Toward computational modeling of the comprehension deficit in Broca's aphasia

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Abstract

Broca's aphasics suffer a highly restricted receptive disorder of syntax (Grodzinsky, 2000). They have severe comprehension difficulties with syntactic structures containing transformational operations (i.e., syntactic movement), and exhibit near-normal performance in most other domains of syntax. However, despite the deficit in receptive mechanisms of grammatical analysis, Broca's aphasics use, in certain cases, semantic cues (i.e., the general knowledge of the world) to get around their deficit. Understanding of cognitive mechanisms that underlay this behavior may be valuable for researchers that aim at addressing the question of enabling dialogue systems to process spontaneously produced user's utterances of different syntactic forms with no explicit syntactic expectations. This paper presents a cognitively-inspired approach to computational modeling of the comprehension deficit in Broca's aphasia. We consider a neurolinguistics insight into the comprehension deficit, and introduce three basic requirements for an approach aimed at modeling this deficit. Finally, we discuss that the focus tree is appropriate for modeling the most salient aspects of the comprehension deficit in Broca's aphasia.

V smeri računalniškega modeliranja motenj v razumevanju pri Brockovi afaziji

Pacienti z Brockovo afazijo imajo zelo specifično motnjo pri razumevanju sintakse (Grodzinsky, 2000). Imajo resne težave pri razumevanju sintaksnih struktur, ki vključujejo t.i. sintaksni premik, medtem ko je njihovo razumevanje v preostalih domenah sintakse blizu normalnemu. Vendar lahko ti pacienti navkljub motnji v receptivnem mehanizmu gramatične analize v določenih primerih uporabljajo semantične namige (t.j. splošno znanje o svetu), da bi zaobšli motnjo pri razumevanju sintakse. Razumevanje kognitivnih mehanizmov, ki botrujejo takemu obnašanju, je lahko ključnega pomena za razvoj sistemov dialoga za obdelavo spontano izgovorjenih sporočil z različnimi sintaksnimi strukturami brez predefinirane gramatike. Članek predstavlja kognitivno naravnan pristop k računalniškemu modeliranju motenj v razumevanju pri Brockovi afaziji. Obravnava nevrolingvistični vpogled v deficit pri razumevanju ter predlaga tri osnovne zahteve za modeliranje te motnje. Iz zaključne diskusije je razvidno, da je model fokusnega drevesa primeren za modeliranje najbolj izrazitih vidikov motnje v razumevanju pri Brockovi afaziji.

1. Introduction

One of the fundamental understandings of language is that it is a modularly organized neurological entity (Grodzinsky, 2000, pp. 1–3). The insight in the cognitive neuroscience shows that syntax is anatomically distinguished from semantics and the lexicon. Discussing the neurolinguistic model of language perception, Grodzinsky notes that it is widely accepted that syntax is represented in the part of the left anterior cortex (i.e., Broca's area and its vicinity), while semantics and the lexicon are located temporoparietally around the Sylvian fissure. This anatomical distinction may be illustrated by observing a specific language impairment—Broca's aphasia.

The term "aphasia" refers to an impairment of language ability caused by a brain injury due to stroke, brain tumor, head trauma, etc. There are many types of aphasia that, with respect to the location of the brain injury, affect different communicative skills, e.g., coming up with specific lexical items, generating syntactic strings of words, comprehension, repetition, etc. (for a detailed overview cf. Obler and Gjerlow (1999)). Here, we consider one particular type of aphasia, i.e., Broca's aphasia, caused by an injury to a part of the brain in the left frontal lobe, called Broca's area, and its vicinity (represented in Brodmann's cytoarchitectonic map as areas 44 and 45, cf. Dronkers et al. (2007, p. 2)). It is commonly characterized by a nonfluent and effortful speech that contains only content words, while function words, morphemes and syntactic constructions are missing (Van der Meulen, 2004, p. 6). However, we focus on the less salient, although not less fundamental, comprehension deficit in Broca's aphasia that has a syntactic character. Broca's aphasics suffer a highly restricted receptive disorder of syntax. They have severe comprehension difficulties with syntactic structures containing transformational operations (i.e., syntactic movement), and exhibit near-normal performance in most other domains of syntax (Grodzinsky, 2000, p. 4).

