Not all languages are like English: some exhibit so-called *variable force modals*, which specify flavor but not force. This has been found at least in St’át’imcets (Rullmann, Matthewson & Davis 2008), Nez Perce (Deal 2011), Old English (Yanovich 2016), and Pintupi-Luritja (Gray 2021).³ We illustrate the phenomenon with elicited examples of St’át’imcets *k’a* from Rullmann et al. (2008):⁴

- (3) a. (Context: You have a headache that won’t go away, so you go to the doctor. All the tests show negative. There is nothing wrong, so it must just be tension.)

nilh *k’a* lh(el)-(t)-en-s-wá(7)-(a) ptinus-em-sút
 FOC INFER from-DET-1SG.POSS-NOM-IMPF-DET think-MID-OOC

‘It *must* be from my worrying.’

- b. (Context: His car isn’t there.)

plan *k’a* qwatsáts
 already INFER leave

‘Maybe he’s already gone.’

(3a) shows *k’a* being used with strong force and epistemic flavor. (3b) shows *k’a* being used with weak force and epistemic flavor. Further analysis in Rullmann et al. (2008) shows that *k’a* can only be used with epistemic flavor, so it is an example with lexically specified flavor but variable force. The discussed semantic variation across English and St’át’imcets is summarized by Table 1.

² Typical implementations determine the flavor as the product of two further parameters: a modal base and an ordering source. We set aside this distinction for present purposes.

³ We will discuss modals that specify neither force nor flavor in the next section.

⁴ These are examples (5c) and (5e) from Rullmann et al. (2008), p. 321. See their footnote 5 on p. 320 for the abbreviations.

St'át'imcets <i>ka</i>			English <i>must</i>				
	epistemic	deontic	...		epistemic	deontic	...
weak		✓		weak			
strong		✓		strong	✓		✓

Table 1 Two kinds of modal semantic underspecification: *variable-force* and *variable-flavor*.

In order to state universals for modals in a relatively theory-neutral manner (i.e. in a way that does not presuppose a particular formal semantic implementation), we make the following assumptions. We assume that force and flavor are fundamentally properties of contexts of use. This reflects current practice in semantic fieldwork as applied to modality (Matthewson 2004; Bochnak & Matthewson 2020; Vander Klok 2021).⁵ For example, the modal questionnaire of Vander Klok (2021) consists exactly of discourse contexts designed to isolate a single force-flavor pair. These contexts can be used at least for elicitation, translation, and acceptability tasks. Finally, we will say that a modal *M* can express a force-flavor pair just in case a bare positive sentence of the form *Mp* is judged felicitous in a context with that pair.⁶

At this level of generality, we will represent the meaning of a modal as being a set of force-flavor pairs. The semantic universals that we will discuss will be constraints on what kinds of meanings (sets of such pairs) are attested in the languages of the world. For notation, for a modal *m*, let $\llbracket m \rrbracket$ be the set of force-flavor pairs it can express. Furthermore, we will write $\text{fo}(m) = \{\text{fo} \mid \exists \text{fl s.t. } (\text{fo}, \text{fl}) \in \llbracket m \rrbracket\}$ and *mutatis mutandis* for $\text{fl}(m)$.

We adopt this level of generality because it avoids commitment on the exact formal semantics of these expressions, which is often still being debated. For example, we can say that a *variable force modal* is one that can express more than one pair with the same flavor. This is useful because there are two broad approaches to the semantics of such variable force modals: they actually encode existential quantification but lack a universal scalemate (Deal 2011) or they encode universal quantification but rely on some mechanism of domain restriction (Rullmann et al. 2008; Bochnak 2015a; Močnik & Abramovitz 2019). On such analyses, the underlying semantics contains one specific quantifier; in the present setting, they will still be considered variable force since bare positive sentences are used in contexts

⁵ In addition to the particular studies already mentioned, see Matthewson (2013); Cable (2017) for more examples of the application of these methods.

⁶ We intend ‘judged felicitous’ to also include the case where such sentences are produced naturally in elicitation tasks, as well as when such sentences are found in naturally-occurring contexts which have a clear force-flavor pair.

with multiple forces.

