# BIDIRECTIONALITY IN LANGUAGE ACQUISITION

-Research thesis -

(Speciality: language- and speech technology)

B. Valkenier (s1090704)

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Internal advisor: Dr. P.Hendriks
Second advisor: Dr. H. van Rijn
Artificial intelligence
University of Groningen

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# ABSTRACT

From empirical research it follows that children's interpretation of indefinite objects and indefinite subjects differs from the interpretation that adults give to the same sentences. This can be explained by assuming that children use unidirectional optimization and adults use bidirectional optimization. The primary aim of this study is to investigate how children progress from unidirectional to bidirectional performance.

The cognitive architecture ACT-R is used to model this transition. Bidirectional optimization is implemented as the serial processing of two unidirectional processes and thus it takes more time to process bidirectionally. It is assumed that children lack time to process bidirectionally. In the model efficiency is gained by means of automization processes. The empirical data can be explained well by the model and also some empirical predictions can be made.

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# 2 INTRODUCTION

Empirical research shows that children up to 7 years of age differ from adults in the interpretation of sentences that contain an indefinite object or subject (De Hoop & Krämer, to appear). A cross linguistic pattern is found that the subject of a sentence is interpreted as referential while the object of a sentence is not. Sentences that conform to this cross-linguistic tendency are interpreted in the same way by children and adults. When sentences do not conform to this rule, children seem to have trouble to deviate from this regularity. In an experiment (Krämer, 2000) children were shown a picture in which a girl picked two apples and left one in the tree. Children were then asked whether a particular sentence is true or not, according to the picture. One of the sentences presented is:

1. *"Het meisje heeft een appel niet geplukt."*
   *The girl has an apple not picked*
   *(An apple is not picked by the girl).*

Normally, objects are interpreted non-referential. In this sentence, the object "een appel" is placed in a particular position (in scrambled position, see Section 4.1.1.) and should therefore be interpreted referentially (de Hoop and Krämer, to appear). Given the context of the picture, "een appel" refers to one specified apple not being picked, which is a referential interpretation instead of a non-referential one. Because this interpretation deviates from the "rule" presented above it is interpreted differently by children and adults. Only in 15% of the cases children in the age from 4 to 7;7[1] years interpret this sentence in the same way as adults do, namely referentially. In contrast, both children and adults give the same interpretation to sentences in which objects should be interpreted non-referentially, as the rule presented above states. For example the sentence below (2) is interpreted by all children from age 4 to 6;10 in the same way as adults do (Krämer, 2000).

2. *"Het meisje heeft geen appel geplukt."*
   *The girl has no apple picked*
   *(The girl did not pick an apple).*

The cross-linguistic tendency is for subjects to be interpreted referentially. An example of a sentence which deviates from this rule is given in 3. In this sentence the subject is

[1] Age 7;7 means 7 years and 7 months of age. This notation will be used throughout the rest of the paper.

placed in sentence-internal position and therefore should be interpreted non-referential (3):

3. *"Er ging twee keer een jongen van de glijbaan af".*
*There went two times a boy off the slide (off)*
*(Two times a boy went off the slide).*

This sentence also deviates from the rule presented above and it is also interpreted differently by adults and children (Termeer, 2002). Adults interpret the subject, "een jongen", non-referentially whereas children interpret it referentially. Under a non-referential interpretation of this sentence "een jongen" is not necessarily interpreted as referring to one and the same boy going off the slide. However, children in the age 8;7 to 10;4 use the non-referential interpretation in only 38% of the cases. In 62% of the cases children interpret it as referring to one specific boy going off the slide two times (Termeer, 2002). The sentence in which the subject should be interpreted referentially is interpreted as such by children:

4. *"Een jongen ging twee keer van de glijbaan af".*
*A boy went two time off the slide (off)*
*(A boy went two times off the slide).*

De Hoop and Krämer (to appear) explain this data by a theory of language called Optimality Theory (subsequently referred to as OT, an overview of this theory will be given in Section 4.1.) According to the explanation of de Hoop and Krämer children use another OT model than adults do. They suggest that children use unidirectional OT whereas adults use bidirectional OT. Hendriks and Spenader (2004) show that the pronoun interpretation problem can be explained by the same two OT models. We will discuss the pronoun interpretation problem in more depth later on.

# 3 RESEARCH QUESTION

Optimality Theory (OT) is a theory of language (See Section 4.1. for an introduction). It gives a description on how language is produced and interpreted. In this study OT will be used as a basic framework. From empirical research it follows that children's interpretation of indefinite objects and indefinite subjects, differs from the interpretation that adults give to the same sentences. De Hoop and Krämer (to appear) explain this by assuming that children use another OT model than adults do. This study aims to investigate how the transition from using one OT model to using the other OT model can be characterized (Question 1). What triggers the transition and is it being performed in one or more developmental steps?

To specify the transition that is taking place, it must be made clear what OT model children use and what OT model adults use. In Chapter 5 of this paper we will refer to some literature on these first two questions (Question 2 and 3).

Optimality Theory does incorporate some theories on language learning (See Section 4.1.2). Because these ideas do not solve the question how a transition from one OT model to another OT model can be made (See Section 5.3), this transition will be investigated by implementing it in the cognitive architecture ACT-R.

**Question 1:**

How can the transition from the OT model used by children towards the OT model used by adults be characterized?

**Question 2:**

Which OT model explains children's language production and comprehension best?

**Question 3:**

Which OT model explains adult's language production and comprehension best?

# 4 THEORETICAL BACKGROUND

Within the framework of Optimality Theory the empirical data presented in the introduction can be explained by assuming that adults use weak bidirectional optimization whereas children use strong bidirectional-, or unidirectional optimization (De Hoop & Krämer, to appear). (Unidirectional) OT and bidirectionality will be introduced in this chapter.

Optimality Theory was introduced by Prince and Smolensky (1993/2004; 1997) as a new theory for phonology. Since then it has been extended to all fields of linguistics. OT specifies the relation between a linguistic input and a linguistic output. It models, for example, the process that takes place when a speaker wants to express a meaning. The input for the process is the meaning that the speaker wants to express and the output of the process is the final utterance.

## 4.1 Overview of Optimality Theory

Optimality Theory states that the relation between input and output is mediated by two mechanisms, GEN (for Generator) and EVAL (for Evaluator). Given an input GEN will generate a set of potential outputs. The set of potential outputs is called the candidate set. EVAL will then evaluate which of these candidates is the optimal one. To evaluate the candidates the language specific constraint ranking of the constraint set (CON) will be used. CON is a set of violable constraints put in a hierarchical order. Constraints can be violated by candidates. The seriousness of a violation depends on the hierarchical ranking of a constraint.

The optimal candidate is the candidate that minimally violates the constraints. A classical example is the example of syllabification (Archangeli, 1997). *Figure 1* illustrates this classical example and depicts the entire process that OT proposes to take place. Words can be split up in syllables, which is called syllabification. In *figure 1* the successive steps of the OT process for syllabification of "doctor" are depicted from the top to the bottom of the picture. "Doctor" is the input for the process. The possible outputs that GEN creates are in this case the many ways that the word "doctor" can be split up. In the next step EVAL chooses the optimal candidate by comparing the violations on constraints that the different candidates do. In this case the output exists of the syllables of "doctor": doc.tor.

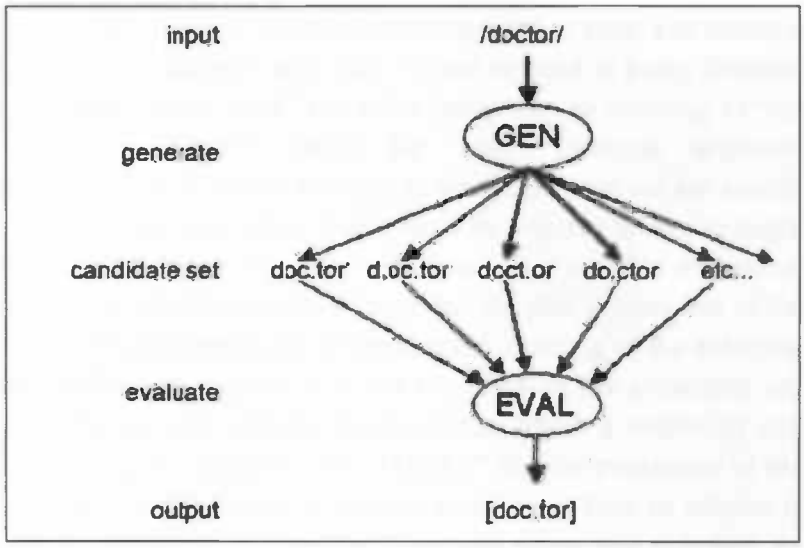


*Figure 1: The process of Optimality Theory.*

The evaluation of candidates can be depicted in a table. In OT this is called a tableau. By means of an example on interpretation it will be shown how the evaluation is depicted in a tableau. In the case of interpretation the optimal interpretation is sought given a syntactic **input**. In our example the input is (4):

4. *"Often when I talk to a doctor the doctor disagrees with him".*

Although you presumably have a preferred interpretation of *sentence 4*, it can be interpreted in more than one way. How can OT describe this problem? The input of the OT process is the sentence (*sentence 4*) that has to be interpreted. In the tableau below *(Tableau 1)* the input of the process is given in the left-upper cell. The **candidate set** that is generated consists of the different possible interpretations. For example a possible interpretation is that "the doctor" in *sentence 4* refers to "a doctor" ("the doctor" and "a doctor" are one and the same person) and that "him" refers to another person. In *Tableau 1* these possible references are depicted by indices. "A doctor" and "the doctor" have the same index if they refer to the same person. Part of the candidate set generated by "GEN" is presented in the cells of the first column (except the upper cell in the first column, which represents the input).

