Language and Mind: A Complex Dynamic Relation

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Abstract
This paper describes a view of language as a natural system that evolved by self-organizing to simultaneously fit the goal of successful communication and the constraints of the human system for storing and processing information. I will present relevant research findings to illustrate the immense level of attunement between natural language and human mind. I will also compare natural language and programming language to demonstrate multiple similarities, but to also pinpoint the crucial differences. I will argue that natural languages are tailored to fit communication between two interlocutors that share common experience, using the cues to evoke intended state within the interlocutor, whereas programming languages are tailored to instruct the machines using closed system of keywords and rules. Finally, I will layout proposals for possible future directions in making programming more human-friendly.

1. Introduction
Frequently, our cultural products are revealing of our important biological features. For example, the hight of the step, or a chair is determined by the average hight of the human lower leg; the size of the keyboard keys is determined by the average size of the human fingertip etc. Therefore, by studying the features of the cultural products, we would be able to learn something of the species that created them.

When perceived as a natural system, language is seen as a cultural product that evolved in adapting the communicative goals to the constraints of the human mind (Beckner et al., 2009; Christiansen & Chater, 2008; Gibson et al., 2019). In this process, an open self-organizing system has evolved as a structure that mirrors the human mind. Within psychology, such state is seen as an opportunity to understand cognitive system, i.e. to use the language as a window into human mind. In the earliest days of Experimental Psychology, some researchers were even as extreme as to claim that the only way to analyse higher mental functions if by understanding its products (Wundt, 1900).

2. Language as a complex adaptive system
To illustrate this view, we will demonstrate the sensitivity of language processing on the information load of the language input, the importance of all disposable channels of experiencing the world as humans in language use, as well as the adaptivity potential of the processing system to contextual challenges and the resistance of processing system to such challenges.

2.1. Information based language processing
Cognitive system is highly sensitive to the probabilistic structure of the environment and consequently to language as a highly structured communication system. Natural language processing is not only attuned to the individual probabilities of linguistic events, but also to fine grained relations of language systems nested within other language systems. We will show the interplay of the cognitive system and the complex informational structure of natural language that is built throughout the extensive experience with language and the environment. The rich repertoire of measures developed within the framework of Information Theory will be applied to describe complexities within language, and a repertoire of behavioural measures developed within the framework of Experimental Psychology to describe the human language behavior.

One of the basic Information Theory measures is the Surprisal, which is calculated as the negative logarithm of the probability of the given event to quantify the amount of information conveyed by the event in question. Frequent (i.e. highly probable) events are predictable and hence not highly informative. On the other hand, rare (i.e. improbable) events are unexpected, hence convey information and impose high load on the processing system. For example, when processing isolated words in a visual lexical decision task (where participants read orthographic strings and perform button-press to indicate whether they represent words), word recognition latencies are influenced by the Surprisal derived from word probability, which is in turn based on the surface frequency of the word (how many times the word in question occurs in a linguistic corpus). This effect represents one of the benchmarks in Psycholinguistics and was one of the first findings to demonstrate the sensitivity of human processing to probabilities in language. However, the Surprisal can be applied to demonstrate much more subtle sensitivities of the cognitive system to the complex structure of language. For example, it can be applied to inflected word forms to describe their morpho-syntactic complexity. In Serbian, each adjective can take different inflected forms to denote grammatical gender (masculine, feminine, neuter), grammatical number (singular, plural), and case (nominative, genitive, dative etc.). These grammatical features enable us to unravel the precise syntactic role the given inflected form serves in the sentence ("who is doing what to whom"). However, most of the inflected forms are grammatically ambiguous and can denote multiple syntactic roles. For example, inflected form *lepim* of the adjective *lep* (beautiful) can denote twelve different combinations of gender, number, and case (e.g. masculine plural dative, masculine instrumental singular, feminine instrumental plural, etc.). In our studies, we described each inflected form by the Surprisal that is calculated from the average frequency per syntactic function/meaning, relative to all other inflected forms. By doing so, we obtained the Surprisal that is informed not only by the probability of the surface form of the word, but also by its syntactic potential (the complexity of the roles it can serve in a sentence), in relation to the whole set of its possible inflected form (the morphological system it belongs to). This measure was successful in predicting processing latencies in a lexical decision task with adjectives (Filipović & Kostić, 2003; 2004), and even more successful with nouns (Kostić, 1991; 1995; Kostić et al., 2003). Such findings spoke in favour of the sensitivity of the cognitive system to the probabilities informed by the deeper structure of language.