3 Two Semantic Universals for Modality

While the previous section has shown that some modals exhibit variability on the flavor axis (e.g. English *may*) and some modals exhibit variability on the force axis (e.g. St’át’imcets *k’a*), all of the previously discussed expressions are not variable on the other axis. This pattern was observed across many languages from many different families. As a result of a detailed study of the modal systems of six typologically unrelated languages, Nauze (2008) proposed a semantic universal stating that modals cross-linguistically can in fact only exhibit variation along a single axis:

THE SINGLE AXIS OF VARIABILITY (SAV) UNIVERSAL: All modals in natural language satisfy the single axis of variability property: if a modal can express more than one flavor, it can only express one force (and *mutatis mutandis* for force and flavor). That is to say: a modal may exhibit variable force or variable flavor, but not both.⁷

(Alternative formulation: $|\text{fo}(m)| = 1$ or $|\text{fl}(m)| = 1$, where $|\cdot|$ is the set cardinality function.)

This universal says that no language will have a modal expression which, for example, can express both pairs (weak, epistemic) and (strong, deontic).

Based on work on Gitksan and Javanese, a refinement of Nauze’s universal has been proposed which we may call the Domain-Level Single-Axis of Variability (DL-SAV). In particular, Vander Klok proposes that *a modal system as a whole* may only exhibit variability on a single axis in each of the root and epistemic domains. That is: if one root modal exhibits variability on the flavor axis, no other root modal exhibits variability on the force axis (though an epistemic modal may do so) and *mutatis mutandis* for epistemic modals and also for the force axis.

An example of a modal system predicted to exist under the SAV typology, but not the DL-SAV typology is illustrated in Table 2. A language with such a modal inventory violates DL-SAV because the modal m_2 exhibits variability across the force axis while m_3 does so across the flavor axis, but both m_2, m_3 are in the root (non-epistemic) domain.

⁷ Here is the formulation in Nauze (2008), p. 222: “Modal elements can only have more than one meaning along a unique axis of the semantic space: they either vary on the horizontal axis and thus are polyfunctional in the original sense of expressing different types of modality or they vary on the vertical axis and can express possibility and necessity, but they cannot vary on both axes.”

	epistemic	deontic	circumstantial	goal-oriented
weak	m_1	m_2	m_3	m_3
strong	m_1	m_2	m_4	m_5

Table 2 A modal system predicted to exist under the SAV typology and not the DL-SAV (Matthewson 2019).

Notice that Vander Klok’s proposal is strictly stronger than Nauze’s: if a language satisfies DL-SAV, then every modal therein satisfies SAV. For this reason, counterexamples to the SAV are also counterexamples to DL-SAV. In fact there exist at least two counterexamples to SAV from Washo (Bochnak 2015b,a) and from Koryak (Močnik & Abramovitz 2019). Readers are referred to Steinert-Threlkeld, Imel & Guo (2022), as well as Section 6.1, for further discussion and a refined semantic universal. Although the two proposals are not strict universals, they might still be robust constraints on modal lexicons, and also represent motivated measures of the ‘naturalness’ of a language, as we will describe in Section 5.

4 The simplicity/informativeness trade-off

4.1 The efficient communication hypothesis

A language can be simple and uninformative (e.g. containing a single expression). A language can be complex and informative (e.g. containing unique expressions for each possible thought to be expressed). A language cannot be both simple and informative: these two pressures trade-off against each other. A hypothesis in linguistics is that the natural languages are (near) solutions to this multi-objective optimization problem, and that these efficiency pressures explain constraints on crosslinguistic variation (Kemp et al. 2018).

This efficient communication hypothesis has been successfully applied across a variety of semantic domains including kinship terms, color terms, number terms, container terms, quantifiers, boolean connectives and indefinite pronouns (Kemp & Regier 2012; Regier, Kemp & Kay 2015; Xu & Regier 2014; Xu, Regier & Malt 2016; Steinert-Threlkeld 2021; Uegaki 2021; Denić, Steinert-Threlkeld & Szymanik 2022). We follow others in this literature in using a computational experiment to simulate the simplicity/informativeness trade-off. Generally, analyses use the following argument: if the natural languages are optimal solutions to the trade-off (or closer to being optimal than non-natural languages), there is evidence that efficient communication shapes the lexicons of that semantic domain.