Hendriks and de Hoop (2001) give an OT description of these type of sentences. They propose two constraints: "Principle B" and "DOAP". In their article they give a thorough reasoning for the choice of these two constraints. Their example will be adopted to show how OT handles interpreting of sentences. The first constraint "Principle B" is violated if

two arguments that are not marked as being identical are interpreted as such. For example "him" in the sentence "The doctor disagrees with him." is not marked as being identical to "the doctor". Principle B does expect "him" not to be interpreted as referring to "the doctor". The second constraint "DOAP" stands for "Don't overlook anaphoric possibilities". This constraint is violated if opportunities to anaphorize text are not seized. This means that if there is a possible antecedent, then it must be referred to. For example "the doctor" in the sentence "The doctor disagrees with him." is a possible antecedent and should thus be referred to. In a tableau every column but the first depicts one of the constraints. The hierarchy of the constraints can be seen in the ordering of the columns, the left column depicting the highest constraint in the hierarchy of the constraint set. Thus, in our example both the second and the third column depict a constraint and "Principle B" is higher posited in the hierarchy than "DOAP" is. The evaluation of the candidates is given by asterisks (*). If a candidate violates a constraint then an asterisk is added in the tableau (and if a candidate violates the constraint twice two asterisks are added). An exclamation mark (!) means that the violation is fatal. The winner(s) of the evaluation process get(s) a pointing finger (☞). In our example there are two optimal candidates. Probably the interpretation(s) you had in mind?

Principle B: If two arguments of the same semantic relation are not marked as being identical, interpret them as being distinct.

DOAP: Don't overlook anaphoric possibilities: Opportunities to anaphorize text must be seized.

| INPUT:<br>Often when I talk to a doctor, the doctor disagrees with him. | Principle B | DOAP |
|---|---|---|
| ☞ A doctor $^{1}$ – the doctor $^{1}$ – him $^{2}$ | | * |
| ☞ A doctor $^{1}$ – the doctor $^{2}$ – him $^{1}$ | | * |
| A doctor $^{1}$ – the doctor $^{1}$ – him $^{1}$ | * ! | |
| A doctor $^{1}$ – the doctor $^{2}$ – him $^{2}$ | * ! | * |
| A doctor $^{1}$ – the doctor $^{2}$ – him $^{3}$ | | ** ! |

*Tableau 1: The interpretation of a sentence in OT*

### 4.1.1 Bidirectionality

It is argued (De Hoop & de Swart, 2000; Hendriks & de Hoop, 2001) that Optimality Theory as applied in interpretation is fundamentally different from Optimality Theory as applied in syntax. According to these authors OT as applied in interpretation (unidirectional interpretation OT) takes the viewpoint of the hearer (comprehension perspective), whereas OT as applied in syntax (unidirectional production OT) takes the viewpoint of the speaker (production perspective). Blutner (2000) points out that this is not enough. Taking only the production perspective into account in the case of syntax leads to the problem that interpretive preferences cannot be explained. In the same way, blocking effects (see Section 5.1.1.3) cannot be explained when only the comprehension perspective is taken into account in the case of semantics. Integration of the production and comprehension perspective can solve this problem. This integration is given by bidirectionality (Blutner, 2000).

Within the theoretical framework of bidirectionality the comprehension perspective as well as the production perspective are taken into account. Taking these two perspectives into account can lead to a conflicting situation. On the one hand the perspective of the speaker is regarded, who selects the message that is both economic and possible. This is called the I-principle (Horn, 1984); minimization of the speaker's effort. On the other hand the hearer tries to select the most coherent interpretation. This is called the Q-principle (Horn, 1984); minimization of the hearer's effort. In bidirectional OT this conflict is solved by modelling constraints for form as well as meaning. Two clusters of constraints can be distinguished: one for determining the optimal form and one for determining the optimal meaning. Blutner (2000) proposes two different algorithms that combine these two clusters of constraints. These two algorithms are strong bidirectional OT versus weak bidirectional OT. Blutner defines them as follows:

In strong bidirectional OT a form-meaning pair, <f,m> is called bidirectionally optimal iff[2]:

(q) there is no distinct pair <f',m> such that <f',m> is more harmonic than <f,m>

(i) there is no distinct pair <f,m'> such that <f,m'> is more harmonic than <f,m>

In weak bidirectional OT a form-meaning pair, <f,m> is called super-optimal iff:

(q) there is no distinct pair <f',m> such that <f',m> is more harmonic than <f,m> and <f',m> satisfies i.

(i) there is no distinct pair <f,m'> such that <f,m'> is more harmonic than <f,m> and <f,m'> satisfies q.

[2] In logic iff is an abbreviation for *if and only if*, indicating that one statement is both necessary and sufficient for the other.

An output must be optimal within both the production perspective and the comprehension perspective to be strong bidirectionally optimal.

To clarify these definitions the two algorithms will be illustrated with an example. In Tableau 2 the bidirectional interpretation process for indefinite objects is given. In Dutch an object can be placed before or after the adverb. If the object is placed before the adverb, this is called a scrambled sentence. For example in the sentence (sentence 1) "het meisje heeft een appel niet geplukt" an indefinite object has been placed in scrambled position. An example of an indefinite object in a non-scrambled sentence is the sentence (sentence 2) "het meisje heeft geen appel geplukt". These are two different forms of sentences with an indefinite object in it.
Also two different meanings are possible. If the indefinite object ("een appel") is interpreted referentially than it is interpreted as referring to one particular apple. If, on the other hand, "een appel" is interpreted as being not referentially than it is interpreted as referring to any apple.

For the interpretation of indefinite objects, De Hoop and Krämer (to appear) propose the following constraints:

*M1:* Subjects get a referential interpretation, while objects get a non-referential interpretation.
*M2:* Indefinite noun phrases get a non-referential interpretation.
*F1:* Indefinite objects do not scramble.

From *Tableau 2* it follows that the form meaning pair <-scrambling, non-referential> does not violate any of these constraints. This form meaning pair is marked by ✌, it is called the super-optimal form meaning pair. In strong bidirectional OT this is the only optimal form meaning pair.

Weak bidirectional OT accounts for yet another reading of the indefinite object. From the definition of weak bidirectional OT it follows that both <-scrambling, referential> and <+scrambling, non-referential> are blocked by the super optimal form meaning pair <-scrambling, non-referential>. For both of these form meaning pairs it is true that there does exists a pair where the form or the meaning is more optimal, namely <-scrambling, non-referential>. This is not the case for the interpretation <+scrambling, referential> on line five in the tableau. Therefore this interpretation is another super-optimal form meaning pair (☝) even though it violates all three constraints.

| INPUT:<br>Indefinite object<br>< form, meaning > | M1 | M2 | F1 |
|---|---|---|---|
| ☝<- scrambling, non-referential> | | | |
| <- scrambling, referential> | *! | *! | |
| <+ scrambling, non-referential> | | | *! |
| ✌ <+ scrambling, referential> | * | * | * |

*Tableau 2: weak bidirectional OT*

### 4.1.2 Learning in Optimality Theory

In OT it is assumed that the different languages of the world use the same constraints. A different hierarchical ordering of these universal constraints causes the differences between languages (Archangeli, 1997). According to this hypothesis, these constraints are inborn. A child learns the language of his parents by reranking the constraints in such a way that the hierarchical ordering of constraints is in line with the language to which the child is exposed. Two different algorithms for the learning of constraint rankings will be introduced.

According to Tesar and Smolensky (2000) the ranking of constraints will be learned by error driven constraint demotion. If an output (say an utterance) is heard, this is presumably an optimal candidate. Therefore it can be deduced that the constraints that are violated by this candidate must be arranged below at least one constraint that is violated by the other candidates (this mechanism is called "robust interpretive parsing"). The highest constraint that is violated by the heard form will be demoted such that this condition will be met.

Boersma (1998) proposes an algorithm which he calls "gradual learning algorithm". In his algorithm constraints are stochastic distributions, which can possibly overlap each other. The actual ordering of constraints is the result of a process of change. For learning the correct constraint ranking the algorithm needs a learning datum, which is an observation. With the actual constraint ranking a hypothetical output will be formulated on base of the input. If this hypothetical output does not correspond to the observation, all constraints that favour the learning datum are promoted a little and all constraints that do not are demoted a little.

## 4.2 Overview of ACT-R

The aim of this research is the modelling of the learning of bidirectionality within the cognitive architecture of ACT-R. In this section the theory of ACT-R will be introduced for as far as relevant to this thesis.

ACT-R is a cognitive architecture meant for computational modelling of human cognition (Anderson & Lebiere, 1998). The basic theoretical foundation of ACT-R is rationality. Rationality is expressed by optimization with respect to demands from the environment. This implies that the costs and the gains of an action will be weighted against each other. So, a rational action is to select the optimal strategy given the environmental and computational limitations. ACT-R is a so called hybrid architecture which means that it operates on a symbolic level as well as a subsymbolic level.

On the symbolic level two kinds of memory can be distinguished, namely declarative memory and procedural memory. Declarative memory is defined as knowledge of facts. In ACT-R this knowledge is represented in chunks. Procedural memory can be defined as knowledge of how to perform an action, which is represented by competing IF-THEN rules, known as production rules. Cognition is represented by actions (production rules) performed upon declarative knowledge (chunks). Only one production can be performed at a given time. Depending on the buffer state an action will be chosen. This action can modify the buffer state which changes the subset of possible actions.

On the subsymbolic level the main topic is competition. When more then one production rule matches the buffer state, there will be a competition between the different production rules. This competition makes use of the costs and benefits of a production rule. The production with the highest expected utility will be executed. In a similar way chunks are retrieved depending on recency or frequency of use.

# 5 OT AND THE DATA

In Section 4.1. three different OT models were introduced: unidirectional OT, strong bidirectional OT and weak bidirectional OT. These OT models differ in their predictions towards the empirical data. Unidirectional OT does in some cases not differentiate between the meanings of two different utterances. Take sentences 1 and 2 of the introduction. According to unidirectional OT, the meaning of both of these sentences would be the same. Furhermore, differences between the empirical data of children and adults are found. Sentence 1, for example, is differently interpreted by children and adults. Is it possible that language data of children and adults is explained by different OT models? To specify the transition that takes place, it must be made clear what OT model children use and what OT model adults use. We will discuss some literature on this.

## 5.1 Which OT model explains child language best?

### 5.1.1 Indefinite objects and subjects

De Hoop and Krämer (to appear) suggest that children use unidirectional OT whereas adults use bidirectional OT. "Before the 4-year old child will be a competent, adultlike hearer of her language, she must acquire the full process of optimization of interpretation, which not only involves taking into account cross-modular constraint interaction but also the speaker's perspective of optimization in a bidirectional approach." In Section 4.1.1. we discussed their explanation of the adult data of indefinites. Child data of indefinites can be explained using the same constraints but the unidirectional OT model. This is shown in the tableaux below *(Tableau 3 and 4)*.

| INPUT:<br>Het meisje heeft een appel niet geplukt<br>< +scrambling > | M1 | M2 |
|---|---|---|
| Referential | *! | * |
| ☞ non-referential | | |

*Tableau 3: Unidirectional interpretation of indefinites*

| INPUT:<br>Het meisje heeft geen appel geplukt<br>< -scrambling > | M1 | M2 |
|---|---|---|
| ☞ non-referential | | |
| Referential | *! | * |

*Tableau 4: Unidirectional interpretation of indefinites*

From *Tableau 3 and 4* it follows that a non-referential interpretation is unidirectionally optimal for scrambled (*tableau 3*) as well as non-scrambled (*tableau 4*) sentences. These predictions are in line with the empirical data of children. Children give a non-referential interpretation to scrambled as well as non-scrambled sentences.