It is important to note that Broca's aphasics rely on use of the lexicon and the general knowledge of the world in order to get around their comprehension deficit. In other words, despite the deficit in receptive mechanisms of grammatical analysis, they use, in certain cases, semantic cues in order to correctly interpret the given input. Understanding of cognitive mechanisms that underlay this behavior may be valuable for researchers that aim at addressing the question of enabling dialogue systems to process spontaneously produced user's utterances of different syntactic forms with no explicit syntactic expectations.

This paper presents a cognitively-inspired approach to computational modeling of the comprehension deficit in Broca's aphasia. It expands upon previous work. Our approach is based on the focus tree—a computational model

Table 1: Description of the pictures used in the study of Caramazza and Zurif (1976). The list is adopted and adjusted from the work of Van der Meulen (2004, p. 8).

Picture description	***Change***
(1) A dog chasing a brown cat.	Correct response
(2) A dog chasing a *black* cat.	Lexical change (adjective)
(3) A dog *biting* a brown cat.	Lexical change (verb)
(4) A dog *biting* a *black* cat.	Lexical change (adjective and verb)
(5) A cat chasing a brown dog.	Syntactic change (subject-object reversal)

of attentional state in task-oriented human-machine interaction (Gnjatović et al., 2011). From the methodological point of view, the focus tree is inspired by human information processing system, i.e., it is a computationally appropriate representation of attentional information that imitates the function of a focus of attention in human perception. It integrates neurocognitive understanding of the focus of attention (Bledowski et al., 2010; Oberauer and Lange, 2009) and notions of attention in computational (Grosz and Sidner, 1986) and corpora linguistics (Gnjatović and Rösner, 2010).

The paper is organized as follows. Section 2. considers the comprehension deficit in Broca's aphasia in more detail. Bases on this neurolinguistics insight, Section 3. introduces the basic requirements for an approach aimed at modeling this deficit. In Section 4., we discuss that the focus tree is appropriate for modeling the most salient aspects of the comprehension deficit in Broca's aphasia.

2. A neurolinguistics insight into the comprehension deficit in Broca's aphasia

In terms of Grodzinsky (2000, pp. 2–3), syntax constitutes a central combinatorial aspect of language. From the functional point of view, syntax is related to capacity to produce and analyze meaningful expressions through rule-based combinations. The role of Broca's area in syntax is highly specific and related to computation of transformational relations between moved phrasal constituents and their extraction sites. This is in line with brain imaging studies indicating that in language comprehension Broca's area is activated when higher levels of linguistic processing are required (D'Ausilio et al., 2010). To illustrate this, we refer to the milestone study conducted by Caramazza and Zurif (1976). In a part of their study, Broca's patients were asked to select a picture that represents the object relative clause "The cat that the dog is chasing is brown". Each subject was given two pictures—a picture that represents the correct answer, and one of the four pictures that represent incorrect situations, as described in Table 1.

(i) Broca's aphasics do not have impairment in their lexicon, but in syntax (Grodzinsky, 2000, p. 4). As summarized by Van der Meulen (2004, pp. 7–8), the study shows that Broca's patients never mistakenly selected the pictures (2), (3) or (4), i.e., they did not make lexical errors. On the other hand, when they had to choose between the pictures (1) and (5), the study reports chance-level performance of patients (i.e., guessing). This experimental condition is particularly illustrative for their comprehension deficit. The clause "The cat that the dog is chasing is brown" contains two noun phrases ("the cat" and "the dog"), the first carrying the Theme role, and the second carrying the Agent role. If these phrases changed their positions in the clause, they would also change their semantic roles, but the new clause (i.e., "The *dog* that the *cat* is chasing is brown") would still be semantically possible. That is why these clauses are referred to as *semantically reversible*. In order to interpret these clauses, the listener must correctly assign the semantic roles to the noun phrases. However, it should be noted that both these noun phrases are animate and, when observed outside of the syntactic structure of the given clause, could be assigned the Agent role. Therefore, assignment of the semantic roles in this case is determined only by the syntactic structure of the clause. Due to their deficit in receptive mechanisms of grammatical analysis, Broca's patients cannot distinguish between these two semantic cases, and, thus, they can only try to guess the Agent of the action, which, in turn, results in chance-level performance.