In the particular case of modals under study here, we will show that the existence

of semantic universals can be (partially) explained as properties that emerge from these general pressures for communicative efficiency. In the remainder of this section, we describe how we measure simplicity and informativeness in the case of modals, before providing the full details and results of our computational experiment in the following section.

4.2 Measuring simplicity and informativeness of modals

4.2.1 Simplicity

We define simplicity in terms of its inverse, complexity. We model the complexity of a modal meaning as the fewest number of atoms it takes to express its meaning in a Language of Thought (LoT) (Fodor 1975; Feldman 2000; Goodman, Tenenbaum, Feldman & Griffiths 2008; Piantadosi, Tenenbaum & Goodman 2016; Denić et al. 2022). This representation language is the standard language of propositional logic. The language has an atom both for each flavor and for each force. The primitive operators in the language include conjunction (\wedge), disjunction (\vee), and negation (\neg) of features. In this language, we can express the meaning of English *might*, $\llbracket \textit{might} \rrbracket = \{(\text{weak}, \text{epistemic})\}$ as $w \wedge e$, where w is the atom for weak force and e is the atom for epistemic flavor.

We extend heuristics described in Feldman (2000) to find the shortest boolean formula for a modal. This allows us to map any modal meaning to a discrete measure of its complexity, using a collection of the points it can express. In particular, we write down a disjunctive normal form expressing the disjunction of all pairs that a modal can express. A key rule in the minimization algorithm applies the fact that conjunction distributes over disjunction, allowing one to replace a formula like $(w \wedge e) \vee (w \wedge d)$ with a formula like $w \wedge (e \vee d)$.⁸ This is intended to capture the intuition that some meanings differ in terms of in how difficult it is to compactly represent their variability on the two axes. In particular, when features of meaning share an axis, this axis may be ‘factored’ out in the shortest formula representation. The results of the minimization algorithm are illustrated in Table 3.

⁸ The Quine-McCluskey algorithm is a standard minimization algorithm (Quine 1952), but it only produces minimal disjunctive normal forms. The rules that we apply can produce shorter formulas that are not in such form.

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Modal	Meaning representation					Shortest Formula in LOT	Complexity (# of atoms)
<i>may</i>	w s	e ✓	d ✓	c	t	$w \wedge (e \vee d)$	3
<i>mought</i>	w s	e ✓	d ✓	c	t	$(w \wedge e) \vee (s \wedge d)$	4
<i>notcirc</i>	w s	e ✓	d ✓	c	t ✓	\bar{c}	1

Table 3 Measuring complexity for English *may* and two hypothetical modals *mought* and *notcirc*. First column: meaning representation. Second column: shortest LOT formula. Third column: complexity measure.

Given this measure of the complexity of any modal in isolation, we can measure the overall complexity of a language as a sum of the complexities of the modals therein. For example, if a language consisted of exactly one of each of the modals in Table 3, it would be assigned $comp(may) + comp(mought) + comp(notcirc) = 8$. To summarize, we have used a minimum description length approach to quantify the complexity of languages as a sum of the complexities of each of the items in its modal vocabulary. We now move on to describe the measure of informativeness.

4.2.2 Informativeness

The informativeness of a language L with a set of meaning points M is modeled after the idea of successful communication of signals between literal speakers and listeners (Skyrms 2010; Kemp, Xu & Regier 2018; Steinert-Threlkeld 2021). This measure can be modeled as an expected utility of a language for communication, where the expectation is taken over repeated interactions where a speaker who shares a language with a listener tries to successfully convey a force-flavor pair to that listener. More formally:

$$\begin{aligned}
 I(L) &:= \mathbb{E}[u(p, p')] \\
 &= \sum_{p \in M} \mathbb{P}(p) \sum_{m \in L} \mathbb{P}(m|p) \sum_{p' \in m} \mathbb{P}(p'|m) \cdot u(p', p)
 \end{aligned}$$

Here, $\mathbb{P}(m|p)$ is the probability a speaker selects a specific modal m to communicate a meaning p (a single (fo, fl) pair in the semantic space). $\mathbb{P}(p'|m)$ is the probability that a listener guesses a (fo, fl) pair p' , given the expression heard (m). A prior over meaning points $\mathbb{P}(p)$ models how often agents need to communicate about specific meanings. In the present paper, we use a uniform prior over meaning

points; we leave the task of estimating a more realistic prior (e.g. using an annotated dataset of modalized expressions (Pyatkin, Sadde, Rubinstein, Portner & Tsarfaty 2021)) to future work.