### 5.1.2 Pronoun interpretation

A second article in which the authors suggest that children and adults use a different model is an article by Hendriks and Spenader (2004). In their article Hendriks and Spenader give an OT explanation for the pronoun interpretation problem. They also use unidirectional OT to explain the child data and weak bidirectional OT to explain the adult data. Their analyses will be discussed below.

The pronoun interpretation problem refers to the fact that children continue to perform at chance levels with respect to the interpretation of intrasentential pronouns up to the age of 6;6 (Wexler & Chien, 1985; Grimshaw & Rosen, 1990).
A sentence like *"the boy saw him"*, is only half of the time interpreted correctly (adultlike) by children of these ages. The word "him" is half of the time interpreted as coreferring with the subject "the boy". The other half of the time they interpret the pronoun as referring to another person, which is equal to the adult interpretation. At this same age, however, children do not have any problems with reflexives. Children have learned to interpret reflexives from the age of three. For example "himself" in the sentence *"the boy saw himself"* is most of the times correctly interpreted as referring to "the boy". Contrary to these findings children turn out to produce pronouns as well as reflexives in an appropriate manner by the age of 2 or 3 (Bloom, Bars, Nicol & Conway, 1994). Well before a child learns to interpret pronouns the way adults do, they manage to use them correctly.

According to Hendriks and Spenader (to appear) the child data of pronouns and reflexives can be explained by unidirectional OT. They propose two constraints:

| | |
|---|---|
| *Principle A:* | A reflexive must be bound locally |
| *Referential Economy:* | reflexive >> pronoun >> R-expression<br>Expressions with less referential content are preferred over expressions with more referential content. |

The tableaux (*Tableaux 5, 6, 7 and 8*) are taken from Hendriks and Spenader (to appear). From Tableau 5 and 6 it follows that in language production a reflexive is optimal for a coreferential meaning and a pronoun is optimal for a disjoint meaning which fits to the language production data observed by children. From Tableau 7 it follows that a reflexive should be interpreted coreferentially. Tableau 8 shows that pronouns can be interpreted disjoint as well as coreferential. According to unidirectional OT both the disjoint and the coreferential interpretation are optimal. These findings explain the empirical data of child language interpretation and production.

| INPUT:<br>coreferential meaning | Principle A | Referential Economy |
|---|---|---|
| ☞ Reflexive | | |
| Pronoun | | *! |

*Tableau 5: Unidirectional optimization for production*

| INPUT: disjoint meaning | Principle A | Referential Economy |
|---|---|---|
| Reflexive | *! | |
| ☞ Pronoun | | * |

*Tableau 6: Unidirectional optimization for production*

| INPUT: reflexive | Principle A | ~~Referential Economy~~ |
|---|---|---|
| ☞ coreferential meaning | | |
| Disjoint meaning | *! | |

*Tableau 7: Unidirectional optimization for interpretation*

| INPUT: pronoun | Principle A | ~~Referential Economy~~ |
|---|---|---|
| ☞coreferential meaning | | |
| ☞disjoint meaning | | |

*Tableau 8: Unidirectional optimization for interpretation*

### 5.1.3 Input output mismatches

It is an interesting question how strong bidirectional OT and unidirectional OT differ in the predictions that they make. Beaver and Lee (2004) compare different OT models. They point out some differences in predictions depending on the OT model that is used. Strong bidirectional OT and unidirectional OT differ in their predictions towards blocking and freezing. Note that Beaver and Lee used an idealized version of OT, which means that constraint hierarchies were fully ranked and constraints were not stochastic. In the light of these predictions we will take a look at the child language data.

#### *5.1.3.1 Blocking*

In the case of blocking two forms may be linked to one meaning in comprehension, but a preference for one form in production destroys the link between the other form and the meaning. The form that has been blocked is called a marked form. For example the existence of the irregular form "wrote" blocks the regular form "writed" from being used. The form "writed" is in this case a marked form. Another example can be found by the interpretation of pronouns. The reflexive as well as the pronoun are linked to a coreferential meaning. But because the use of a reflexive is preferred for producing a coreferential meaning this blocks the link between the pronoun and the coreferential meaning.

Blocking phenomena cannot be explained by unidirectional OT. This implies that marked forms should be found in production data of children, which turns out to be the case. From empirical research it follows that children do use overregularized forms like "writed".

In contrast to unidirectional OT strong bidirectional OT does explain total blocking. This means that a marked form will not be produced and will even not be interpretable. For example, strong bidirectional OT predicts that the utterance "cause to die" is uninterpretable since it is blocked by the lexicalized form "kill".
According to Hendriks and Spenader a pronoun is a marked form. In strong bidirectional OT it gets only a disjoint meaning because the coreferential meaning is blocked by the reflexive. This does not correspond to the analysis of pronoun interpretation by children

(See section 5.1.2). Children turn out to give coreferential as well as disjoint interpretations to pronouns. Therefore strong bidirectional OT cannot be used to explain this data.[3]

#### *5.1.3.2 Freezing*

An example of word order freezing can be given in Dutch. In Dutch the most commonly used ordering of words is Subject-Verb-Object. An example of this can be found in the following sentence in Dutch:

| | | | |
|---|---|---|---|
| *"Peter* | *bijt* | *de* | *hond."* |
| *Peter* | *bites* | *the* | *dog* |

*(Peter bites the dog).*

Despite the fact that the world knowledge suggests something else, the sentence will preferentially be interpreted as the dog being bitten by Peter.

Unidirectional OT does not explain freezing, while bidirectional OT does. This can for example be the restriction of word order freedom to prevent ambiguous interpretation of object and subject. If children use unidirectional OT it is expected that scrambled as well as non-scrambled sentences will be found in their production data.

## 5.2 What kind of OT model explains the data of adult language?

Beaver and Lee (2004) conclude their article with the observation that although weak bidirectional OT has its shortages, at least a variant of this OT model will probably fit best to the data. Strong bidirectional OT is too restrictive, a marked form will always be

[3] One possible reason why children learn the language at the rate they do is by elimination of potential meanings of words. Clark (1987) and Markman (1987) propose that children eliminate a great deal of potential meanings by assuming that category terms are mutually exclusive. For example a child learned that the word "car" refers to what we call a car. For the child this implies that for example the word "bike" cannot refer to a car and that the word "car" cannot refer to anything else. From empirical research it follows that children find class inclusion difficult. A doll is not a toy, because it was a doll already!
In terms of OT "toy" and "doll" can both be seen as referring to a doll. For adults these two forms "doll" and "toy" have, in a special case, as optimal meaning "doll". In unidirectional OT both forms would not belong to the same candidate set and thus both be grammatical, whereas in strong bidirectional OT one of the forms may be blocked. This data can be explained by strong bidirectional OT and not by unidirectional OT.

blocked by the optimal form. Alternatively weak bidirectional OT suffers from problems like overgeneration because total blocking does never occur.

Blutner and Zeevat (2004) argue in their article that they prefer the weak version of bidirectional OT over the strong version of bidirectional OT for explaining adult language data because weak bidirectional OT does account for marked forms, which strong bidirectional OT does not.

Weak bidirectional optimization is the only implementation of OT that explains partial blocking. The data of adult interpretation that is introduced in this study (De Hoop & Krämer, to appear; Hendriks & Spenader, to appear) can only be explained by weak bidirectional OT.

## 5.3 Stagnation

In the previous sections some arguments were given for elementary decisions that have to be made. We found evidence to assume that children use unidirectional OT and that adults use bidirectional OT. The main question that remains is how the transition from unidirectional OT to bidirectional OT can take place. In this section it will be shown that learning will stagnate before adult skill level is reached if unidirectional OT is used. To show this the learning mechanisms using constraint reranking will be applied.

From Tableau 7 it follows that, according to unidirectional OT, a pronoun can be interpreted coreferential as well as disjoint. "Him" in the sentence "Ernie sees him" will half of the time be interpreted as referring to "Ernie" and the other half of the time as referring to another person, for example "Bert". Thus, according to unidirectional OT the coreferential and the disjoint interpretation will both be chosen half of the time. This turns out to be in line with the empirical data of pronoun interpretation by children. Chien and Wexler (1990) and Thornton and Wexler (1999) showed that in roughly 50% of the cases the children's interpretation of the pronoun turns out to be appropriate for the situation. As can be seen in T*ableau 7* only one constraint is relevant for the interpretation of pronouns. Therefore the constraint ranking cannot be changed. So, stagnation of learning will occur before adult language capacities are reached.

A similar problem can be seen by the interpretation of indefinite objects. According to unidirectional OT the optimal interpretation for an object in a scrambled sentence is the non-referential interpretation (see introduction: "een appel" in the sentence "het meisje heeft een appel niet geplukt" is interpreted as referring to any apple). The optimal interpretation that adults give to the sentence cannot be learned by reranking of

constraints. Two constraints are relevant and both are violated only by the referential interpretation. Reranking of the constraints does not inflict any change on this. Despite reranking of constraints the optimal candidate will still be the same (*see Tableau 3*).

A last example of the stagnation of learning can be given by scrambling. Here stagnation of learning will occur in production OT. According to unidirectional production OT scrambled sentences will not be used. Nevertheless scrambled sentences will be met and thus the constraints must be reranked. As is true with learning pronouns only one constraint is used for the production of indefinites and so the constraints cannot be reranked (*see Tableau 2*).

## 5.4 Conclusion

In Section 5.1. we pointed out that the empirical data of the interpretation of indefinites by children can only be explained by unidirectional OT (Section 5.1.1). The same accounts for the interpretation and production of pronouns (Section 5.1.2.). Blocking and freezing phenomena can only be explained by bidirectional OT, but blocking as well as freezing predict data that is not obtained by children (Section 5.1.3). It is even the case that data is obtained contradictory to the predictions of blocking (Section 5.1.3.1). From this it can be concluded that it is more plausible that children use unidirectional OT than strong or weak bidirectional OT.