(ii) Broca's aphasics are able to use semantic cues (i.e., the general knowledge of the world) to get around their comprehension deficit (Grodzinsky, 2000, p. 4). The study of Caramazza and Zurif also considers the following *semantically irreversible* sentence: "The apple that the boy is eating is red". The patients were confronted with the same syntactic structure as in the previous sentence, but, in this case, it is not possible to reverse the semantic roles, i.e., the interpretation that the apple eats the boy is semantically incorrect. It is important to note that Broca's aphasics are able to use their knowledge of the world to correctly interpret this sentence (i.e., to assign the Agent role to the boy), although they cannot comprehend the underlying syntactic structure (Van der Meulen, 2004, pp. 7–8).

Grodzinsky (2000, pp. 4–7) and Van der Meulen (2004, pp. 21–26) provide useful overviews of this deficit in receptive mechanisms of grammatical analysis that is characteristics for Broca's aphasia. Here, we highlight some aspects that are most relevant for this contribution. A widely accepted patterns of comprehension data taken from dozens of experiments that investigated aphasics' interpretive abilities are summarized in Tables 2 and 3 (Grodzinsky, 2000, pp. 4–5). The clauses given in Table 2 reflect construction types that Broca's aphasics correctly interpret at above chance-level of performance, while the clauses given in Table 3 reflect construction types with chance-level of performance.

(iii) Broca's aphasics can comprehend basic phrase syntactic structures. The experimental record shows that Broca's aphasics are able to comprehend basic syntactic trees (i.e., phrase structures) for simple sentences that do not contain intrasentential dependency relations, such as active sentences, e.g., "the girl pushed the boy" (6) or "a dog chasing a brown cat" (1), etc. (Grodzinsky, 2000, p. 4). This observation is in line with Chomsky's notion of *kernel sentences* (cf. also Kay (2000)). According to him, every sentence of the language either belongs to the kernel

Table 2: Clause patterns with above chance-level performance, adopted and adjusted from the work of Grodzinsky (2000, p. 5).

Clause pattern
(6) The girl pushed the boy.
(7) The girl who pushed the boy was tall.
(8) Show me the girl who pushed the boy.
(9) It is the girl who pushed the boy.
(10) The boy was interested in the girl.

Table 3: Clause patterns with chance-level performance, adopted and adjusted from the work of Grodzinsky (2000, p. 5).

Clause pattern
(11) The boy was pushed by the girl.
(12) The boy who the girl pushed was tall.
(13) Show me the boy who the girl pushed.
(14) It is the boy who the girl pushed.

or can be derived from the strings underlying one or more kernel sentences by a sequence of one or more transformation (Chomsky, 1957, p. 45). The kernel consists of simple, declarative, active sentences that reflect basic grammatical relations such as subject-predicate or verb-object, i.e., the terminal strings underlying the kernel sentences are derived by a simple system of phrase structure (Chomsky, 1957, pp. 61, 80).

(iv) Broca's aphasics have difficulties in comprehending sentences with syntactic movement. Syntactic movement is a grammatical transformation in which a sentence constituent is pronounced in a different position than the one in which it is generated (Van der Meulen, 2004, p. 10). For example, passive sentences "the boy was pushed by the girl" (11) is derived from its active counterpart "the girl pushed the boy." (6) through NP-movement of the object, as illustrated in Fig. 1 (Van der Meulen, 2004, pp. 22-23). This grammatical transformation restrains Broca's aphasics' ability to comprehend the given passive sentence. It should be noted that comprehension difficulties are related to syntactic movement, and not to the passive morphology. Sentence (11) is a verbal passive sentence and, thus, includes NP-movement. In contrast to this, sentence "the boy was interested in the girl" (10) is adjectival passive and does not include syntactic movement. Therefore, Broca's aphasics are able to comprehend the latter sentence.

Still, not every syntactic movement equally affects comprehension ability of Broca's aphasics. Subject relative sentence "show me the girl who pushed the boy" (8) contains syntactic movement of the subject (cf. Fig. 2), while object relative sentence "show me the boy who the girl pushed" (13) contains syntactic movement of the object (cf. Fig. 3). The experimental record shows that Broca's aphasics can comprehend the first sentence, but not the latter. A similar observation holds for subject cleft (9) and object cleft sentences (14). This subject/object asymmetry may be summarized as follows—Broca's aphasics have intact comprehension of sentences involving movement out of the subject position, and impaired comprehension of sentences involving movement out of the object position (Van der Meulen, 2004, pp. 24-25).

The boy is pushed t_{boy} by the girl.

Figure 1: Verbal passive sentence derived through NP-movement of the object (cf. Van der Meulen (2004, p. 23)).