The utility function $u(p', p)$ measures how ‘good’ the listener’s guess p' was when the speaker wanted to convey p . Related work measuring efficient communication of color terms and vague terms argues for quantifying the success of listener’s guesses on a scale, as opposed to an “all-or-nothing” affair (Jager 2007; O’Connor 2014). With the structure available for the modal meaning space, it is also possible to model a graded value for utility. In particular, we define a utility scoring function $u(p', p)$ which gives half-credit (0.5) to correctly guessing each of the force and the flavor of p . Thus, if p' shares neither axis value with p , the utility will be 0; if it shares both, 1; and if it shares neither, 0. More precisely:

$$u(p', p) = 0.5 \cdot \mathbf{1}\{\text{fo}(p) = \text{fo}(p')\} + 0.5 \cdot \mathbf{1}\{\text{fl}(p) = \text{fl}(p')\}$$

where $\mathbf{1}\{x\}$ is the indicator function which returns 1 if x is true, and 0 if x is false.

Lastly, just as we measure complexity instead of simplicity, we define the *communicative cost* of a language as the ‘inverse’ of its informativeness: $\text{Cost}(L) = 1 - I(L)$. In other words, while simplicity and informativeness are “desirable” features for a language, complexity and communicative costs are “undesirable” features: they should both be *minimized* to the extent possible.

5 Computational experiment

In order to evaluate the simplicity/informativeness trade-off for modals, we will measure the *optimality* of a language—a set of modals—as the distance to the optimal solutions along the Pareto frontier.⁹ We will also measure the two semantic universals described in Section 3 to see whether they correlate with optimality. To do all of this, the experiment involves the following steps: (1) fix a semantic feature map from which to generate meanings; (2) find the shortest expression for each meaning; (3) estimate the Pareto frontier; (4) generate a sample of languages with varying levels of satisfaction with the modal universals; and (5) measure each language’s distance to the frontier. We describe these steps in turn in the next section, before presenting our main results. The code for reproducing these results can be found at <https://github.com/nathimel/modals-effcomm/releases/tag/salt>.

5.1 Methods

Meaning space We consider here a meaning space with two forces (weak / strong) and three flavors (epistemic, deontic, circumstantial), for a total of six possible

⁹ More precisely, a language is a multi-set of modals, which allows for synonymy.

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meaning points. At present, we assume that all modals in all languages can express meanings in this space; the possibility of modeling languages with different ‘domains’ of modality (possibly hierarchically structured with, e.g. root/epistemic as being fundamental) will be left for future work.

Shortest expressions There are $2^6 - 1 = 63$ modal meanings in this space (non-empty sets of force/flavor pairs). For each of these, we apply the minimization algorithm described in Section 4.2.1 to find the shortest formula expressing that meaning, thereby determining the complexity of each modal meaning.

Estimating the Pareto frontier To estimate the Pareto frontier of languages that optimally balance complexity and communicative cost, we apply an evolutionary algorithm to directly optimize these two objectives (Steinert-Threlkeld 2020, 2021; Denić et al. 2022). This works as follows. In the beginning, a seed population of 2000 artificial modal languages is randomly generated (using the first sampling procedure described in the next section). There are then several (200) ‘generations’. At the end of each generation, a random choice of between 1 and 5 mutations is applied to each of the dominant languages. These dominant languages represent the subset of their generation best optimizing the simplicity/informativeness trade-off. The mutations include randomly adding a modal to a language, removing a modal from a language, and replacing a modal in a language. Another mutation removes a single force/flavor pair from the meaning of a given modal in a language, and the last mutation adds to a language one modal that can express only a single force/flavor pair. Each dominant language has enough ‘offspring’ via mutation to create 2000 languages at each generation. After 200 generations of this process, the dominant languages are the estimated Pareto frontier.¹⁰

Sampling languages In this work, we do not directly measure the modal inventories of natural languages because a comprehensive dataset describing them for of a sufficiently general sample of languages does not yet exist.¹¹ Instead, we follow the methodology pursued in Steinert-Threlkeld (2021) and use the two proposed semantic universals, SAV and DL-SAV, to generate artificial languages with varying degrees of quasi-naturalness. Furthermore, because exhaustive enumeration of the space of possible modal languages is not feasible,¹² we use several sampling

¹⁰ The full details of this algorithm, including pseudocode, can be found in Steinert-Threlkeld (2021: §Appendix A).