A demonstration of the even more deep atonement between language and cognition came from the studies demonstrating that human language processing is sensitive not only to the overall morpho-syntactic structure, but also to the relation between the morpho-syntactic complexity of the individual lemma (a full set of the inflected forms of the given stem) and the class to which it belongs. To illustrate, each lemma can be described by the probability distribution of its inflected forms (so called inflected paradigm, e.g. the paradigm of the lemma *sauna* consists of six forms: *sauna*, *saune*, *sauni*, *saunu*, *saunom*, *saunama*). At the same time, it can be described by the probability distribution of the suffixes that are used to create inflected forms within a group of words that are inflected in the same way (so called inflected class, e.g. feminine nouns: *-a*, *-e*, *-i*, *-u*, *-om*, *-ama*). When we compare the two distributions pairwise for different lemmas, we find a range of patterns – for some lemmas the two distributions are almost identical, whereas for others they differ significantly. This divergence can be quantified using the Information Theory measure of Relative Entropy (Kullback-Leibler Divergence), and our studies revealed that it also predicted word recognition latencies – the larger the divergence, the more effortful the processing was (Filipović Đurđević & Gatarić, 2018; Filipović Đurđević & Milin, 2019; Milin et al., 2009). This indicated that human processing system builds expectations based on entrenchment of the linguistic units within the complex hierarchy of relations built from the exposure to language.

A similar Information Theory measure is Entropy, which quantifies the uncertainty within a random variable with multiple discrete outcomes. It is affected both by the number of outcomes (the more outcomes, the higher the uncertainty) and the balance of the outcomes' probabilities (the more balanced the probabilities, the higher the uncertainty). We investigated the phenomenon of polysemy (a form of lexical ambiguity) to demonstrate the sensitivity of cognitive system to both sources of uncertainty. Polysemous words are those that have multiple related senses (e.g. *paper as material*, *wrapping paper*, *scientific paper*, etc.). Psycholinguistic studies revealed that vast majority of words are polysemous (Rodd et al., 2002). Additionally, it is shown that the number of related senses facilitated word recognition time (Filipović Đurđević & Kostić, 2008). Therefore, not only that polysemy is pervasive in language, but it also aids the process of word recognition, thus suggesting that cognitive system uses words as multifunctional units that can be recycled and adapted to the current communicative need. Moreover, word recognition is also facilitated with the balance of probabilities of individual senses. For example, there are words such as *horn*, which can be used equally frequently to denote a part of the animal, and a sound device, whereas some other words, such as *shell,* tend to be dominantly used in one of their senses (animal), and only occasionally in other senses (ammunition). The imbalance of probabilities can be separately quantified using the Information Theory of Redundancy. Our research demonstrated that in addition to the number of senses, recognition latencies of polysemous words are also affected by Redundancy, with more balanced probabilities leading to faster recognition, and that the two sources of uncertainty combine in a single Entropy measure (Filipović Đurđević et al., 2009; Filipović Đurđević & Kostić, 2023; Mišić & Filipović Đurđević, 2022a; 2022b; but see Filipović Đurđević, 2019 for a different effect on homonymy).

If we place the relation between the maximum uncertainty allowed by the given number of polysemous senses (Maximum Entropy calculated as the log number of senses) and the observed Entropy of sense probabilities under the research scrutiny, we observe several important points. Firstly, the observed Entropy generally follows the logarithmic trend of the Maximum Entropy. Secondly, there is significant variation in the observed Entropy within a group of words with the same number of senses. Finally, we note that the observed variation is not unlimited but follows a narrow range (approximately around the levels of 80% of Maximum Entropy; Filipović Đurđević & Kostić, 2017). Therefore, it appears that there exists a "sweet spot" of uncertainty in language, and we suggest that it represents a compromise between informativity of the communication system and its learnability by humans. To strengthen such a claim, we conducted a study in which we ran a simulation based on error-driven learning of polysemous words represented via their co-occurrence patterns in language (distributional semantics). We demonstrated that measures derived from association weights that emerged in the simulation (and are related to polysemy indices) were successful in predicting word recognition latencies (Filipović Đurđević & Kostić, 2023). By doing so, we demonstrated that complex linguistic relations can be captured via simple learning rules.

2.2. Embodied language processing

In addition to relying on the information structure of the input, human cognitive system uses multiple additional channels of experience with the environment. Here, we will focus on sensorimotor experience, emotions and motivation.