Show me the girl **who** t_{who} pushed the boy.

Figure 2: Subject relative sentence derived through *wh*-movement of the subject (cf. Van der Meulen (2004, p. 24)).

Show me the boy **who** the girl pushed t_{who}.

Figure 3: Object relative sentence derived through *wh*-movement of the object (cf. Van der Meulen (2004, p. 24)).

3. Basic requirements

Based on the discussion from the previous section, we introduce three basic requirements for developing a model of the comprehension deficit in Broca's aphasia:

- *Performance requirement:* The model should interpret the following sentences at above-chance level of performance: basic phrase syntactic structures, sentences containing syntactic movement out of the subject position (cf. Table 2), and semantically irreversible sentences that contain syntactic movement out of the object position (e.g., "the apple was eaten by the boy"). The model should interpret semantically reversible sentences containing syntactic movement out of the object position (cf. Table 3) at chance-level of performance.

- *Methodological requirement:* The model should rely on use of the lexicon and semantic cues (i.e., the general knowledge of the world), rather than on syntactic analysis.

- *Parsimony requirement:* The model should be as simple as possible (cf. Mirman et al. (2011, p. 61)). In this particular case, it means that the model should give an economical account of the comprehension deficit in Broca's aphasia.

Here, we use the verb "to interpret" in a restricted scope. It refers to identifying two fundamental semantic relationships of sentence constituents, i.e., the semantic roles of Agent and Theme. In the previous discussion, we stated that Broca's aphasics have difficulties in comprehending semantically reversible sentences that contain syntactic movement out of the object position. In contrast to this, Kay (2000) notes that Grodzinsky's comprehension deficit data (cf. Tables 2 and 3) can be more economically accounted for without reference to movement, with traditional grammatical concepts that are less theory-internal and more empirically based. His point of departure is that in the canonical clause of English language (i.e., simple, active and declarative clause like clause (6) in Table 2), the subject comes first, followed by the verb and object. Therefore, the interpretive strategy employed by English-speaking Broca's aphasics may be formulated as follows—a logical subject precedes its coarguments. Following Kay, the chance-level comprehension by the Broca's aphasics occurs if and only if a clause constituent that carries the Theme role precedes a clause constituent that carries the Agent role. This rather simple rule appears to be appropriate for predicting whether a given clause should be interpreted at chance or above-chance level. However, identifying semantic roles would require some sort of syntactic analysis (cf. Gildea and Jurafsky (2002)), which violates the methodological requirement. In the following section, we discuss that the focus tree is appropriate for modeling the considered aspects of the comprehension deficit in Broca's aphasia, while still satisfying the introduced requirements.

4. Applying the focus tree

The focus tree model was primarily introduced to address the research question of robust automatic processing of different syntactic forms of spontaneously uttered users' commands with no explicit syntactic expectations (Gnjatović et al., 2011). This model was implemented within several prototypical dialogue systems with diverse interaction domains, including: solving problems in a graphics system (Gnjatović and Rösner, 2008; Gnjatović and Rösner, 2007), retrieving textual contents from web sites over the telephone line (Gnjatović et al., 2011), identifying the semantic entities of Figure and Ground in a spatial context (Gnjatović and Delić, in press), etc. These implementations demonstrated that the focus tree model enables the system to handle flexible mapping relations between the spontaneously produced user's commands and the system's actions, including processing of ellipses, context-dependent commands, constituent negations, anaphora, nonverbal commands, pauses in the conversation, etc. Here, we discuss only those aspects of the model that relate to the research question of modeling the considered aspects of the comprehension deficit in Broca's aphasia.

4.1. Knowledge representation

For the purpose of this discussion, let us assume that the knowledge of the world includes three animate entities (i.e., a boy, a girl, and a dog) and an inanimate entity (i.e., an apple). It also includes the following actions: the boy and girl can push each other, the boy can wash himself (in a reflexive sense) and he can wash the dog, the girl can eat the apple, and the dog can eat the apple. Thus, the animate entities may carry both the Agent and the Theme role, while the inanimate entity can carry only the Theme role. The focus tree that represents this restricted knowledge of the world is given in Fig. 4.

Table 4: Possible interpretations in the scope of the restricted knowledge of the world.

