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A Comparative Study of Optimality Theory and Dorsal-Ventral Model of Speech processing

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Abstract

This article conducts a comparative study between Optimality Theory in linguistics (Prince and Smolensky 1993) and the Dorsal-Ventral Model of Speech processing (Hickok and Poeppel 2004). The study makes use of the descriptive-analytical method. In Optimality Theory there are two major types of constraints: Faithfulness and Markedness. According to this theory, linguistic forms arise from interaction between Faithfulness and Markedness constraints. In contrast, the Dorsal-Ventral model of speech processing has two dorsal and ventral streams. The ventral stream is for speech comprehension, and the dorsal stream is for speech production. Here we first compared the ventral and then dorsal stream with the Optimality Theory. By comparing the ventral stream with Optimality Theory, the selection of optimal phonological representation has been described. By comparing the dorsal stream, the selection of optimal phonetic representation has been described. Following this stage, clinical evidences are mentioned to increase the strength of research analyses, and finally conclusions are presented. The results show that Optimality Theory is also neurologically compatible with the Dorsal-Ventral model of speech processing. Since in Optimality Theory, it is constraints that determine the optimal output, the neural explanation of constraints is currently not possible.

Keywords: Optimality Theory, constraint, dorsal stream, ventral stream, speech.

1. Introduction

The purpose of this study is to conduct a comparative study between the Optimality Theory (Prince and Smolensky 1993/2004) and the Dorsal-Ventral speech processing model (Hickok and Poeppel, 2004) in the brain. This article introduces and compares the functional framework of cognitive neuroscience of language and Optimality Theory, which is one of the latest achievements of modern linguistics in the field of phonology. These two theories are reviewed, discussed, and finally, based on the latest findings of the cognitive neuroscience of language, the relationship of its functional framework of Optimality Theory is analyzed and explained in order to gain a better understanding of these theories in clinical and theoretical fields. Moreover, the idea that Optimality Theory is naturally close to the neurological nature of the brain can be judged. For this purpose, it is first necessary to clearly and concisely define the concepts and theoretical framework of the Optimality Theory, and then to examine the Dorsal-Ventral speech processing model that is proposed by Hickok and Poeppel (2004), and in the final part of the discussion, arguments and analyses will be offered.

Today, with the assumption that language is one of the most important human cognitive faculties, cognitive sciences, especially cognitive neuroscience, are among the leading fields in research and studies about language. Thus, cognitive sciences, on the one hand, and linguistics, on the other, examine the structure, role, and function of language. In cognitive linguistics, language is considered as one of the human cognitive faculties that is influenced by society and culture as well (Nilipour, 2017: 82) and on the other hand, Chomsky's formal linguistics has a modular approach to language and its processing in the brain; so it ignores social and cultural factors in the development and processing of language and assumes that language is a separate domain in the brain and believes that language is not part of human general cognition but is a separate domain within the cognition (Dabir Moghaddam, 2014). In order to examine the relation of this theory to the neural nature of the brain during language processing, this paper attempts to illustrate the relationship between the Optimality Theory framework and the function of the neural network in the brain. Moreover, it is an attempt to answer the fourth question proposed by Chomsky (1988): "What are the physical mechanisms that are the material essence of language knowledge?" According to Chomsky, brain specialists should answer this question and discover the mechanisms and physical processes that represent the features that are known and assumed in the abstract theory of language (Dabir Moghaddam, 2014: 489-90). Therefore, in this paper, the abstract theory of linguistics is the Optimality Theory and its physical counterpart is Dorsal-Ventral speech processing model of Hickok and Poeppel. To see whether these two theories are compatible, the final part of the paper offers the conclusion of the discussion.