In Section 5.2. it is pointed out that the adult data that is relevant in this study (interpretation of indefinites and pronouns) can only be explained by weak bidirectional OT. Apart from further possible considerations on which OT model explains the adult data best we conclude that weak bidirectional OT explains the data best that is relevant to us.

Taking for granted that children use unidirectional OT we depicted how learning stagnates before adult language capacities are being reached. In order to do this the existing learning mechanisms were applied that are proposed in the OT framework (Section 5.3.). Two possible conclusions can be drawn from the fact that learning stagnates too early. One possibility is that the existing learning theories are not correct. However the stagnation is seen in empirical data as well. Children learn to use their language well before they learn the bidirectional aspects of it. The second possible conclusion is that a supplementary mechanism is missing which models the transition from unidirectional OT to bidirectional OT. The second conclusion will be investigated because it would give an explanation of the stagnation that is being seen in empirical data as well.

# 6 IMPLEMENTATION

## 6.1 A serial process

In Section 5.3. we saw that children will not reach adult language capacity by using unidirectional OT but have to learn bidirectional OT to reach adult levels of performance. Because bidirectional OT must be learned from the starting point of using unidirectional OT it may be useful to describe bidirectional OT in terms of unidirectional processes. In OT bidirectionality is described as a process similar to unidirectional OT but it uses a slightly different algorithm. Here we will propose bidirectional OT as incorporating the two unidirectional processes.

The two unidirectional processes can be combined into a bidirectional process by executing them serially. The output from the first process serves as input for the second process. In the case of interpretation, the unidirectionally optimal interpretation is used as input for production OT. The output from the second process functions as feedback to the correctness of the output from the first process. If the output equals the original input, the unidirectional optimal interpretation is bidirectionally optimal as well.

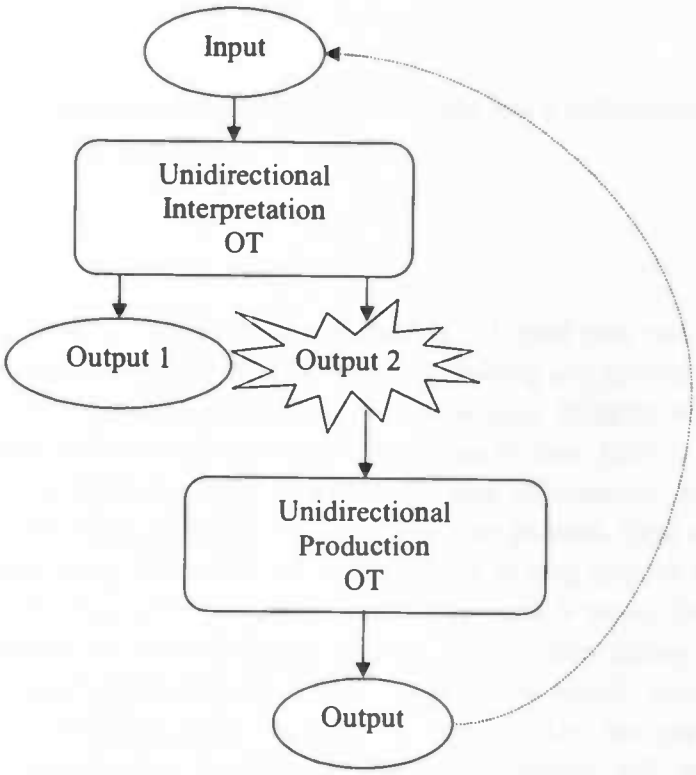


*Figure 2: Bidirectional OT as a serial processing mechanism.*

*Figure 2* visualises the serial execution of two unidirectional processes. The serial processing will be explained with an example as well. Unidirectional interpretation OT is indecisive on the optimal interpretation of sentences like "Jack hit him" (see Section 5.1.2). According to unidirectional interpretation OT the word "him" can refer to "Jack" as well as to someone else. In the figure these two possibilities are depicted with the boxes "output 1" and "output 2". Because by means of unidirectional OT the optimal interpretation cannot be deduced, a referent must be chosen. The referent that is chosen is being used as input for the second process (In the figure the referent being chosen is represented by the box "output 2"). Given that "Jack" is chosen as referent, the optimal production according to production OT is "himself". This optimal production is not equal to the original input and therefore it must be concluded that the interpretation choice (choosing "Jack" as referent) that has been made is not the correct one.

Within the framework of OT, unidirectional OT and bidirectional OT are distinct models. They use slightly different algorithms to find the optimal interpretation or production. In order to find a way to model the transition from using unidirectional OT to bidirectional OT we investigated how these two models relate to each other. For reasons of simplicity it is better to use one model in order to explain the empirical data than to use two models.

Now we have found a way to integrate the unidirectional models into a bidirectional one, we will shift our focus towards the transition.

## 6.2 Processing time

Communication can be defined as exchange of information. At least two parties are involved with communicative processes. They take turns in supplying and processing the information. This turn taking is an important part of communication. Imagine what the party B would do when party A is waiting too long before taking its turn. Party B would probably fill the gap of time supplying party A with more new information. Another possibility is party B walking away, stopping the communicative process. Both actions are the result of the long time party A takes for the interpretation. If long silences are the result of slow language processing, new information would only make it worse. So, both actions of party B will disrupt the communicative process. So, the turn taking of the parties involved in communication is a delicate process. To steer this delicate process in the right direction some assumptions must be made to rely on. On the one hand communicators formulate assumptions according to the time someone will need to interpret the information. This assumption may depend on several factors such as age of the communicative partner, type of information and intelligibility of the speaker. On the other hand a listener will try not to exceed the time that the speaker expects him to use. If processing takes too long, it may be preferable to guess what is meant or to use a word that resembles the optimal description. This is an important aspect of our final implementation.

## 6.3 Possible ACT-R implementations

In this section three possible implementations will be proposed. The first two models use a serial processing mechanism in which bidirectional optimization is a result of the serial processing of interpretation OT and production OT. These two models use different learning mechanisms to integrate the two unidirectional processes. The third model is distinguished from the first two in that bidirectional OT is not obtained by integration of the two unidirectional processes. These three possibilities will be evaluated by criteria that are posted in Section 6.3.4. The one that fits the criteria best will be implemented.

### 6.3.1 Learning by production compilation

Bidirectional OT will be implemented by the serial processing of the two unidirectional processes. A serial processing of unidirectional interpretation- and unidirectional

production OT will need about twice the time a single unidirectional process would take. Therefore it can be expected that bidirectional OT needs either more processing time or higher processing efficiency than unidirectional OT does. More processing time is not available because long interpreting times could lead to confusion (6.2.). However higher processing efficiency can be gained by means of learning by production compilation. The implementation returns unidirectional optimal data as long as processing efficiency is not high enough to use bidirectional optimization in the given amount of time. Thus, the only barrier to bidirectional optimization is a limited amount of time and it is assumed that the failure of using bidirectional optimization processes results in unidirectional optimization.

The first model we propose assumes that unidirectional interpretation- and unidirectional production OT can be processed in series as soon as both single processes have been speeded up enough. It is thus assumed that potentially, children have the ability to use bidirectional optimization processes. They do not manage to do so, because they lack processing time. An implementation for unidirectional interpretation OT as well as for unidirectional production OT will be developed. Whether an interpretation is bidirectionally optimal can be deduced by using the two processes in succession. Hereto the output of the interpretation process serves as input for the production process and vice versa. Initially the two unidirectional processes are not thoroughly mastered; processing is not fast enough to pass through the two processes successively. At this stage unidirectional optimal data will be produced. By the means of production compilation, processing will gain efficiency. Production compilation is a mechanism in which new production rules are learned on the basis of combining existing rules and declarative knowledge (Taatgen & Anderson, 2002). By integrating two existing production rules into one new rule the process can be performed using fewer production rules, which means less processing time. If enough time is left to complete both processes bidirectional optimal data is generated.

### 6.3.2 Learning by feedback

Unidirectional interpretation- and production OT do not always produce data which is symmetrical. For example the word "him" is produced in the sentence "Jack hit him" to refer to another person (i.e., anyone but Jack). In interpretation OT, however, this same word "him" can refer to another person as well as to Jack. This asymmetry will probably result in some kind of friction between speaker and hearer which can function as a feedback mechanism. This or another kind of feedback is our main force in learning bidirectional OT in the second model we propose.

In contrast to the previous proposed model it is assumed that initially children do not have the potential to use bidirectional optimization processes. By means of a feedback mechanism the child deduces that it needs another source of information to reach adult interpretational levels. New constraints can function as source of information. New constraints are available from the second process. Which means that in the case of interpretation OT production constraints can be introduced. We will discuss two possible methods to introduce constraints of one process into the other process.
New constraints can be introduced one by one. The constraint carrying the most information, which is the strongest constraint, reduces uncertainty most and can thus be expected to be introduced first. In the case of production the first constraint to be added is the strongest constraint from the interpretation process. New constraints will be added to the existing constraint set, until symmetric data is being retrieved. Bidirectional OT is being learned by using the constraints of the interpretation process one by one until a uncertainty is being diminished.
The second possibility is that, in the case of interpretation, the production process is taken into account as a whole. This option combines features of the production compilation model and the feedback model. Production compilation comprises optimization steps into one or a few steps. As the results of feedback, the child deduces that another source of information is needed which is the comprised production process.

### 6.3.3 Bidirectional OT as a side-effect from learning and exclusivity

A third possible model is not serial, nor parallel. In fact, it does not implement bidirectional OT, but merely produces bidirectional data at the end of the process. The main new process that is assumed by this implementation is the mutual exclusivity principle. Markman shows that once a meaning is given to an object, this meaning is excluded and can temporarily not be given to another object. This is called the mutual exclusivity principle (Markman, 1998). The model assumes this principle to be active with sentences as well as words, which is not proven. A sentence which is used often will be connected tightly to its meaning, which according to the exclusivity principle applied to sentence interpretation, is exclusively given to this particular type of sentence. If a deviant utterance is being met, a deviant interpretation will be given.