The Embodied cognition framework posits that the systems for storing and manipulating information (memory) use the same resources as the systems involved with interacting with the world around us, namely perception (sensation) and action. According to this view, activating a representation in memory is heavily linked to reenactment of the same processes that were involved in gaining the experiences leading to the representation in question (e.g. thinking about a cat reenacts the sound it makes, the colour, the shape, the tenderness of its fur, the hand movements involved in handling the cat etc.). Moreover, it asserts that such knowledge is also involved in language processing of the word *cat*. These claims were tested by collecting sensorimotor norms, i.e. by providing speakers with a word and asking them to rate the level in which they see, smell, taste, hear, etc. the object denoted by the word. Based on the collected ratings, a single measure of perceptual richness (but also sensorimotor richness) can be derived. The research shows that words that denote objects with higher perceptual richness are recognised faster and memorised more accurately (Božić & Filipović Đurđević, 2025; Connell & Lynott, 2012; Filipović Đurđević & Živanović, 2011; Filipović Đurđević et al., 2016; Lynott et al., 2019; Popović Stijačić & Filipović Đurđević, 2015; 2018). Moreover, this applies not only to the typical speakers, but also to the speakers with Mild Cognitive Decline and First Episode Psychosis (Filipović Đurđević, et al., 2024; 2025).

In addition to sensorimotor experiences, human language processing heavily relies on emotional and motivational experience with the objects denoted by the words. Multiple dimensions of such experience have been proposed, but the most frequent ones are Emotional Valence, which captures the difference between unpleasant and pleasant items (e.g. *war* vs. *flower*), and Arousal, which captures the difference between objects that do not provoke our reactions as opposed to objects that invite us to act, or motivate us (e.g. *sunset* vs. *slide*). Although precise nature of the effect is still debated, the evidence speaks clearly in favour of the relevance of emotional/motivational dimensions on language processing and cognition (Gorišek, et al., 2024; Kousta et al., 2009; 2011).

2.3. Adaptive language processing

Finally, we will demonstrate how resistant language processing is to different challenges posed by the environment, and how quickly the processing system adapts to keep the communication successful.

For example, if we look carefully into the relation between Emotional Valence and Arousal, we will find a U-shaped curve indicating that words that elicit negative emotions and words denoting positive emotions are highly arousing, whereas neutral words leave us in an unaroused, relaxed state (Kuperman et al., 2014; Warriner et al., 2013; 2017). However, the arousing potential of words seems to be dependent on the wider environmental context. For example, it was documented that the signature U-shaped curve, as documented before the onset of COVID-19, started flattening during the pandemics, and became almost linear during the course of time. Although the Emotional Valence ratings did not change, their arousing potential changed in such a way to denote that negative words elicited higher arousal, whereas the arousing potential of positive words decreased, thus turning the U-shaped curve into the linear relation (Popović Stijačić et al., 2023), This finding revealed how the interaction between linguistic stimuli and cognitive processing was changed by the wider environmental context without noticeable effects on language communication.

Human language processing is also adaptable to local context, as elicited by the task conditions. This was observed in a study of visual word recognition during switching of the alphabets. The demonstration was carried out in Serbian, a language that relies on two writing systems – Cyrillic and Roman, with Serbian speakers being fluent in both alphabets and adjusted to frequent alphabet switching across discourse (e.g. reading a book in Cyrillic and turning to computer to check email in Roman alphabet). Code-switching is facilitated by language control, which is typically studied in bilingual language switching. In our study, we wanted to demonstrate that it also applied to within-language alphabet switching. To do so, we presented participants with two experimental blocks with visual lexical decision task. In the first block, all the stimuli (including consent form, instructions, practice trials and the main trials) were presented in a single alphabet, thus leading the participants to adapt to a single alphabet. However, in the second block, stimuli were randomly presented either in Cyrillic or Roman, and the task was to denote if a letter string was a word in either alphabet (or a meaningless string – pseudoword). The task was particularly hard because some of the strings could be pronounced in both alphabets but had lexical meaning only in one. Such design enabled us to detect two types of language control. The effects of sustained control were visible due to the initial adaptation to the single language block, whereas transient language control was elicited by random alphabet switching in the second block. Therefore, on some trials, our participants needed to resolve dual conflicts – the change of the alphabet as compared to the initial single-alphabet block (global switch) and the change of the alphabet as compared to the alphabet of the previous trial in a mixed-alphabet block (local switch). In addition to confirming that both sustained and transient language control were applied, the study also revealed an exciting pattern of adaptation. The adaptation is indicated by a decrease in processing latencies as observed during experiment. In the mixed-alphabet block, we found evidence of two simultaneous adaptation processes. Although the participants were generally becoming faster during the course of the experiment due to practice effects, this acceleration was dramatically more pronounced for globally switched Cyrillic and locally switched Roman alphabet. This indicates that two separate streams of adaptation were at place for different alphabets governed by two different control processes. The effects of sustained control were being dynamically adaptive for Cyrillic, whereas the effects of transient control were being dynamically adaptive for Roman alphabet. In addition to illustrating the flexibility of human processing system, this finding also reveals its amazing resistance to highly challenging conditions.