2. Concepts of Optimality Theory

The purpose of linguistic theory is to explain the grammatical system of languages. Phonological Optimality theory is one of the theories that is constraint-based. This theory entered the field of linguistics since the early nineties and has originated from Generative linguistics. This theory aims to use a set of universals in phonology, morphology and syntax in order to describe and explain similarities, differences, and variations between languages. Optimality Theory was first proposed at the Phonology Conference of Arizona University in April 1991. At that conference, Alan Prince and Paul Smolensky presented an article entitled Optimality (Dabir Moghaddam, 2014: 644-645). Optimality phonology is one of the constraint-based phonologies which, like the rule and parameter-based phonology, has an input-output mechanism. McCarthy (2002: 10) presents the box diagram of the optimality phonology as follows:

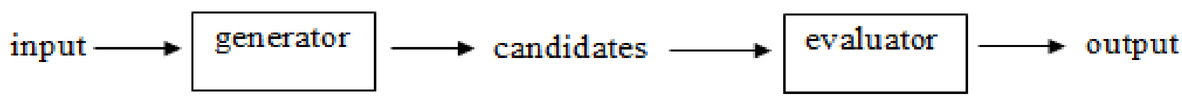

Fig. 1. Box diagram of the Optimality Theory (Bijan Khan, 2005: 35, quoted by McCarthy 2002).

According to the Optimality Theory, a mechanism called Generator from one input produces innumerable candidates. Then, the Evaluator ranks a number of hierarchical constraints, applies these constraints to the candidates produced by the Generator, and finally selects the candidate that is most consistent with the higher-order constraints as the optimal candidate (Firoozian pour Isfahani, 2014: 69).

2.1. Input and output

In optimality phonology, instead of the terms "phonological representation" or "deep structure representation" that are used in rule and parameter-based phonology, the term "input" and instead of the terms "phonetic representation" or "surface structure representation" the term "output" is used (Bijan Khan, 2005: 35).

2.2. Generator and candidates

Generator is a one-to-many mathematical function, so that it maps an input into a number of lexical options. This number can be theoretically infinite. If we show the generator with GEN, the input with Input and the candidate with Cand, then we will have: GEN (input) = $\{Cand_1, Cand_2 ...\}$: (Bijan Khan, 2005: 35).

In fact, the Generator assigns a large number of phonetic words to each word of the language that someone may produce or understand that word in the form of those words (Bijan Khan, 2005: 35). Generator is the fixed part of the Universal Grammar (UG). This means that the candidates generated by the Generator from a specific input, are the same in all languages. These candidates are diverse and differ from the input in many respects. This feature of the Generatore is called "freedom of analysis" or "inclusiveness". Candidates should be varied enough to match any feature in any language. The only thing that restricts the freedom of analysis is the specific structural parameters of each language (Jam, 2009: 37, quoted by McCarthy 2002).

2.3. Evaluator

The Evaluator is a many-to-one mathematical function that uses the constraints of Markedness and Faithfulness to map the candidates of the Generator into an output. In fact, output is one of the options under which constraints are regarded as the optimal option. Evaluation criteria to extract the optimal output from the candidates offered by the Generator is a set of Markedness and Faithfulness constraints. The constraints of Evaluator are universal, but their order for extracting optimal output from one language to another is different (Bijan Khan, 2005: 37-38). If we denote the Evaluator by EVAL, it can be defined as a many-to-one function:

EVAL ({$Cand_1$, $Cand_2$…}) = Candid: Output € {$Cand_1$, $Cand_2$...} (Bijan khan, 2005: 38).

The Evaluator is undoubtedly the central component of the grammar since it is burdened with the responsibility of accounting for all observable regularities of surface forms. Although any candidate output can be posited by *Gen*, the crucial role of *Eval* is to assess the 'harmony' of outputs with respect to a given ranking of constraints (Kager, 2004: 21).

2.4. The nature of the constraints

In the Optimality Theory, the constraints are of two types: Faithfulness and Markedness. These two types of constraints are always in conflict with each other. In general, it can be said that the Optimality Theory is the delination of these conflicts that lead to the choice of the optimal output. The Faithfulness constraint causes all phonological features or patterns in the deep structure, including unmarked and marked patterns, to be written on the surface structure exactly and without any shortcomings (Bijan Khan, 2005: 34). Therefore, Faithfulness constraints require that the output form retain all the characteristics of the input (Kager, 1999: 10). Three instances of faithfulness constraints are as follows:

A) **MAX**: Segments in the input must correspond to segments in the output. (No deletion.)