¹¹ However, see Guo, Imel & Steinert-Threlkeld (2022) for initial progress in this direction, introducing a database for modal semantic typology. We will return to this work in the Discussion.

¹² In our meaning space with 2 forces and 3 flavors, there are 6 meaning points, yielding $2^6 - 1 = 63$ possible modals. For a fixed vocabulary size of 10 modals (allowing for synonymy), there are

techniques to encourage exploration of the space of possible languages.

Our sampling procedure has two steps. First, one sample of languages is obtained from random/unbiased sampling. We manipulate both the size of the language (from 1 to 10 modals) and the number of modals in the language satisfying the SAV universal (from 1 to the current size). For each combination of these two parameters, we generate languages by drawing random bags of modal expressions from the set of possible expressions that do and do not satisfy SAV. Because of limitations on how many unique languages exist for each combination,¹³ attempting to generate 40000 languages with equal representation of each combination results in 30710 total languages.

Second, to encourage significant exploration of the space of possible languages, especially the low-density regions unlikely to be discovered by the above random sampling procedure, we apply the same evolutionary algorithm for estimating the Pareto frontier of efficient languages three more times: once for each of the other corners of the two-dimensional (complexity, communicative cost) space of possible languages. In other words, while the main evolutionary algorithm sought to *minimize* both measures, in order to encourage exploration, we look at all combinations of minimizing and maximizing both measures.

We combine all the languages discovered in the experiment, (i) by random sampling and (ii) each of the four runs of the evolutionary algorithm, into one pool of languages. This results in a large sample of $N = 89063$ total unique languages.

Measuring optimality Finally, each language is measured for complexity, communicative cost, and *optimality*: minimum Euclidean distance to a point on the Pareto frontier. The SAV typology can be measured as a continuous value of languages (fraction of the vocabulary conforming to the universal), while DL-SAV must be measured as a categorical variable. If the modal inventories in natural language have been shaped by the simplicity/informativeness trade-off, then we expect that optimality will be significantly correlated with the SAV degree, and that the DL-SAV languages will be over-represented among the optimal languages.

$\binom{k+n-1}{k} = \binom{10+63-1}{10} > 5.3 \times 10^{11}$ possible languages.

¹³ For example, there is only one unique language of size 2 with degree-0.5 SAV.