Interpretation (semantic role labeling)
I_1 — Agent: *the boy*; Theme: *the girl*; Action: *push*;
I_2 — Agent: *the boy*; Theme: *the boy*; Action: *wash*;
I_3 — Agent: *the boy*; Theme: *the dog*; Action: *wash*;
I_4 — Agent: *the girl*; Theme: *the boy*; Action: *push*;
I_5 — Agent: *the girl*; Theme: *the apple*; Action: *eat*;
I_6 — Agent: *the dog*; Theme: *the apple*; Action: *eat*;

The entities that may carry the Agent role are represented by nodes at the second level of the focus tree, the actions are represented by nodes at the third level, and the entities that could be assigned the Theme role are represented by nodes at the fourth level. Each direct path from the root node to a terminal node represents a possible interpretation. Thus, the given focus tree contains six possible interpretations in the scope of the restricted knowledge of the world. All encapsulated interpretations are described in Table 4. Although these descriptions are fairly self-explanatory, we note that the verb "wash" in interpretation I_2 is reflexive, e.g., as in "the boy washed in the river". The noun phrase "the boy" carries both the Agent and the Theme role. Therefore, this interpretation does not include a node at the fourth level.

For a given input sentence, the model should choose an interpretation. For example, I_4 interprets sentences (6)–(9) (cf. Table 2) and sentences (11)–(14) (cf. Table 2). However, according to the performance requirement, the model of the comprehension deficit should correctly interpret only sentences (6)–(9). For sentences (11)–(14), the model should randomly choose between two possible interpretations, I_1 and I_4, only one of which represents the correct interpretation. This is discussed in the next subsection.

4.2. Sentence processing

Since Broca's aphasics do not have impairment in their lexicon, the system based on the focus tree model is allowed to recognize and extract noun phrases (NP), verbs (V), and certain verb phrases (VP) that relate to entities and actions from the restricted knowledge of the world. For example, noun phrases "the boy" and "John" may be recognized as relating to the animate entity *boy*, while verb forms "pushes" and "pushed" may be recognized as relating to the action *push*. We refer to these extracted sentence chunks as to *focus stimuli*. In our approach, the lexicon comprises of preset focus stimuli (i.e., NP, V, VP). The general idea underlying the interpretation of a given sentence is that the system detects paths that include nodes relating to all extracted focus stimuli.

Still, extraction of verb phrases deserves additional explanation. We recall that Broca's aphasics have intact comprehension of sentences involving movement out of the subject position, and impaired comprehension of sentences involving movement out of the object position. In

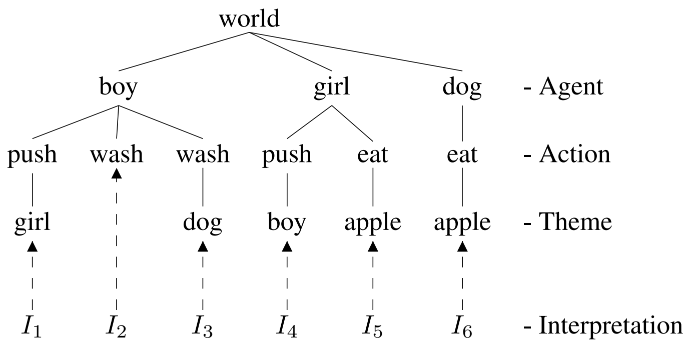

Figure 4: The focus tree representing the restricted knowledge of the world.

other words, movement out of the object position appears to be a critical syntactic transformation. On the other hand, Broca's aphasics can correctly interpret simple, active and declarative sentences, e.g., the canonical Subject-Verb-Object clauses of English language. Therefore, we introduce a more economical account of the comprehension deficit data that does not involve syntax analysis. At the level of surface (linguistic) expression, if the given sentence contains a *canonical* verb phrase VP $\rightarrow$ V NP, then NP involved in the verb phrase caries the Theme role, and the Agent role is assigned to other (if any) NP involved in the sentence. Otherwise, no assumption on semantic role labeling can be made based only on the surface elements. It should be noted, however, that extraction of such verb phrases is not a matter of syntactic analysis. These phrases are part of a preset lexicon, and their recognition is reduced to string matching.

We illustrate sentence processing with the following examples.