B) **DEP**: Segments in the output must correspond to segments in the input. (No insertion.)

C) **IDENT** $_{\textbf{(feature)}}$: The place, voice, and manner features of segments of the input must surface in the corresponding segments in the output. (Barlow and Gierat, 1999: 1484). In general, the function of Faithfulness constraints is to monitor the identity between input and output. Therefore, this constraint has access to input and output and penalizes any difference between input and output candidates (Jam, 2009: 42).

Markedness constraints govern the structural description of a tissue-sensitive rule. The speakers of a language to achieve optimal economics in speech production and comprehension and easy and convenience in speech production from the speaker view and transparency and clarity in speech comprehension from the listener view tend to not to follow the marked pattern (Bijan

Khan, 2005: 33). Markedness generally refers to the complexity of one construction over another. Markedness constraints are known as structural or well-made constraints (Barlow and Gierat, 1999: 1484). Here are two examples of markedness constraints:

A) **NO-Coda**: This constraint is against syllable-final consonants (codas), and therefore prohibits codas from outputs.

B) **NO-Complex**: The presence of complex clusters complicates and marks the desired construction (Barlow, 2001: 244).

Kager also mentions a number of markedness constraints as follows:

1- Syllables must not have codas.

2. Vowels must not be nasal.

3. Sonorants must be voiced.

4. Syllables must have onsets.

5. Obstruents must be voiced after nasals

6. Obstruents must not be voiced in coda position (Kager, 2004: 9).

2.5. Optimality

Optimality is a relative concept. A candidate is optimal, if and only if it has the least violation of the arranged constraints. Optimality is the same as relative well-markedness. No optimal output is necessarily absolutely well-made (Bijan Khan, 2005: 39).

3. Dorsal-Ventral speech processing model of Hickok and Poeppel

Hickok and Poeppel proposed a model of dual streams of speech processing. In this model, a ventral stream processes speech signals for language comprehension, and a dorsal stream maps acoustic speech signals to speech production networks in the frontal lobe. Acording to Hickok and Poeppel the ventral stream is supported by both the right and left hemispheres of the brain. However, the two hemispheres have computational differences in speech comprehension processing, and the dorsal stream is strongly and prominently left-handed (Hickok and Poeppel, 2007: 393). Now the question arises, what is the basis of this computational difference between the two hemispheres in speech comprehension processing? From one perspective, this difference is due to the selectivity of the left hemisphere versus the visual analysis of the right hemisphere. Another suggestion is that the two hemispheres of the brain are different in sampling, with the left hemisphere sampling at high speeds (25-50 Hz) and the right hemisphere at lower speeds (3-5 Hz). In any event, what is important now is that performance asymmetry indicates that recognition of the produced word involves multiple mapping streams, from sound to meaning (Hickok, 2009: 769). The following are the anatomical streams of these two streams:

1- Ventral stream: Sound mapping to meaning includes and encompasses the middle and upper parts of the temporal lobe.

2. Dorsal stream: Sound mapping to motor includes and encompasses the posterior parts of the frontal lobe, the parietal operculum and the posterior part of the frontal lobe are involved (Hickok and Poeppel, 2007: 394). The following (fig. 2) shows these two streams:

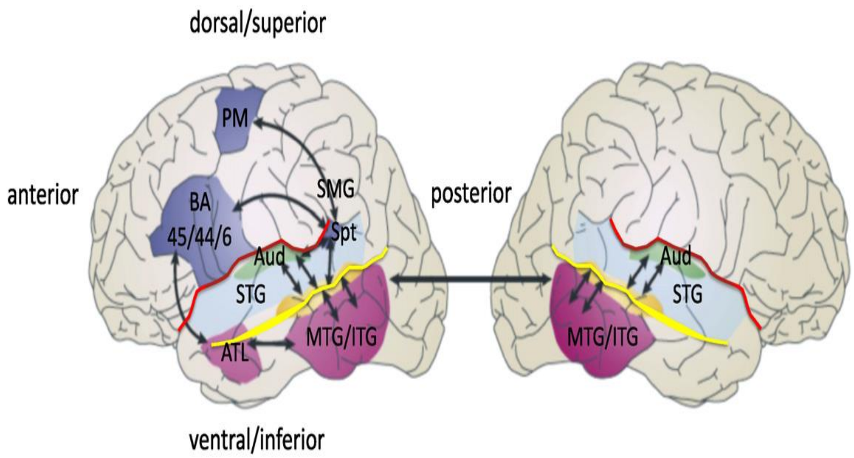

Fig. 2. Dorsal and Ventral streams in the brain (Hickok, 2009: 123)

4. Discussion and Argument

Once more, it should be noted that the method of this research is descriptive-analytical. According to the theoretical issues raised at the beginning of the analysis first, the Optimality Theory is elaborated on, and in the next step, the compatible cases with the speech processing model of Hickok and Poeppel will be discussed. As stated above, the Optimality Theory has an input-output mechanism. It should also be pointed out that, Hickok and Poeppel speech processing model has two dorsal and ventral streams. Here we try to compare both the ventral and dorsal streams with the Optimality Theory. The ventral stream projects ventrolaterally to the middle and inferior temporal cortices and serves as a sound-to-meaning interface by mapping sound-based representations of speech to widely distributed conceptual representations. (Saur et al., 2008: 18035). In addition, in contrast to the typical view that speech processing is mainly left-hemisphere dependent, the model suggests that the ventral stream is bilaterally organized (although with important computational differences between the two hemispheres); so, the ventral stream itself comprises parallel processing streams. (Hickok and Poeppel, 2007: 394). Fig. 3 shows the ventral stream:

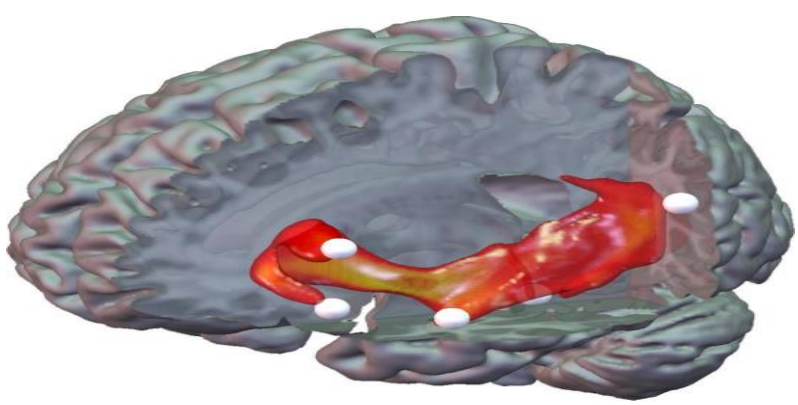

Fig. 3. Ventral stream (Saur et al., 2007: 18037)