5.2 Results

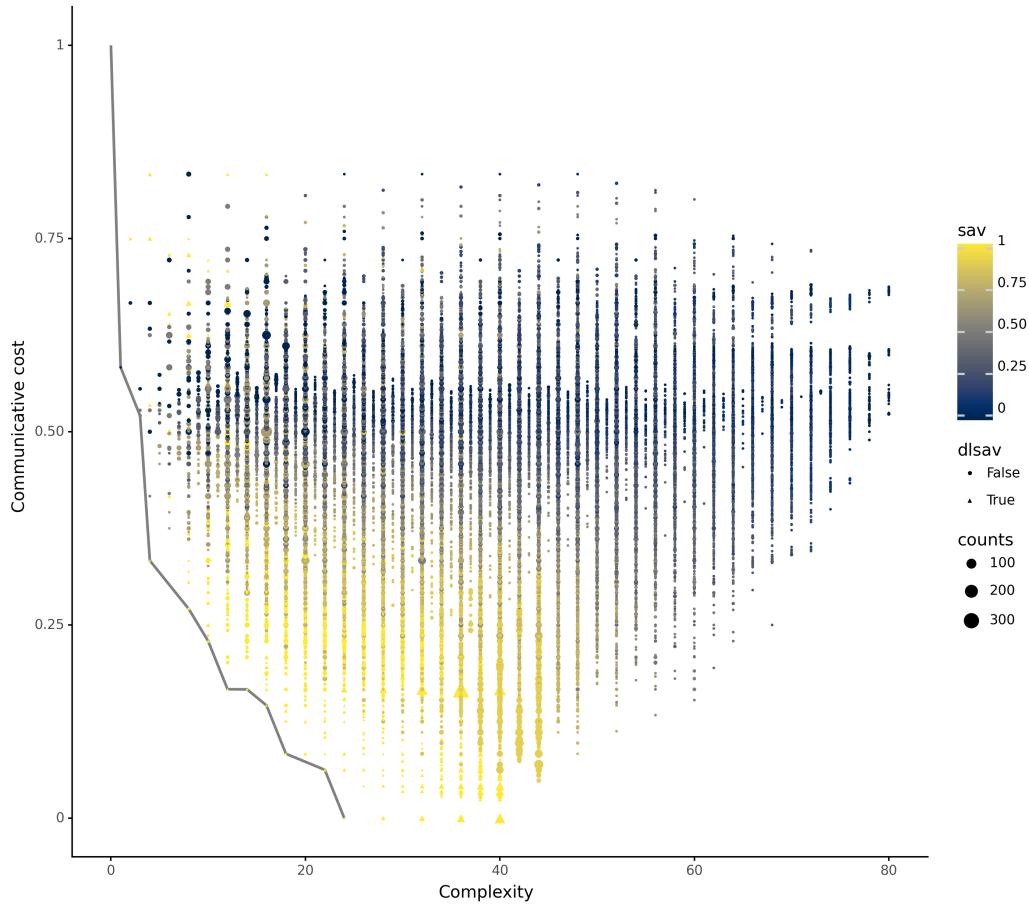


Figure 1 The complexity/communicative cost trade-off for modal languages. The gray line is the Pareto frontier (optimal solutions). Size corresponds to the number of languages at a given point in the trade-off space. Triangles are DL-SAV languages proposed by Vander Klok (2013). The color of a language is its degree of naturalness (satisfaction of SAV proposed by Nauze (2008)).

Figure 1 depicts the main results. This plot shows all of the $N = 89063$ languages generated as described above, plotted in a two-dimensional space, with the x -axis being complexity and the y -axis being communicative cost. The solid gray line is the estimated Pareto frontier. The size of the dots correspond to the number of distinct languages mapped to that point in this complexity/cost space. Triangles

are languages satisfying DL-SAV. The color corresponds to the degree of SAV satisfaction, i.e. what percentage of the modals in the language satisfy SAV (with 0 being blue and 1 being yellow).

Visual inspection suggests that the languages that are more optimal (closer to the Pareto frontier) also tend to satisfy both DL-SAV and have a higher degree of SAV modals. These patterns are borne out numerically. In particular, measuring Pearson correlations shows that the degree of SAV-satisfaction is strongly correlated with Pareto optimality ($r(N) = .57$). This suggests that languages which have more modals satisfying SAV tend to do better at optimizing the simplicity/informativeness trade-off. In addition, degree-SAV has significant correlation with simplicity ($r(N) = .30$) and strong correlation with informativeness ($r(N) = .75$). This indicates that as languages become more natural, they become simpler and (especially) more informative.

A comparison of mean simplicity, informativeness and Pareto optimality for languages satisfying the DL-SAV proposal and those that do not is given in Table 4. This table shows that the DL-SAV languages are simpler, more informative, and thus also more optimal than other languages.¹⁴

language	N	simplicity	informativeness	optimality
mean DL-SAV	4573	.64	.77	.88
mean population	89063	.53	.57	.74

Table 4 Mean simplicity, informativeness, and Pareto optimality for the DL-SAV typology.

Figure 1 and Table 4 suggest that the proposed modal universals optimize for an optimal balance of the simplicity and informativeness. We note that the Pareto frontier consists mostly (9 out of 13) of languages satisfying DL-SAV. In the upper left, there are several optimal languages which are ‘unnatural’ (low degree SAV). These languages contain a small number of modal expressions that are highly underspecified. Specifically, one language contains just one modal that can be used to express every force/flavor pair. Three others contain combinations of this modal and others that have meanings underspecified across an entire axis of meaning. It is worth noting that there are similarly very underspecified modals in natural languages (e.g. the Washo verb *-e?* (Bochnak 2015b,a)); in the Discussion, we return to an important step in future work of determining whether more accurate modal universals are also optimal (Steinert-Threlkeld et al. 2022).