A unidirectional model will be implemented. As with the other two models, optimal meanings and productions will be deduced by means of this implementation. Production compilation automatizes this basic implementation so that form-meaning pairs will be learned by heart. It must be noted that utterances that appear frequently as well as utterances that can be interpreted unambiguous are learned more easily in an implementation in ACT-R. The process of interpretation becomes faster and connections become stronger as a particular sentence is interpreted more often. If an interpretation is

ambiguous this entails that each interpretation is chosen half of the time in the case of two possible interpretations. The exclusivity principle applied to sentences will prevent this particular meaning to be given to another sentence. This can, for example, be implemented by marking candidates as being occupied. So, learning the form-meaning pair <himself, reflexive> prevents the pair <him, reflexive> to be generated. Therefore the alternative meaning, a disjoint meaning must be given. Also, learning the form-meaning pair <het meisje heeft een appeltje niet geplukt, referential> prevents the pair <het meisje heeft een appeltje niet geplukt, referential> to be generated. So, the alternative meaning, non-referential must be given. Although bidirectional OT was not implemented as such, this implementation will result in bidirectionally optimal data.

### 6.3.4 Conclusion

The model has to meet several empirical criteria. The criteria will be discussed first. Then it will be established which model fulfils the criteria best. On the basis of this hypotheses it will be decided which model to implement.

Three different phases in developing bidirectional language skills can be distinguished. In the first phase the constraint ranking of unidirectional OT is being learned. This will be followed with a relatively stable period in which unidirectional optimization processes are being used. In the last phase bidirectional OT is learned. The model data is expected to account for the last two characteristics. The first phase, in which the correct constraint ranking is being learned, falls beyond the scope of this study.

All proposed models start when the constraint ranking is being learned. Until the constraint ranking is being learned the produced data will be subject to change. Therefore it can be expected that the data has not been stable yet and so the learning process itself must result in a stable period.
The first model uses production compilation. Until the process is efficient enough to use bidirectional OT within time limits, it will return unidirectional optimal data. This period of speeding up the process reflects a stable phase in which unidirectional optimal data is being produced.
The second model makes use of feedback. Feedback results in adding either a new constraint or a new process to the first process. Adding a new constraint can be seen as some kind of extended period of instable data production. As long as bidirectional OT is not being learned data production is instable. In the case of adding a new process to the existing one, unidirecional data production will result in a stable period.
The third model learns form-meaning pairs by heart. As soon as blocking starts, bidirectional optimal data is being produced. Until then unidirectional optimal data is

begin produced which accounts for a relatively stable period in which unidirectional OT is being used.

The first two models use bidirectional OT at the end of the process. The two unidirectional processes are processed in series which is the serial implementation of bidirectional OT. The third model only produces bidirectional data at the end of the process which violates the criterion that states that bidirectional OT must be used. The first model will be implemented because it is the simplest explanation and it does not need any feedback.

## 6.4 Design

In this section the high level design of the model will be introduced, for the complete code see the appendix. In Section 6.6.2. we will have a closer look at the different components of the model and the choices that are made will be discussed.

*Figure 3* pictures the main elements of the model. Input exists of a pronoun or a reflexive (labeled as such). First two candidates (boxes 1 and 2) and a constraint (box 3) are retrieved. Both candidates are evaluated on the basis of the constraint. If only one of the two is being violated (box 4) and there is still processing time left (box 4b) a new candidate will be retrieved which replaces the violated one (solid arrow from box 4b to box 2). The candidate that does not violate the constraint is optimal with respect to the other and will be compared to the next candidate. If either both candidates violate the constraint or both candidates do not (box 5) and there is still time processing time left (box 5b) the next constraint will be retrieved and the same two candidates are evaluated again (dotted arrow). In this case it is not clear which of the two candidates is optimal with respect to the other; the next constraint may clarify this. The striped arrow reflects the case that it remains unclear which of two candidates is optimal despite of evaluation by all constraints. One of them will be chosen and a next candidate will be retrieved. These two processes of retrieving constraints and candidates will be repeated until there are no unevaluated candidates left (box 6). The optimal candidate (with respect to all others) is returned as output. The process will be terminated earlier if processing time is over.

Each box in the figure represents one or more production rules. The main characteristics of OT are GEN and EVAL. Both described in Chapter 2. The generation of candidates (GEN) is reflected by the first two boxes and the evaluation is reflected by the third, fourth and fifth box at the right side of the picture. The choices that are made according to the specific implementation will be discussed in Section 6.6.2.

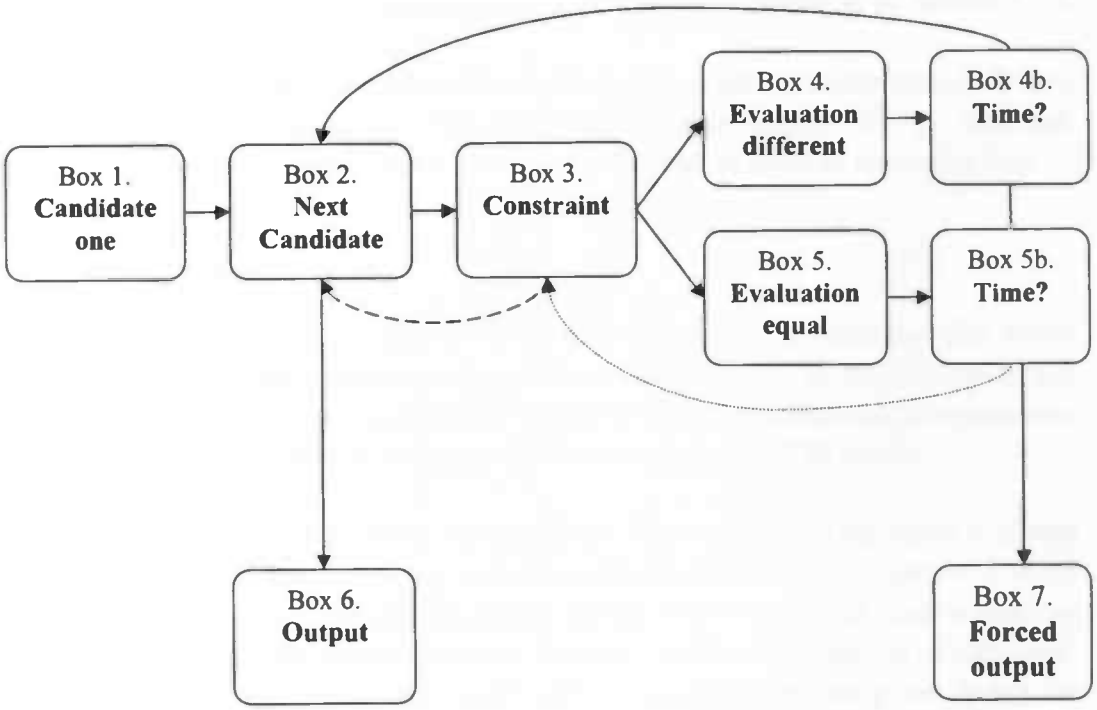


*Figure 3: Structure of the model.*

## 6.5 Learning bidirectional OT

An example of production compilation in our model will be given. It will explain the first steps towards the learning of bidirectional OT. The following steps that lead to learning bidirectional OT will be explained after the example. Box 1 and Box 2 both represent a production rule which retrieves a candidate from declarative memory. These two can be integrated into a single production rule retrieving two different candidates from memory. It is possible that this single production rule will finally use about as much time as one of the two single production rules would. This new production rule is treated as all other production rules are. So it can be integrated with the next production rule, represented by box 3. This process can theoretically be repeated until finally the unidirectional OT finds place in one production rule.

## 6.6 Results

In Section 6.3.4 the proposed models were evaluated on the basis of hypothesized characteristics of their output. A computational simulation model is realized, the

simulated data will be used to evaluate the model. The same criteria as in Section 6.3.4. will be used, which are repeated here:
The model data is expected to account for two phases. A relatively stable period of using unidirectional OT followed by the mastering of bidirectional OT is expected. Furthermore we will try to explain all observations that can be made to the model data.

### 6.6.1 Observations

Each model run simulates the interpretation of a pronoun or a reflexive. The model archives whether an interpretation is generated unidirectionally or bidirectionally and whether the interpretation is correct or not. The proportion of bidirectional interpretations and of correct interpretations is computed by taking the average of 30 results.

In *Figure 4* the proportion of correct interpretations for pronouns and reflexives is plotted as a function of time. As can be seen in the figure the interpretation of reflexives is about 100% correct from the beginning. This can be explained by the fact that unidirectional as well as bidirectional optimization processes lead to a correct interpretation of reflexives. Furthermore it can be seen that about 50% correct interpretations are given during the first half of this learning period. The second half of the learning period this is increased to about 80% correct interpretations. According to this model data it would be expected that an increase of correct interpretations can be observed.

*Figure 5* shows us how the use of bidirectional OT increases with time. The use of bidirectional OT (in proportion to the whole) is plotted as a function of time for both the interpretation of pronouns and the interpretation of reflexives. As can be seen in the figure both lines reach 100% which means that at the end of the process bidirectional OT is mastered. The dark line represents the use of bidirectional OT for the interpretation of pronouns. Three periods can be distinguished. During the first period of time only unidirectional optimization processes are being used (0% in the figure). The intermediate period shows a smooth upwards sloping line which implicates that bidirectional OT is mastered gradually. During the last period of time only bidirectional OT is being used (100%) in the figure. The grey line represents the learning of bidirectional OT by the interpretation of reflexives. Here, only the second, intermediate, and the third period can be seen. Above that the intermediate period is less smooth and takes longer time. This unexpected finding will be explained in Section 6.6.2.3.