Taking the above explanations into account, it seems that the ventral stream is compatible with the Optimality Theory and is related to speech perception. In other words, it seems that in adapting the ventral stream to the Optimality Theory, phonological processing can be pursued in the brain. In the Optimality Theory, input is a lexical representation of the deep structure from which the Generator maps a set of candidates. In fact, the Generator considers a number of phonetic words for each word, this makes it possible for the speakers of a given language to produce or understand the intended word in the form of those words (Bijan Khan, 2005: 37).Likewise, the same process, according to Hickok, is understood and represented in the ventral stream of what is heard, and this stream has access to conceptual representations (Hickok, 2009: 122). For a precise look at the ventral stream, we now turn to Fig. 2. As can be seen in the image, the ventral stream includes middle-inferior parts of both hemispheres in the brain and has two parts. This stream, based on Fig. 2, includes lexical interface and combinational network. In the middle of Fig. 2, phonological network and spectrotemporal analysis diagram box is seen, which includes the STS phonological network (Superior Temporal Sulcus) and the STG spectrotemporal analysis (Superior Temporal Gyrus, its dorsal part). These two parts send the auditory information of the ear to the ventral stream that covers the upper, posterior, and anterior-inferior structures of the temporal lobe of the two hemispheres and has two components. This stream, according to Fig. 2, includes lexical interface and combinational network. The lexical interface maps the phonological structures of words to semantic structures, that is, the phonological nature of the optimal candidate is determined by the phonological dimension. This component includes the PMTG (Posterior Middle Temporal Gyrus) and the PITS (Posterior Inferior Temporal Sulcus), which is bilateral and slightly inclined to the left hemisphere. The next component, the combinational network that plays a key role in syntactic processing and sentence level, is the ATL (Anterior Temporal Lobe), which itself includes AMTG (Anterior Middle Temporal Gyrus) and AITS (Anterior-Inferior Temporal Sulcus) (Kemmerer, 2014: 134). According to Hickok, the lexical stages of word recognition by the nervous system in the superior temporal lobe, including STS and STG, are bilaterally supported (Hickok, 2009: 123), and similarly, in the Generator system in the Optimality Theory, a lexical representation and an optimal candidate is presented in the Generator and the Evaluator selects an optimal candidate. The lower and middle regions of the temporal lobe, especially MTG (Middle Temporal Gyrus) and ITG (Inferior Temporal Gyrus), are important in mapping sound to meaning (Hickok, 2009: 123). This means that the deep structural nature of the word heard is specified here, and MTG (Middle Temporal Gyrus) and ITG (Inferior Temporal Gyrus), acting as evaluator, determine the optimal candidate from a phonological point of view, and the output of these regions is considered as the sensory-motor input (STP area). In order to strengthen the above explanations from the clinical point of view, the following points are mentioned:

1- Perceptual defects in Wernicke aphasia and sensory transcortical aphasia are often associated with damage to the posterior parts of the upper temporal lobe (STG and STS). In most cases deep comprehension deficiencies are not seen in these two aphasias, and this is due to the remaining ability of the right hemisphere to understand speech (Hickok and Poeppel, 2000: 132).

2-Word deafness is a form of auditory agnosia that impairs the ability to understand heard speech. The word deafness indicates severe speech comprehension defects not seen in one-sided aphasias. And since speech perception according to the above analysis is bilaterally organized, word deafness suggests that the injury in such a situation should be bilateral in the Posterior Superior Temporal lobe (Hickok and Poeppel, 2000: 133).

3- Studies on patients with splitted brain and Wada method show that the auditory perception of speech by the right hemisphere is maintained at the word level, ie except in cases with complex syntax (Hickok, 2009: 768).

In view of the above, it can be concluded that damage to the left upper temporal lobe alone cannot cause defects in phonological processing in speech recognition, and this leads to the claim that phonological processing is bilaterally organized in the upper temporal lobe. And this predicts that bilateral damage to the STG (Superior Temporal Gyrus) leads to profound impairments in speech recognition that are in fact similar to word deafness (Hickok, 2009: 769). And since phonological processing takes place in both hemispheres, in these aphasias only the phonological processing of the damaged hemisphere is disrupted. This means that the Generator and Evaluator which play roles in determining the optimal form of phonological inputs are damaged in only one hemisphere.