(i) Show me the girl that pushed the boy. The system extracts the following focus stimuli from the sentence: "the girl", "the boy", "pushed", and "pushed the boy". Since a canonical verb phase is recognized, the system concludes that the Theme role should be assigned to the entity *boy*. Consequently, the Agent role is assigned to the entity *girl*. Finally, the system unambiguously determines that I_4 is the interpretation of the given sentence, because it includes nodes that relate to all extracted focus stimuli, and the entity *boy* carries the Theme role. All sentences (6)–(9) are processed in the same manner.

(ii) The boy was pushed by the girl. The system extracts the following focus stimuli: "the girl", "the boy", and "pushed". Since no canonical verb phrase was identified, the system cannot assign semantic roles at this point. Instead, it tries to find possible interpretations that relate to the extracted focus stimuli. In the given focus tree, there are two possible interpretations that satisfy this condition: I_1 and I_4. The system randomly choose one of them. Therefore, the interpretation of this sentence results in a chance-level performance, as required for semantically reversible, verbal passive sentences. All sentences (11)–(14) are processed in the same manner.

(iii) The apple was eaten by the dog. In contrast to the previous case, this verbal passive sentence is semantically irreversible, and should be correctly interpreted by the system. The system extracts the following focus stimuli: "the apple", "the dog", and "eaten". Although no canonical verb phase was detected, and the system cannot make any assumptions on semantic role labeling based only on the surface elements, it can use semantic cues. Namely, in the given focus tree, there is only one interpretation, i.e., I_6, that contains nodes that relate to all extracted focus stimuli.

(iv) John washed in the river. This sentence contains only two focus stimuli: "John" and "washed", the first relating to the entity *boy*, and the second to the action *wash*. In the given focus tree, there are two interpretations, i.e., I_2 and I_3, that include nodes related to these stimuli. However, these interpretations differ in one point: all nodes contained in I_2 are related to some focus stimulus, while there is one node in I_3 (i.e., the terminal node *dog*) that does not relate to any focus stimuli. Therefore, the system select I_2 as more appropriate interpretation. It should be noted that if the given sentence contained any chunk that could relate to entity *dog* (e.g., the noun "dog", dog's name or an anaphoric reference to this entity), the system would select interpretation I_3.

(v) She ate the apple. The interpretation of this sentence depends on the knowledge of the world. If this knowledge includes a female dog, then pronoun "she" (which is also included in the lexicon) may refer to two entities; *girl* and *dog*. In this case, both interpretations I_5 and I_6 would be applicable. Otherwise, the system unambiguously determines that I_5 is the interpretation of the given sentence.

5. Discussion and conclusion

This paper presented a cognitively-inspired approach to computational modeling of the comprehension deficit in Broca's aphasia. We considered a neurolinguistics insight, and, based on this, introduced three basic requirements for an approach aimed at modeling this comprehension deficit. Then, we discussed that the focus tree is appropriate for modeling the most salient aspects of the comprehension deficit in Broca's aphasia.

The discussion in this paper was primarily focused on English language. The proposed model exploits, to some extent, the fact that fixed word order in English is used to indicate the Theme semantic relations. Still, it does not mean that the model is not applicable to free word-order languages, like Serbian. In Serbian, case is conveyed by noun-inflections (Lukatela et al., 1995, pp. 96–7). Case markers and other agreement markers are used in comprehending relative clauses. For example, the English sentence "The girl pushed the boy" may be translated into two Serbian sentences having the same meaning but different word orders: "Девојчица$_{(nom)}$ је гурнула дечка$_{(accus)}$" and "Дечка$_{(accus)}$ је гурнула девојчица$_{(nom)}$". In order to enable the system to use these markers to label the semantic roles, two minor changes are required at the implementation level: the lexicon should be expanded to include inflected forms, and the inflected forms should be appropriately related to nodes in the focus tree. However, case and agreement markers are not always sufficient. For example, the Serbian sentence "Зец$_{(nom)}$ кога јури пас$_{(nom)}$ је браон" cannot be correctly interpreted only on the basis of markers. This is analogous to the case of the English sentence "The rabbit that the dog is chasing is brown" (i.e., English translation of the Serbian sentence) which cannot be correctly interpreted only on the basis of word order.

Finally, it should be noted that this approach is not intended to address all diverse aspects of the comprehension deficit in Broca'aphasia, but just the most salient aspects of this phenomenon. Understanding of mechanisms that underlay the interpretive strategy of Broca's aphasics to use semantic cues in order to get around their deficit and to correctly interpret the given input may provide a better insight into potentialities and limitations of semantic analysis in human-machine interaction.

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