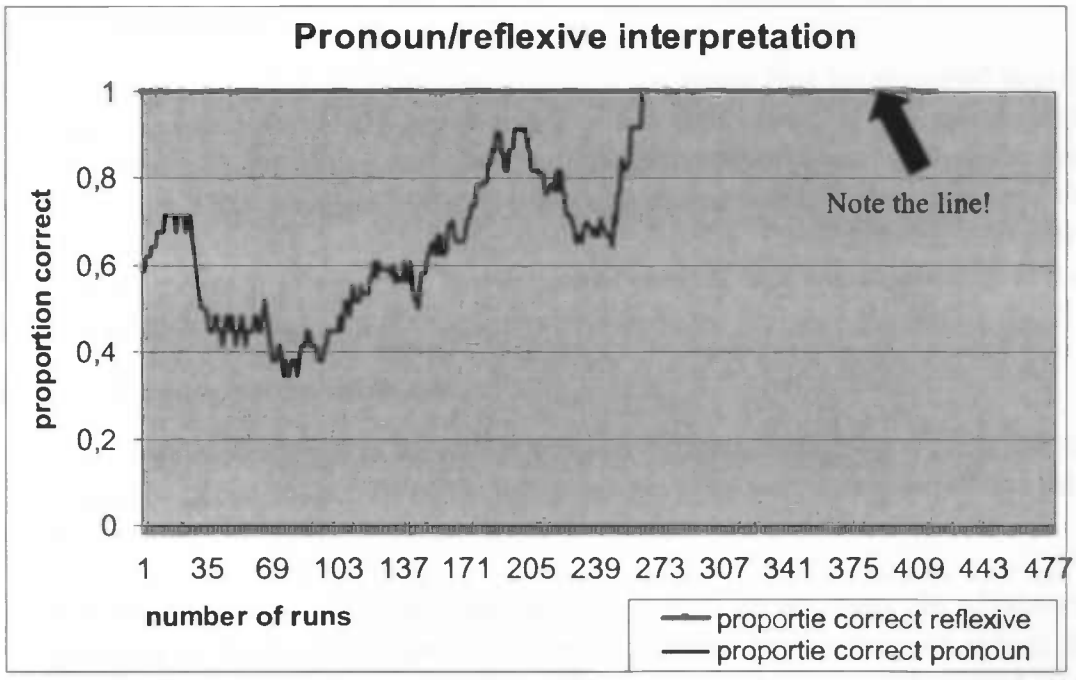


*Figure 4: Level of performance on the interpretation of pronouns and reflexives (model data).*

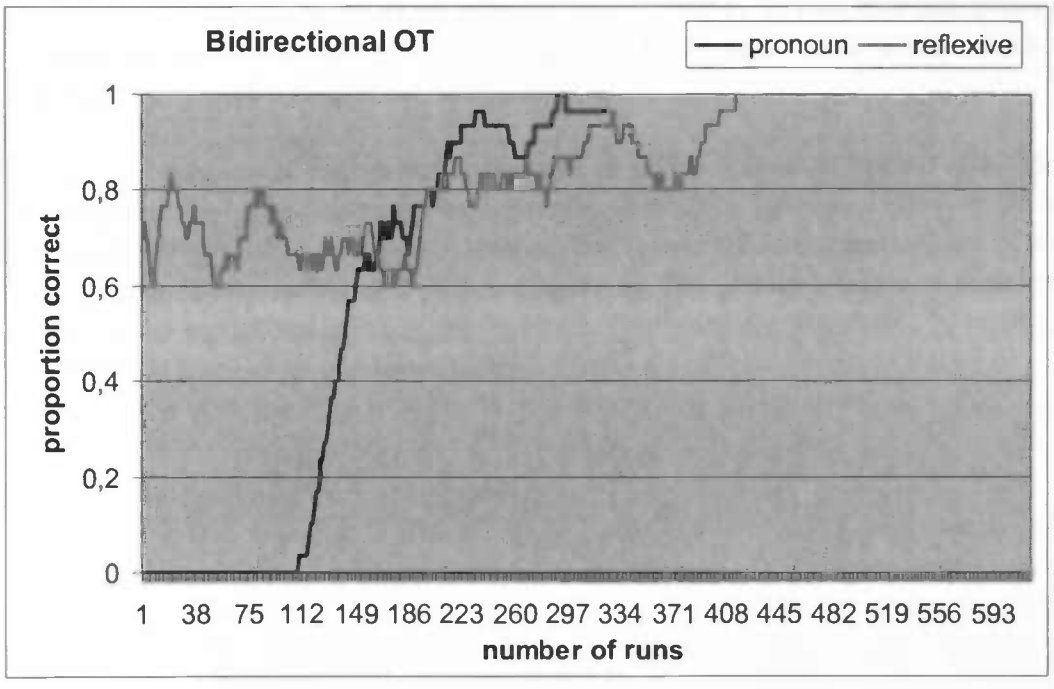


*Figure 5: Percentage use of bidirectional optimization processes (model data).*

### 6.6.2 Implications

In this section we will discuss the implications of the model data we presented above. Note that the data simulate the learning data of one child. Level of performance and learning slope are particular characteristic for this simulated child and can therefore not be generalized. Other simulated children will show another learning slope and level of performance will differ between different simulated children. These differences between children are the result of variables, like amount of received data and adaptability of the child's cognitive system.

#### *6.6.2.1 Pronoun interpretation data*

In *Figure 4* we depicted that in the case of pronoun interpretation during the first half of the simulation period about 50% of the interpretations is correct, during the second half of the period about 80% of the interpretations is correct.

From empirical studies it follows that in roughly 50% of the cases the children's interpretation of the pronoun turns out to be appropriate for the situation (Chien & Wexler, 1990; Thornton & Wexler, 1999). Whereas the model data we presented may look similar, it is a simulation of only one child. A new model run would result in another initial level of performance. Deviances between the empirical- and the model data may be attributed to a different incidence of pronouns and reflexives. In everyday life, pronouns are used more often than reflexives. Although this is not represented in our model, we expected this not to be relevant for our question.

The gradual increase of correct responses must be noted. A gradual instead of a sudden learning slope may, in this case, be the result of random influences. Due to random influences the procedure of optimization does not always take the same amount of time. This is explained by means of a picture (*Figure 5*). The picture is made to explain the results of the model and so only the main characteristics are presented. In reality the model data is much more capricious (see the *figures 4 and 5*).

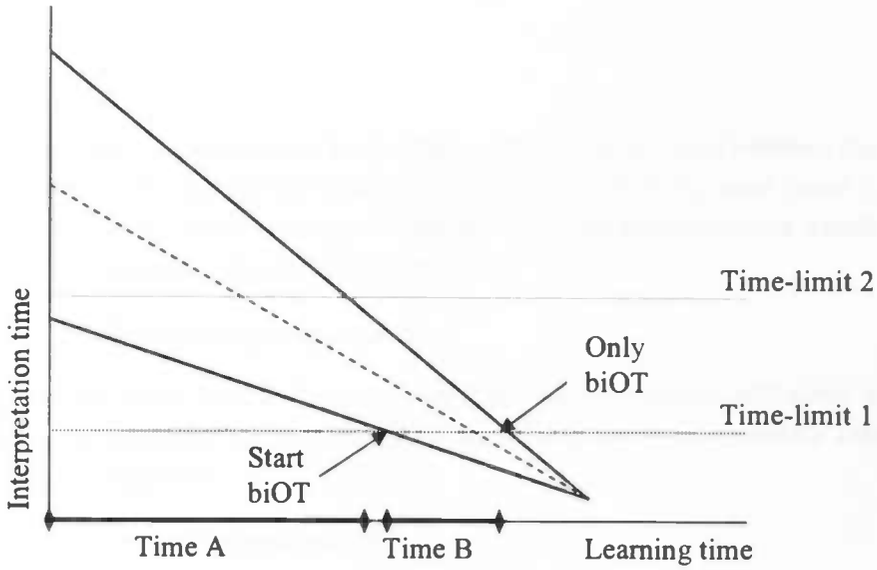


*Figure 6: Gradual learning of bidirectional OT.*

The horizontal (dotted) line represents the time an interpretation may take. This limited amount of time may not be exceeded. The dashed line in *Figure 6* represents an abstracted but possible learning curve. The space between the two black lines represents the variance of time needed to reach a bidirectional optimal interpretation. As can be seen, this variance is bigger at the beginning of the process than it is at the end. This is due to the fact that more production rules are used at the beginning of the process than at the end. Because of stochastic elements, the time it takes to interpret or produce a sentence is variable. So, it can be seen in the picture that production compilation has two effects. Because fewer production rules are being used, less processing time is needed and because fewer memory facts need to be retrieved random influences diminishes. The decline of processing time results in a crossing of the "lowest variance" line through the "time limit 1" line. At this point (see arrow) bidirectional data can be obtained, but mostly will not. As learning (production compilation) goes on the chances of obtaining bidirectional data within the time limits increases, which can be seen by the increase of space beneath the "time-limit" line. Bidirectional OT is completely mastered if also the "highest variance" line crosses the "time limit 1" line. This point is again marked with an arrow. The period between the two arrows represents the time that is needed to learn bidirectional OT. Within this period of time, bidirectional- as well as unidirectional optimal data can be seen.

So, our model predicts a gradual increase of correct responses in the case of pronoun interpretation. What can be found about that in the literature? Kraemer (2000) investigated children's interpretation of indefinites. One of the findings she reported is that most children gave either an adultlike or a child typical interpretation. In one of the experiments 14% of the children showed a mixed pattern. This implies that a relatively quick change from using unidirectional to bidirectional OT can be expected. This is

coherent with our model data. In the Figure (*Figure 6*) the time between the start of using bidirectional OT and the last time unidirectional OT is being used (time A) is relatively short. This diminishes the change to test at exactly the transition time which explains why so little "in between" data is being found.

#### *6.6.2.2 Reflexive interpretation data*

The unidirectional- and bidirectional optimal interpretation of reflexives are exactly the same. This explains the fact that they are always interpret correctly according to our model (see *Figure 5*).

#### *6.6.2.3 Learning bidirectional OT*

The early use of bidirectional OT in the case of reflexives as well as the flat learning slope that is observed by the learning of reflexives can also be explained by means of *Figure 6*. The model uses fewer production rules for the interpretation of reflexives than for the interpretation of pronouns. Because fewer production rules are being used for the interpretation of reflexives, less time is needed to interpret this kind of input. Therefore, the process is further at the moment the time limit is reached. This results in the same effect as giving more interpretation time which is easier to add to the figure. In *Figure 6* this is presented by the "time limit 2" line. Bidirectional interpretations are given from the beginning of the learning process because interpretation is relatively fast. Because of the relatively large random influences at the beginning of the process it takes much time to interpret bidirectionally in all cases which explains the flat learning slope in *Figure 5*. This is represented by the period of time in which the "time-limit 2" line cuts through the variance area (represented by time A). See for a similar finding, in the domains of proportional reasoning Jansen and Van der Maas (2002)

#### *6.6.2.4 Model*

It is important to note that less production rules are being used for the processing of reflexives than for the processing of pronouns depends on an implementational choice. With the help of *Figure 3* these implementational differences can be illustrated. The first constraint that is relevant by interpretation of reflexives (principle A) violates one of the two candidates we used (reflexive, pronoun). Therefore box 4 will be entered, resulting in an output immediately. This is however not the case by interpretation of pronouns. The first relevant constraint (principle A) is not violated by any of the candidates and therefore the next constraint will be retrieved (referential economy) and evaluated. Because our implementation is a serial one, using two constraints takes more time than using one. A prediction that follows from this is that some interpretations take on average more time than others.