4-Injury to the Temporal-Parietal-Occipital junction is associated with sensory transcortical aphasia, which can cause post-phonemic defects. This area is also associated with the Wernicke aphasia mentioned above. This interface system may correspond to the ‘LEMMA’ level of representation in psycholinguistic models in the sense that it serves to bind together different types of information, such as phonemic, semantic, and although not discussed here, perhaps morpho-syntactic information, all of which together define the content of individual entries in the mental lexicon. (Hickok and Poeppel, 2000: 134). Of course, as mentioned above, the Middle Temporal Gyrus regions and the Inferior Temporal Sulcus (MTG and ITS) also cooperate in the mapping of sound to meaning with the Parietal, Temporal, and Occipital junctions. The following figure (4) shows the adaptation of the ventral stream by combining it with the Optimality Theory, which leads to the selection of the phonologically optimal output:

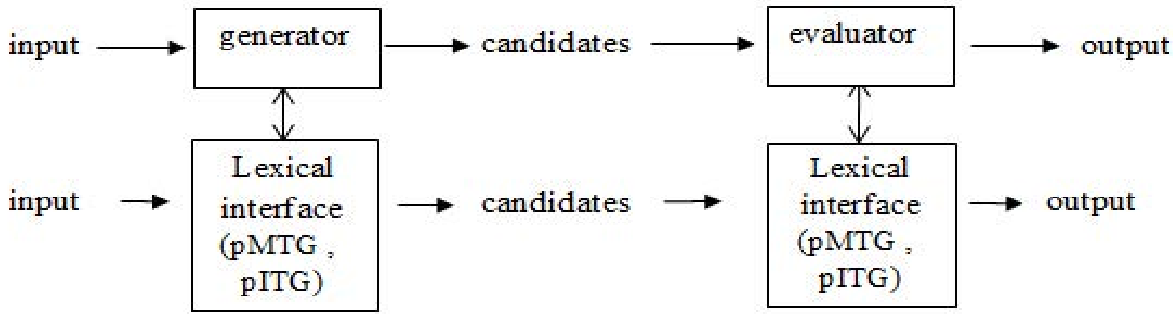

Fig. 4. Diagram optimality theory in combination with the ventral stream to select the optimal phonological candidate

Now let's turn to a clinical example based on the Optimality Theory. Hickok and Poeppel (2000), quoting Baker et al (1981), report a person who has Wernicke aphasia, suffers from difficulty in understanding speech, and has a damage in ventral tract. The patient has difficulty in matching the word with the image and has phonological paraphasia. This patient pronounces the target word /bear/, as [pear]. Here in the deep structure phoneme /b/ which is bilabial and voiced becomes [p] which is a bilabial and unvoiced sound in the surface structure. In describing this process in the framework of the Optimality Theory, it should be said that there is a conflict between the following constraints:

1- Markedness constraint: Prohibition of using voiced-bilabial consonant in the surface structure: (* voiced labial)

2- Faithfulness constraint: The corresponding consonants of input and output must be the same in the input and output: (IDENT $_{(voice)}$).

Based on the above constraints, the Generator has produced two candidates, and since the Markedness constraint has a higher status than the Faithfulness constraint in the ranking, the word [pear] is determined as the optimal candidate by the Evaluator. The following table shows the ranking of these constraints and the determination of the optimal candidate:

Table 1. Convert the /b/ phonem to [p]

Input:/bear/	*voiced labial	IDENT $_{(voice)}$
A.[bear]	*!	
☞ B.[pear]		*

Based on the above table, the Generator has proposed two options based on the input. A Wernicke aphasia patient produces the word [pear] as an optimal option in surface structure based on high constraints because of damage to the ventral tract of speech processing and impaired comprehension. Of course, it should be noted here that the issue is viewed theoretically. Therefore, in the framework of the Optimality Theory, it seems that the ventral stream is for speech comprehension. The Generator and Evaluator anatomical location is the middle-inferior parts of the temporal lobe at both hemispheres in the brain. Here the Generator proposes two options and the Evaluator on the basis of the above constraints selects the optimal option from the phonological dimension, the word [pear], which is the input of the dorsal stream.