¹⁴ Given the large sample sizes in our data, we do not report significance tests for these means or the aforementioned correlations, which are sensitive thereto.

Overall, these results suggest that both proposed modal universals, [Nauze’s](#) SAV and [Vander Klok’s](#) DL-SAV, optimally balance the simplicity and informativeness. This indicates that very general pressures for efficient communication can explain constraints on cross-linguistic variation in modal meanings.

6 Discussion

The results of the computational experiment suggest that the two modal typologies presented by [Nauze](#) and [Vander Klok](#) are optimized for the simplicity/informativeness trade-off. We now follow [Denić et al. \(2022\)](#) in describing some of the choice points necessary for modeling in this context and what alternative choices may be made. For the present case of modals, most of our decisions are driven by two criteria: (1) we have an appropriate way to measure the difference between natural languages and non-natural languages and (2) our measures are motivated from research on human cognition and communication. Below we address these choices, highlighting directions for future work.

6.1 Typology

What are the actual modal systems of the world? What is the range of quantificational forces and modal flavors that can be expressed across languages? One promising strategy for answering these questions is to exploit the wealth of data available contained in descriptive grammars, in addition to the cross-linguistic survey offered by [Nauze \(2008\)](#) that is focused on the formal semantics of modality, among other resources. While collecting the entire modal inventory for each language may present difficulties, we look forward to implementing in future work a systematic extraction of relevant data from such primary descriptive resources.

[Guo et al. \(2022\)](#) presents a preliminary effort in this direction, gathering typological data from a suite of reference grammars as well as from published semantic fieldwork, in a unified format that can be used in our style of experiments. Two primary issues arise with these data. On the one hand, the grammars very often lack *negative data*, i.e. judgments expressing that a modal explicitly cannot express a particular force and/or flavor. Secondly, such resources do not use a consistent annotation scheme for either forces or flavors. Some of this is merely terminological, and work can be done to unify different terms for the ‘same’ flavor (e.g. “bouletic” and “desiderative”). More deeply, while we have been assuming a constant meaning space, it is possible that not all languages do in fact share the same conceptual categories for modality. In that event, a technique will need to be developed which takes the measures of simplicity and informativeness across languages with possibly different force and flavor distinctions, and normalizes these values to enable a

comparison of their relative optimality.

Additionally, one might ask: what makes this analysis specific to modals? Where does this work draw the line, for example, between mood and modality? Does this analysis extend to intensional predicates in general (including adjectives such as *fragile* and attitude verbs like *believe* and *doubt*)? We have been concerned more with accommodating modals than overgenerating. As a result, the efficient communication results in our main experiment hold for any semantic phenomena with a meaning space that has two axes of variation and where languages exhibit underspecification across two kinds of atomic features. Modals are the intended targets, but our analysis might include expressions falling under mood and perhaps other categories unrelated to displacement.

Finally, as mentioned in Section 3, we note that both SAV and DL-SAV have been shown to have counter-examples, from a Washo modal verb (Bochnak 2015b,a) and from a Koryak attitude verb (Močnik & Abramovitz 2019). A recent refinement of these universals called the INDEPENDENCE OF FORCE AND FLAVOR (IFF) has been proposed (Steinert-Threlkeld et al. 2022). This universal still provides a strong constraint on the lexicalization of modals, but accommodates the two known counterexamples and can be seen as a form of convexity in this semantic domain. Ongoing work extends the experiments reported here but (i) using IFF instead of SAV, and (ii) incorporating actual natural languages from Guo et al. (2022).

We also note that it is possible for efficient communication analyses like these to generate robust cross-linguistic hypotheses, instead of merely testing existing proposals. For example, what *are* the properties shared by optimal (in possibly many senses) languages, and can such analyses be used to generate default hypotheses for cross-linguistic semantics investigations? We regard an exploration of candidate universals and other hypotheses constructed from the results of efficiency analyses as a promising area of future research. For some recent work moving in this direction, by way of using efficient communication to narrow down on hypothesis space for the mental representation of numerals, see Denić & Szymanik (2022).