The model predicts that high frequent words will be learned faster. Each time an utterance is being met, production compilation can take place. It can be expected that different processes in which bidirectionality is expected to be learned will not be managed at the same time. If the only influence on the speed of learning is frequency, it can be expected that high frequent constructions will be learned faster than low frequent ones.

We will have a look at the empirical data on this. In Chapter 2 we saw that children from 4 years up to 7;7 give deviant interpretations to indefinite objects (Krämer, 2000). We also saw that from another study it followed that children in the age range of 8;7 to 10;4 give a deviant interpretation to indefinite subjects (Termeer, 2002). In Chapter 5 these data was explained by assuming that children use unidirectional OT and adults use bidirectional OT. The pronoun interpretation problem we implemented is evident for children up to the age of 6;6 (Chien & Wexler, 1990). This data does not give exclusive information on whether children use all phenomena at once. The empirical data that is available only indicates that the different phenomena are learned within a range of ages. This could be experimentally investigated by studying the performance of a single child on several tasks.

## 6.7 Model discussion

### 6.7.1 Generating a candidate set

In Optimality Theory it is assumed that an infinite candidate set is being generated at once. Within ACT-R, each module is considered to be a serial mechanism. If an infinite set of candidates is generated serially, this would take an infinite amount of time. Because cognitive processes are bound to time we choose to reject the assumption of an infinite candidate set and use a finite one.

In our model a finite set of candidates is represented by chunks in declarative memory. During the interpretation process this whole set of candidates will be activated one by one. Following Misker and Anderson (2003) the active candidate is compared with the optimal the candidate that is optimal until that time. The model iterates over the candidates retrieved from declarative memory until there are no candidates left. Misker implemented his model such that the generation and evaluation of the candidate set take place outside the scope of ACT-R. In our model it is easier to implement the candidates as chunks in declarative memory. And, more importantly, the final results according to learning bidirectional OT are not affected by this choice.

### 6.7.2 Constraint set

Constraints are stored as chunks in declarative memory. As with the candidates the constraints are retrieved one by one. A constraint is stored in the goal, the candidates are evaluated and the next constraint will be retrieved to be stored in the goal again. It turned out to be impossible within the framework of ACT-R to keep "in mind" which constraint and also which candidate must be selected next. Therefore the production rules contained this information. This is not an elegant way of implementing our model; the choice is made out of pragmatism. However, given the type of analysis this paper focuses at, this does not pose a serious problem as bidirectional OT would also be learned if constraints are implemented as production rules (see below in this section, the method of Misker and Anderson). Only one type of sentence served as input and therefore the set of relevant constraint is fairly small. If, however, more input types must be generated it is not doable to specify for each particular input a path of constraints to use. It is possible though to adopt another strategy. Misker and Anderson (2003) implemented the constraints as production rules. For each particular type of input, the relevant productions are used to evaluate the candidates in order of constraint ranking.

### 6.7.3 Evaluation mechanism

Each violation has been implemented as a different declaration in declarative memory. If constraints are implemented as production rules, then the evaluation is also not a declarative memory fact. This would be plausible, because people can not report the rules of their own language, but they can report candidates.

# 7 DISCUSSION

## 7.1 Research questions

This study aims to investigate how children learn the OT model used by adults. In Chapter 3 research questions were introduced which will be repeated and evaluated here.

**Question 1:**
Which OT model explains children's language production and comprehension best?

We pointed out how children's interpretation and production data can be explained by unidirectional OT whereas adult interpretation and production data can be explained by bidirectional OT (Section 5.1.1). This answers the first two questions (Question 1 and Question 2).

**Question 2:**
Which OT model explains adult's language production and comprehension best?

Specific learning algorithms have been proposed for Optimality Theory (Section 4.3). In Section 5.1.3 we discussed how, according to these learning mechanisms, learning stagnates before adult language levels are being reached. It was concluded that the algorithms do not account for the learning of another OT model.

**Question 3:**

How does the transition from the OT model used by children towards the OT model used by adults look like?

To answer the third question (Question 3) an implementation was realized in ACT-R which models the learning of bidirectional OT. Both the child- and the adult interpretation data of pronouns can be explained by the model. We assumed that bidirectional OT is the result of the serial processing of unidirectional interpretation- and production OT. Initially, as a child is learning the language given to him, processing will be too slow to parse the two unidirectional mechanisms in series. By means of automization processing will become faster until bidirectional processing can take place within the limited time that is given.

**Question 3a:**

What triggers the transitional step?

The model does not rely on an external trigger to initiate the process (Question 3a). As we pointed out bidirectional OT is the result of increasing processing efficiency which makes processing possible within the time limits language is liable to. A prediction that follows from this is that, unless compensational strategies are being adopted, language must be mastered at a certain degree before bidirectional optimal data will be produced. So, children who experience difficulties learning language will be found to use bidirectional optimization later in age than other children.

**Question 3b:**

Is this transition being performed in one or more developmental steps?

The gain of efficiency is a gradual process and so is the learning of bidirectional OT (Question 3b). As learning progresses, chances increase that bidirectional optimization has taken place within the time limits. This explains the gradual increase of bidirectional optimization. As we pointed out before, according to the model, it can be expected that "intermediate" data will be found.

## 7.2 Parallel processing

An implementation in ACT-R is realized which models the learning of bidirectional OT. The main difference between this implementation and the theoretical OT approach is that the processes of the theoretical approach to OT are serialized in the implementation. Not only is bidirectional OT implemented as the serial processing of the two unidirectional mechanisms. It is also the case that the unidirectional mechanisms are serial versions of OT.

From the viewpoint of OT the different units (GEN, EVAL and CON) are parallel mechanisms. GEN generates the candidate set which is expected to be a parallel mechanism; the candidates are generated at once. EVAL is expected to evaluate all candidates at once by means of CON, an existing constraint set which is not subject to time at all. In contrast to this the model we implemented retrieves the candidates as well as the constraints one by one from memory.

Above the serial implementation of the units of OT, bidirectional OT is implemented as the serial processing of unidirectional interpretation- and unidirectional production OT. From the viewpoint of Optimality Theory, bidirectional OT evaluates all candidates at once; the interpretation- as well as the production constraints are applied in one single mechanism.

Presented as such, the model seems to make a major violation upon the main framework of OT. It can be argued, however, that in fact this violation is not as rude as it seems. Initially, it is indeed the fact that the model retrieves and evaluates all candidates one by one. But if learning starts, productions are compiled together by means of the production compilation mechanism. For example, production compilation can result in the retrieval of two candidates from memory within one production rule instead of two production rules. Generalizing this example leads us to the possibility that in constructions that appear frequently finally many candidates are retrieved and evaluated within one production rule, resulting in an output immediately. This brings us close to the OT characteristic of parallel processing. We can even go one step further; the two unidirectional mechanisms can theoretically be processed within one production rule. Note that this can only be the case in frequently appearing constructions. This means that fixed constructions can be processed in such a way that this is indistinguishable from parallel processing, but the compositional interpretation of infrequent sentences probably not. Thus, whereas the model differs from OT before learning starts, the difference diminishes soon.

## 7.3 Generalizing the model

Earlier, it has been pointed out that the model explains the empirical data we discussed. This implies that the model is a possible model of the reality. If a model is applicable to more than one phenomenon it can be said to have explanatory power. It is implemented for one phenomenon, but explains more than that. For example the gravitation models / formulae of physics cannot be applied to all possible falling objects, but nonetheless models all of them. In the same manner our model cannot be applied to all possible bidirectional processes, but it gains power if it can be proven to model all of them.

The model is designed to explain how bidirectional OT can be learned from the starting point of using unidirectional OT. It is only applied to the learning of pronoun interpretation which can be explained by learning bidirectional OT. There are, however, more phenomena that can be explained this way. This is for example the case in interpreting indefinites (De Hoop & Krämer, to appear) which is introduced in Chapter 1. Also the interpretation of scalar implicatures (Novek, 2001) can be learned by learning to use bidirectional OT. It can be expected that the model does account for all phenomena that can be explained by the change from using unidirectional OT to using bidirectional OT.

So, it can be concluded that the automization part of the model can be applied to more than one linguistic phenomenon and that more than one bidirectional linguistic

phenomenon can be modeled using the approach taken in this paper. Besides bidirectional linguistic phenomena literature refers to bidirectional phenomena in at least one other cognitive domain, namely formal reasoning. Dekker and van Rooij (2000) describe some parallels between game theoretic principals and OT. Bidirectional principles may possibly be used in reasoning about someone else's knowledge. They describe how a Nash equilibrium in strategic games can be compared to optimality. The optimal choice must be learned as is the case in OT and the bidirectional optimal choice can be learned later on. The bidirectional optimal choice depends on assumptions that are being made about someone else's knowledge. The advantage of game theoretic research is the formal context in which cognitive processes can be investigated. It may be possible to investigate the learning of bidirectional OT within this context. If a game needs reasoning about others and this can be explained by a bidirectional process it may be possible to detect the different phases in learning this bidirecional process. In the first stage people learn to use the different strategies and choose one or another strategy from their own point of view. As this choice can be made more and more efficiently, it can be expected that the Nash equilibrium from a bidirectional viewpoint will be chosen more and more often. It may be easier to experimentally investigate the learning of the Nash equilibrium than to investigate the linguistic phenomena where bidirectional OT must be learned. It is not easy to find children that are in between the stage of using unidirectional OT and using bidirectional OT. Moreover, if such a child can be found, there is only one change to experimentally investigate the transition. In the case of game-theory, every-one who is able to play a game can join in and their strategic behavior can be investigated experimentally. Assuming that strategies are acquired on the spot, every game player is a potential experimental subject.

## 7.4 Predictions

Different predictions are made throughout the presentation and discussion of the model. We will repeat these predictions.

It is predicted that a period can be found in which child- as well as adult performances can be seen. If it is possible to find children in this stage it is expected that a gradually increasing amount of correct responses will be found (6.6.2.1.).

Further it is expected that different processes (interpretation of pronouns, indefinites, scalar implicatures) are not learned at exactly the same time. If the only influence on the speed of learning is the frequency of offerings, than it can be expected that utterances with high frequency will be learned faster than utterances with low frequency (6.6.2.4.). Until now pronoun interpretation by children is investigated separately from the

interpretation of scalar implicatures or indefinites. These should be taken together in one experiment so that it can be shown whether children learn the different interpretations one by one or not.