The dorsal stream is projected posteriorly and includes the inferior parietal and dorsal regions of the frontal lobe. This stream supports speech production and includes Sensory-Motor integration with acoustic mapping of speech sounds that converts to articulation representations. This stream is unilateral and left-handed and performs Sensory-Motor integration through the posterior structures of the frontal lobe and involves the Parietal-Temporal Junction (Saur et al., 2008: 18035). Fig. 5 shows the dorsal stream:

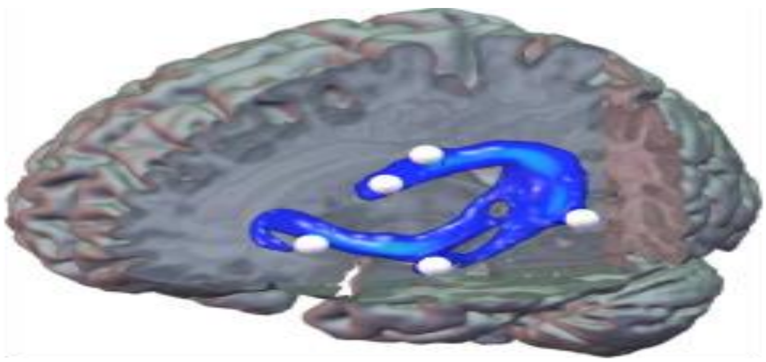

Fig. 5. Dorsal stream (Saur et al., 2008: 18037)

This stream has explicit access to certain sublexical phonological segments of speech and maps phonological or sensory representations to articulation representations (Hickok and Poeppel, 2000: 131). This stream conforms with the Optimality Theory in the field of selecting the optimal phonetic output. The dorsal stream is one-way and more left-handed. This stream involves the structures of the frontal lobe and the parietal-temporal junction (Hickok and Poeppel, 2000: 131). Now, for a more detailed and meticulous examination of the dorsal stream, Fig. 2 is analyzed. Because this stream carries the sensory-motor integration of speech, the relevant areas, which occur only in the left hemisphere, are examined. The first area here is SPT. This region (Sylvian Parietal Temporal) in the left planum temporal that is the place to confirm the sensory-motor coordination of speech (Hickok, 2009: 132) and is functionally connected to the speech motor regions (pre-motor regions and Broca area). According to Hickok, damage to the posterior region of the SPT is associated with conduction aphasia and has been suggested as a defect in the sensory-motor integration of speech (Hickok, 2009: 132). This part connects upwards to the pre-motor regions (PM) and the Broca area and plays a role in translating speech signals into productive representations in the frontal lobe (Hickok, 2009: 140). Therefore, in selecting the output by the Evaluator in Optimality Theory, first the selection of the lexical item (LEMMA) and in the next step the selection of the phonological form is observed, which is the optimal option of the candidates (suggested by Evaluator). In this way, the lexical interface output in the ventral stream, itself being an optimal candidate, is the sensory-motor interface input (SPT), which determines the phonetically optimal candidate and sends it to the motor areas of the frontal lobe. Injury to the Broca area usually causes Broca aphasia (Hickok, 2009: 136, quoted by Damasio 1992 and Hillis 2007), although the Broca aphasia is not limited to Broca area (Hickok 2009: 136, quoted by Mohre et al. 1987). The following fig. 6 shows the Optimality Theory diagram in combination with the dorsal stream:

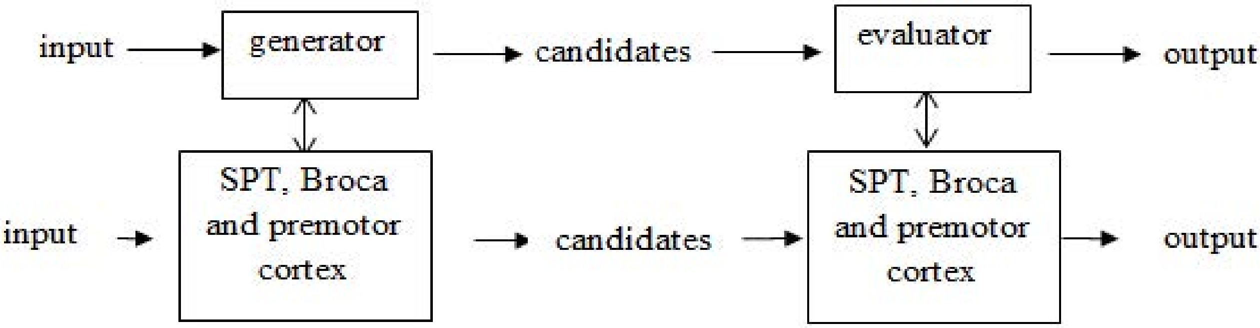

Fig. 6. Diagram of the Optimality Theory in combination with the dorsal stream to select the optimal phonetic candidate