Above all, the uttering of the native language is subjectively effortless to typical speakers, straightforward to such an extent that it took thousands of years of civilisation to face the complexity of the language processing. For example, in early years chess playing was considered to be a hard problem for the machine, whereas early intuition was that teaching a machine to use natural language would be the easy task. These early intuitions were driven by our introspection about problems that are hard for the human mind (but not the machine, as will be demonstrated by the end of the twentieth century). Human language usage is not only unchallenging, but it also allows humans to play with language (e.g. in jokes that rely on linguistic twists, puns, etc.), or even speaking backwards, as documented in some case studies (Preković et al., 2016).

3. The relation of programming language and natural language

Now we turn to programming language and try to investigate how it relates to natural language. We have demonstrated that human language processing is relying on multiple systems of representations, but we should also keep in mind that it also relies on multiple modalities for communication: we use auditory channel when speaking, but also visual for gesturing and the facial expressions accompanying the speech. Multimodality is crucial for successful transmission in a noisy environment which frequently accompanies communication. This process is also critically dependent on the information structure of language, and the high level of redundancy.

We will start the analyses of programming language by placing it under the scrutiny of the proposed linguistic universals, or design features that were applied in attesting communication systems (Hocket, 1958; 1959; 1960; 1963). For purposes of illustration, we will focus only on a subsample of those features, such as semanticity (language symbols have meanings, i.e. refer to something), arbitrariness (symbols do not resemble the referents), discreteness (language units are discrete – their referents may indicate a continuum of change, but the change in the symbols is discrete, e.g. morning vs. dawn), duality of patterning (units without meaning combine into meaningful units), productivity (lower-level units combine to create novel meanings), and displacement (language can refer to events occurring at different time and place compared to the time and place of the speech act). These criteria have been successfully applied to demonstrate that various communication systems used by some animal species cannot be considered a language. For example, the famous dance of the bees (tail wiggling frequency denotes the distance, and the direction points to the location) fails the test of arbitrariness, discreteness, and duality of patterning. Similarly, the voicing of vervets (one sound denotes predator from the ground, different sound denotes predator from the sky) fails the test of duality of patterning, productivity and displacement, etc. The question is if we could attest whether programming language could be considered as a language following the linguistic universals criterion. In doing so, we quickly notice that programming language in fact does follow all the listed design features, and even some that are included later (Chomsky, 2010; Hauzer et al., 2002). For example, recursion is a language feature that denotes the existence of a rule that can be applied to the results of the application of the same rule (e.g. *It is the course taken by the student that had a supervisor that published the work that demonstrated that…*), and programming language tics this box, as well.

However, although programming language passes the language universals test, we will argue that there are crucial differences that separate it from the natural language. Some of the differences would become obvious if we tried to instruct somebody using the precise instructions, based on the premise that they would make no inferences, but only perform what they are explicitly instructed (as beautifully illustrated in “Exact instructions challenge” https://www.youtube.com/watch?v=cDA3_5982h8).

One of the fundamental differences between programming language and natural language is related to the description of the language system itself. Programming languages are easily described via the closed set of keywords and rules that apply to them. In fact, this is a typical way of introducing programming languages in the textbooks and manuals. However, when we try to apply the same principles to the natural language, we soon face difficulties. This is highly visible in grammar books, as they typically list a set of rules, followed by dozens of pages of the exceptions to the rule. A famous linguist used the phrase “All grammars leak” to describe the state of attempt to describe the natural language using the closed set of rules (Sapir, 1921, p. 38). Therefore, the natural language appears to be an open system, eluding the closed-set descriptions, unlike programming language.