A prediction that follows from the fact that we made a serial implementation is that differences in interpretation times will be found. Whereas all constraints can be used in each interpretation or production, the process will be terminated as soon as it can be decided which candidate is optimal (*Figure 3)*.

It is expected that, unless compensational strategies are being adopted, language must be mastered to a certain degree before bidirectional optimal data will be produced. So, children who experience difficulties learning the constraints and their ranking will be found to use bidirectional optimization processes later in age (Section 7.1.).

Another possibility that does not follow directly from the model is the following: In the model it is assumed that processing gains efficiency. However, data on interpreting times is not available. In our model bidirectional OT is the serial application of two unidirectional processes which can be processed within a certain time-limit. If this time-limit is exceeded unidirectional data will be obtained. Normally time-limits would be exceeded as the result of relatively slow processing. Another possibility would probably be to artificially reduce time limits beyond the bidirectional optimization time, by introducing some time pressure or a second task. The interesting result is whether unidirectional data is produced by adults or can be induced by children that just learned to optimize bidirectionally. In an experimental setting, adults can be asked to choose the correct interpretation (by means of a picture for example) as soon as possible. The reaction times can now be coupled to the answers. If unidirectional data is being obtained by fast answers (short interpretation times), this supports our model or at least the assumption of a serial implementation of bidirectional OT.

# 8 CONCLUSION

Child language data can be explained by a unidirectional OT model whereas adult language data can be explained by bidirectional OT. In this study it is investigated how children learn to use the bidirectional OT model by starting from a unidirectional OT model. Therefore an ACT-R model is implemented that models the transition. Bidirecional OT is modeled by the serial processing of unidirectional interpretation and production OT. It is assumed that children lack time to produce a bidirectional optimal meaning or form and therefore produce unidirectionally optimal data. By means of automization the processing of language by the children gains efficiency. It can be concluded that the implemented transition is a possible way in which children learn bidirectional OT.

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# APPENDIX

These are the production rules of the model code. The input exists of a pronoun or a reflexive.

If an utterance is being met, start interpreting by retrieving a relevant candidate.

```
(P start_int
        =goal>
                isa                     language_fact
                input                   =input
                function                =function
                process                 nil
                state                   start
                time                    t
==>
        =goal>
                process                 interpretation
                state                   get_candidate
        +retrieval>
                isa                     candidate
                function                =function
                relevant_for            interpretation
                :recently-retrieved     nil
)
```

If an utterance must be produced, start by retrieving a relevant candidate.

```
(P start_prod
        =goal>
                isa                     language_fact
                input                   =input
                function                =function
                process                 production
                original_input          =or_input
                state                   start
                time                    t
==>
        =goal>
                state                   get_candidate
        +retrieval>
```

```
        isa             candidate
        function        =function
        relevant_for    production
)
```

If one candidate is being retrieved, retrieve a second candidate.

```
(P cand1
        =goal>
                isa                     language_fact
                function                =function
                process                 =process
                state                   get_candidate
                time                    t
        =retrieval>
                isa                     candidate
                cand                    =cand
==>
        =goal>
                cand1                   =cand
                state                   getcand2
        +retrieval>
                isa                     candidate
                function                =function
                relevant_for            =process
                - cand                  =cand
                :recently-retrieved     nil
)
```

If two candidates are being retrieved, retrieve the first constraint.

```
(P cand2
        =goal>
                isa                     language_fact
                function                =function
                cand1                   =val
                state                   getcand2
                time                    t
        =retrieval>
                isa                     candidate
                cand                    =cand
                - cand                  =val
==>
        =goal>
                cand2                   =cand
                state                   getoptimal
```

```
        +retrieval>
                isa                     constraint
                ranking                         first
                function                =function
)
```

If the first constraint does not violate one of the candidates, retrieve the second constraint.

```
(P evaluation_eq1
        =goal>
                isa                     language_fact
                function                =function
                cand1                   =val1
                cand2                   =val2
                state                   getoptimal
                time                    t
        =retrieval>
                isa                     constraint
                ranking                 first
                violates                =violates
==>
        =goal>
                state                   getoptimal
        +retrieval>
                isa                     constraint
                ranking                 second
                function                =function
)
```

If the second constraint does not violate one of the candidates, retrieve the third constraint.

```
(P evaluation_eq2
        =goal>
                isa                     language_fact
                function                =function
                cand1                   =val1
                cand2                   =val2
                state                   getoptimal
                time                    t
        =retrieval>
                isa                     constraint
```

```
            ranking             second
            violates            =violates
==>
        =goal>
            state               unsolved
        +retrieval>
            isa                 constraint
            ranking             third
            function            =function
)
```

If the constraint violates the first candidate, mark the second candidate as optimal and retrieve the next candidate.

```
(P evaluation_diff
        =goal>
            isa                 language_fact
            function            =function
            process             =process
            cand1               =val1
            cand2               =violates
            state               getoptimal
            time                t
        =retrieval>
            isa                 constraint
            violates            =violates
==>
        =goal>
            optimal             =val1
            state               nextcandidate
        +retrieval>
            isa                 candidate
            function            =function
            relevant_for        =process
            - cand              =val1
            - cand              =violates
            :recently-retrieved nil
)
```

If the constraint violates the second candidate, mark the first candidate as optimal and retrieve the next candidate.

```
(P evaluation_diff2
        =goal>
                isa                     language_fact
                function                =function
                process                 =process
                cand1                   =violates
                cand2                   =val2
                state                   getoptimal
                time                    t
        =retrieval>
                isa                     constraint
                violates                =violates
==>
        =goal>
                optimal                 =val2
                state                   nextcandidate
        +retrieval>
                isa                     candidate
                function                =function
                relevant_for            =process
                - cand                  =val2
                - cand                  =violates
                :recently-retrieved     nil
)
```

If no candidate can be retrieved at all an output cannot be given.

```
(P no_candidate1
        =goal>
                isa                     language_fact
                input                   =input
                state                   get_candidate
        ?retrieval>
                state                   error
==>
        =goal>
                optimal                 nil
                original_input          =input
                state                   forced_output
)
```

If a second candidate cannot be retrieved, mark the first candidate as being optimal. Note that this is a forced choice!

```
(P no_candidate2
        =goal>
                isa                     language_fact
                cand1                   =cand
                state                   getcand2
        ?retrieval>
                state                   error
==>
        =goal>
                optimal                 =cand
                state                   done_uni
)
```

If a constraint cannot be retrieved, mark an arbitrary candidate as being optimal. This is also a forced choice situation!

```
(P no_constr12
        =goal>
                isa                     language_fact
                cand1                   =cand1
                cand2                   =cand2
                state                   getoptimal
        ?retrieval>
                state                   error
==>
        =goal>
                optimal                 =cand1
                state                   done_uni
)
```

If no next candidate can be retrieved, the unidirectional optimal interpretation is found.

```
(P no_next_candidate
        =goal>
                isa                     language_fact
                process                 interpretation
                optimal                 =optimal
                state                   nextcandidate
                time                    t
        ?retrieval>
```

```
            state                   error
==>
        =goal>
            state                   done_uni
)
```

If there are no constraints left to be retrieved, mark an arbitrary candidate as being optimal and retrieve a next candidate.

```
(P no_next_constraint
        =goal>
            isa                     language_fact
            function                =function
            process                 =process
            cand1                   =val1
            cand2                   =val2
            state                   unsolved
            time                    t
        ?retrieval>
            state                   error
==>
        =goal>
            optimal                 =val2
            state                   nextcandidate
        +retrieval>
            isa                     candidate
            function                =function
            relevant_for            =process
            - cand                  =val1
            - cand                  =val2
            :recently-retrieved     nil
)

(P no_next_constraint2
        =goal>
            isa                     language_fact
            function                =function
            process                 =process
            cand1                   =val1
            cand2                   =val2
            state                   unsolved
```

```
            time                    t
        ?retrieval>
            state                   error
==>
        =goal>
            optimal                 =val1
            state                   nextcandidate
        +retrieval>
            isa                     candidate
            function                =function
            relevant_for            =process
            - cand                  =val1
            - cand                  =val2
            :recently-retrieved     nil
)
```

If no next candidate can be retrieved, the unidirectional optimal interpretation is found. Find the bidirectional optimal interpretation.

```
(P bidirectional
        =goal>
            isa                     language_fact
            process                 interpretation
            input                   =input
            optimal                 =optimal
            state                   nextcandidate
            time                    t
        ?retrieval>
            state                   error
==>
        =goal>
            input                   =optimal
            original_input          =input
            state                   function
)
```

If the unidirectional optimal interpretation is found, find the bidirectional optimal interpretation.

```
(P bidirectional2
        =goal>
            isa                     language_fact
```

```
            process             interpretation
            input               =input
            optimal             =optimal
            state               done_uni
            time                t
      ?retrieval>
            state               error
==>
      =goal>
            input               =optimal
            original_input      =input
            state               function
)
```

If you were interpreting, start producing.

```
(P function1
      =goal>
            isa                 language_fact
            input               =input
            optimal             pronoun
            original_input      =val
            state               function
            time                t
==>
      =goal>
            function            disjoint
            process             production
            state               start
)
```

If you were interpreting, start producing.

```
(P function2
      =goal>
            isa                 language_fact
            input               =input
            optimal             reflexive
            original_input      =val
            state               function
            time                t
==>
```

```
        =goal>
                function                coreferential
                process                 production
                state                   start
)
```

If no next candidate can be retrieved and the output is equal to the original input, than the interpretation is correct.

```
(P output_bi_pos
        =goal>
                isa                     language_fact
                process                 production
                optimal                 =val
                original_input          =val
                state                   nextcandidate
                time                    t
        ?retrieval>
                state                   error
==>
        =goal>
                state                   done_bi_pos
)
(spp output_bi_pos :success t)
```

If no next candidate can be retrieved and the output is not equal to the original input, than the interpretation is not correct.

```
(P output_bi_neg
        =goal>
                isa                     language_fact
                process                 production
                optimal                 =val
                - original_input        =val
                state                   nextcandidate
                time                    t
        ?retrieval>
                state                   error
==>
        =goal>
                state                   done_bi_neg
)
```

```
(spp output_bi_neg :failure t)

If the timelimit is reached, stop processing.
(P time-limit-reached
        =goal>
                isa                     language_fact
                time                    nil
==>
        =goal>
                state                   time-limit-reached
                time                    time-limit-reached
)
```