An example of Broca aphasia is cited to justify and explain the dorsal stream on the basis of the Optimality Theory. Kemmerer (2014: 76) introduces the patient with Broca aphasia, which pronounces the word /no/ as [non]. As can be seen, the nasal phoneme /n/ has been added to the word /no/ and this phoneme has appeared in the surface structure. In describing this process in the framework of the Optimality Theory, it should be said that there is a conflict between the following constraints:

1- Markedness constraint: The presence of a [CV] cluster in the surface structure produces a marked structure and should not be used in the surface structure. Therefore, the markedness constraint is as follows:

* [CV]

2- DEP (No insertion): Based on this constraint, the output phonological segments must be the same as the input phonological segments.

Based on the above constraints, the Evaluator has produced two candidates, and since the markedness constraint has a higher position than the faithfulness constraint in the ranking, the word [non] is determined as the optimal output. The following table shows the ranking of these constraints and the determination of the optimal output:

Table 2. The phonological process of inserting the consonant /n/

Input:/ no/	*[CV]	DEP
A.[no]	*!	
☞ B.[non]		*

Based on the above table, the Generator has proposed two options based on the input. A Broca aphasia patient produces the word [non] as the optimal surface structure based on high ranking constraints because of damage to the dorsal stream. Therefore, it seems that in the framework of the Optimality Theory, the dorsal stream is for speech production. So, one can conclude that the anatomical location of the Generator and Evaluator is the Sylvian Parietal-Temporal and the motor parts of the upper frontal lobe. That is, the Generator first suggested the above candidates and the Evaluator, based on the constraints of the above table, selected the optimal option in accordance with the phonetic dimension.

Given the above points, an important question arises here, "where is the location of the Markedness and Faithfulness constraints in this stream?" Can it be explained at all? Prince and Smolensky in this point raise another question: Can the concepts of the theory of neural computation be attributed to the formal theories of the mind? (Prince and Smolensky, 1997: 1604). Prince and Smolensky (ibid.) state that grammars have constraints that lead to the production of well-constructed linguistic constructs, and that these constraints conflict even within a given language. Moreover, they believe that these constraints have a biological and genetic structure. Nevertheless, neural networks seek harmony and the input of a computational network includes pattern activity that is constantly repeated in the network. After that, the activity spreads across the network to organize a pattern of activity to increase optimality (harmony) among all existing active patterns, which includes a fixed input pattern. This pattern of harmony is a degree of adaptation to unconscious or implicit constraints in synapses or neural network connections. In fact, the perfect paradigm that emphasizes harmony or optimality is to balance the conflict between the constraints of the neural network (Prince and Smolensky, 1997: 1607). However, it seems that explaining the Markedness and Faithfulness constraints at neural levels is not currently possible due to the in accordance with unconscious nature or implicity of these constraints and the complexity of the neural computations that make these constraints possible.

5. Results

Considering the above issues, it can be concluded that the Optimality Theory can be partially explained by the Dorsal-Ventral speech processing model of Hickok and Poeppel. That is, although the Optimality Theory is stated theoretically, it is also neurologically compatible with the Dorsal-Ventral speech processing model of Hickok and Poeppel. Ultimately, since in Optimiality Theory, there are constraints that determine the optimal output or candidate, and it seems that because constraints occur at the micro levels of neurocognitive, it is not possible at present to explain these constraints neurologically, unless we wait for the computational neuroscience to reveal this in the future.

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