One important feature of the programming language (and even crucial) is that the statements need to be either true or false. For a program to be functional, the compiler must be presented with either of the two values, with no middle ground. However, when it comes to natural language, we find the abundance of the middle ground cases. For example, in one of our studies we asked participants to rate the acceptability of the presented statements (the task was to estimate if they would expect to encounter such a statement in their language). Although we found that for some statements the speakers were clear in categorising them either as acceptable or unacceptable, there was a number of statement categories for which they were not as decisive, thus rating the statements as 50% acceptable (or anywhere in the range between 25% and 75%; Diesing et al., 2009; Kolaković et al., 2022; Zec & Filipović Đurđević, 2017). Human language processing seems to operate despite this vagueness, whereas a compiler would report an error.

When it comes to number of units, the natural language and the programming language differ dramatically. It is estimated that an average twenty-year-old student uses approximately 42 000 of lemmas, 4 200 of multiword expressions, and 11 100 of word families (Brysbaert et al., 2016). At the same time, programming languages use 20-100 keywords (https://github.com/e3b0c442/keywords). Moreover, they are less combinatorial, thus producing flatter probability distributions, i.e. higher entropy (Febres & Jaffe, 2015; Febres et al., 2015). This indicates that programming languages use less symbols to convey more information, i.e. are less redundant.

Finally, we would like to draw attention to the intolerance of programming languages towards ambiguity. Programming languages use unambiguous symbols which clearly map onto the intended function. At the same time, as illustrated in section 2.1, ambiguous mappings are pervasive in natural languages and seem to reflect an important design feature rather than an accident. Human language processing can even benefit from the ambiguities in certain tasks or quickly adapt when they pose a challenge. Such advantage, nor such adaptation occur for programming languages.

4. Conclusions and future directions

Based on the presented evidence we can conclude that language processing and representation is influenced by the information structure of natural language system (information load, entropy, relative entropy, etc.), sensorimotor bodily experiences, but also affective and motivation. We also demonstrated that processing of natural language is highly adaptive, both to local and global context, and that language units (e.g. words) are used as multifunctional tools. Finally, the natural language is structured to learnable and adaptively used by human cognitive system. Therefore, in order to understand the structure and function of the natural language system, we must take into account and explore the processes that underlie its representation, processing, and production (as also suggested by Bybee (2010) in the famous sand dunes analogy – to understand the sand dunes, we must study not only their shape, but also the forces that create them).

We demonstrated that human languages are represented and processed via multiple channels in a manner that is highly adaptable to the local and global communicational context. They are also rich in redundancy which, in addition to the adaptive nature of human cognitive processing also contributes to resilience to noise. It is rich in ambiguous mappings but structured to be learnable by humans. On the other hand, programming languages are less flexible (e.g. either true or false), described by finite set of rules. Although they use fewer symbols, they also apply less combinatorics thus leading to overall higher entropy levels (less redundancy). They are intolerant to ambiguities and structured to dictate.

Although natural and programming languages share multiple features (semanticity, arbitrariness, discreteness, duality of patterning, productivity, displacement, recursiveness, etc.), the most relevant for the processability of programming languages in human mind is what lies outside of the intersection. The natural language serves the role of communication by using the cues to evoke intended state within the interlocutor. The key prerequisite for such a process to be successful, is a shared experience between the interlocutors. On the other hand, programming language serves the role of communication using the instructions to evoke the intended behaviour in the interlocutor who shares no experience with the instructor. Equating the two processes would imply that obtaining the product from a vending machine could be labelled as “chatting with the vending machine”.

The key root to the crucial differences between the natural and the programming languages should be attributed to different goals of the two language systems and the roles they serve. Human-to-human communication is based on shared experience using open but learnable coding system, whereas human-to-machine interaction is based on the instructions using a closed coding system of keywords and rules.

The conundrum of how to make the programming languages more accessible to humans will occupy cognitive and computer scientists alike. Following the conclusions laid out in this analysis, we identify two possible paths to finding the solution. One strategy would be based on constructing the adaptive machines equipped with more human-like experiences. Including the Large Language Models in the process of code writing and code reviewing would be the first obvious option. After all, Large Language Models encapsulate all the human experience as coded in natural language and reveal the power of the natural language as the model of the world (i.e. the aspect of the world relevant for humans). The other strategy would be to take the human constraints into consideration when building the programming languages. The inspiration for this approach can be harvested from the success story of adapting command panels to human attentional capacities during the twentieth century. For example, in the early days of flight industry, accidents were more frequent and typically caused by human error. The detailed analyses would reveal that the crucial information was not provided on time or was disguised by the abundance of other signals leading to human system processing overload. Careful experimental studies helped to pinpoint the precise limitation of the cognitive system and to design the control panels that would present the information in a way that would be beneficial. The future will tell if the same strategy can be applied to programming languages as well.

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