6.2 Measures of complexity and informativeness

We have found that natural language modal universals optimally balance the presented measures of complexity and informativeness. In this section we address some other possible measures.

Ideally, our complexity measure would be aligned with clear evidence for the cognitive cost of modals, including the contribution of form and meaning.¹⁵ We lack direct evidence, unfortunately, of what the mental representation language is

¹⁵ See Mollica, Bacon, Zaslavsky, Xu, Regier & Kemp (2021) for an efficient communication analysis of the forms and meanings of grammatical expressions.

for modals. In light of this challenge, we leverage the feature space for modals as a model for a simple propositional language (a boolean algebra on the finite space), and note that there is some evidence from [Piantadosi et al. \(2016\)](#) for our selection of LoT primitives. They found that the simple propositional logical language was among the best possible LoTs at predicting boolean concept learning curves. Our LoT—and particularly the choice of atoms—also accommodates a specific intuition about complexity: that modals with meanings grouped along one of the axes seem easier to represent than modals lacking such a uniformity, and so should be measured as more simple.¹⁶

Our measure of informativeness is equivalent to the expected communicative utility of standard literal speakers and listeners in the terminology of the Rational Speech Act framework ([Frank & Goodman 2012](#); [Scontras, Tessler & Franke 2018](#)). An important next step would be to evaluate the robustness of our main results with simple pragmatic agents. We also leverage the structure that does exist in our chosen meaning space by rewarding partial recovery of (force, flavor) pairs rather than only full recovery of meanings. Future work will investigate the robustness of the results of our experiment with regard to (i) LoT choices, (ii) literal versus pragmatic agents, and (iii) different utility functions.

6.3 Alternative explanations

Efficient communication appears to explain important variation in the modal typology, but it surely does not explain all of it. In particular, the explanation here is entirely consistent with a potential, competing explanation of the modal typology from a pressure for ease of learnability. The existence of this pressure has been demonstrated for several different semantic universals, and is exemplified in the case of natural language quantifiers, which both optimize the simplicity/informativeness trade-off and are among the easiest quantifiers to learn ([Steinert-Threlkeld & Szymanik 2020](#)).

The most significant challenge to constructing an alternative explanation of the modal typology in terms of ease of learnability will likely be defining a sufficiently rich feature space. In this experiment on efficient communication, we only modeled *contextual underspecification*, encoding no additional structure for the force and flavor features beyond presence/absence. In other words, there is nothing characteristically quantificational in the case of forces, and nothing particularly modal about the flavors. Future work may capture these important aspects of meaning in the

¹⁶ Similar observations motivated us to treat the disjunction of all the points contained in one axis as equivalent to just the atom for that axis. For example, a modal that can be used to express universal force and any modal flavor (e.g., *universal*) seems simpler than a fully unambiguous modal that must specify the exact force and flavor pair (e.g., *universal-deontic*) it can express.

meaning space.

Most generally, there are many factors shaping semantic typology, efficient communication just being one particularly general and powerful one. It will be important to develop methods to adjudicate between alternative explanations, as well as to distinguish between conceptual/cognitive forces shaping semantic variation from cultural/historical/sociological forces. We have focused on the former because semantic universals seem especially likely to arise from such general cognitive pressures.

7 Conclusions

This paper argued that the known variation in modal semantic typology can be explained by a pressure for efficient communication. Specifically, we found that the proposed semantic universals by Nauze (2008) and Vander Klok (2013) restricting the underspecification of modal force and flavor possible in a language appear to approximate optimal solutions to the problem of trading off cognitive simplicity and informativeness. In particular, as languages become more consistent with Nauze's proposal, they approach the Pareto frontier of optimal languages; moreover, the set of optimal languages consists mostly of languages satisfying Vander Klok's proposal. This result ties in with the recent work exploring the efficient communication hypothesis for diverse semantic phenomena. Finally, we discussed directions for future work, including systematically extracting typological data from descriptive resources, evaluating the efficiency of modals with respect to pragmatic agents, and incorporating other universals and measures of naturalness.

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