Modeling the Selective Effects of Slowed-Down Speech in Pronoun Comprehension

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1. Introduction

In this paper we discuss a computational cognitive model of children's well-known difficulties with pronoun comprehension (the so-called Delay of Principle B Effect, or DPBE). In this DPBE/ACT-R model, Hendriks and Spenader's Optimality Theoretic account (2005/2006) is implemented in the cognitive architecture ACT-R (cf., Hendriks, Van Rijn, & Valkenier, 2007). Hendriks and Spenader's OT account attributes the DPBE to children's inability as hearers to also consider the speaker's perspective. The cognitive model predicts that children are in principle able to consider the speakers' perspective but lack the processing efficiency to complete this process within the amount of time available for comprehension. We investigated this prediction of the DPBE/ACT-R model in a psycholinguistic experiment, in which children's pronoun comprehension at a normal speech rate was compared with their comprehension at a slower speech rate. By slowing down the speech rate, children are given more time for interpretation. Slowed-down speech was found to have a beneficial effect on children's pronoun comprehension, but only if the child displays a DPBE, thus supporting the hypothesis of the cognitive model.

2. Delay of Principle B Effect

The DPBE is a delay in the acquisition of pronoun comprehension, in comparison with reflexive comprehension. Research has shown that children are able to comprehend reflexive sentences, such as (1a), correctly from the age of 3;0 on, but show difficulties in the interpretation of pronoun sentences like (1b) up to the age of 6;6 (e.g., Chien & Wexler, 1990; Jakubowicz, 1984; Koster, 1993; Philip & Coopmans, 1996; Spenader, Smits, & Hendriks, 2009).

(1) a. The penguin is hitting himself with a pan.
    b. The penguin is hitting him with a pan.

Children showing the DPBE interpret the reflexive *himself* in (1a) as co-referring with the subject of the local clause, *the penguin*. However, they also incorrectly allow the pronoun *him* in (1b) to co-refer with *the penguin*, in addition to allowing *him* to refer to another antecedent present in the context. Thus pronouns seem to be ambiguous for children, whereas reflexives can only have a coreferential interpretation.

The adult use of reflexives and pronouns can be described by Principles A and B of Binding Theory (Chomsky, 1981). According to Principle A, the reflexive *himself* in (1a) has to co-refer with *the penguin*, because a reflexive must be bound in its local domain. Principle B prohibits the pronoun to co-refer with the subject of the local domain, because it requires a pronoun to be locally free. As a result, for adults the pronoun *him* in (1b) cannot refer to *the penguin*, and can only refer to another antecedent present in the context. So for adults pronouns can only have a disjoint interpretation, whereas for children pronouns can have both a coreferential and a disjoint interpretation.

In contrast to the *comprehension* of pronouns, children show adult-like behavior on the *production* of pronouns (e.g., De Villiers, Cahillane, & Altreuter, 2006; Spenader et al., 2009). Thus there seems to be a second asymmetry in the acquisition of pronouns, namely between comprehension and production. Several explanations have been proposed for children's errors in pronoun comprehension: a deficiency

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in pragmatic skills (e.g., Thornton & Wexler, 1999), working memory limitations (e.g., Reinhart, 2006) and the inability to optimize bidirectionally (Hendriks & Spenader, 2005/2006). In the next section, we discuss the explanation by Hendriks and Spenader in more detail.

3. Explanation of the DPBE

Hendriks, van Rijn and Valkenier (2007) developed a computational model accommodating Hendriks and Spenader's (2005/2006) account of the DPBE. This computational model was implemented within the cognitive architecture ACT-R (Anderson et al., 2004), a modeling environment that constrains simulation models to ensure psychological plausibility. This architecture has previously been used to model both developmental (e.g., Van Rijn, Van Someren, & Van der Maas, 2003) and language phenomena (e.g., Lewis & Vasishth, 2005). We built a refined implementation of the model of Hendriks et al. (2007), that enables us to derive more precise predictions with respect to the DPBE. We will refer to our model in this paper as the DPBE/ACT-R model. This section first discusses Hendriks and Spenader's explanation of the DPBE, then it describes the DPBE/ACT-R model and the section ends with a discussion of the predictions of the model regarding the DPBE.

3.1. OT explanation of the DPBE

Hendriks and Spenader (2005/2006) proposed an explanation of the DPBE within the framework of Optimality Theory (OT, Prince & Smolensky, 2004). Their explanation also accounts for the asymmetry between pronoun production and pronoun comprehension. OT is a linguistic framework that can be used in the domain of semantics to model the relationship between an utterance and its meaning (e.g., Blutner, 2000; Hendriks & De Hoop, 2001; Prince & Smolensky, 2004). Hendriks and Spenader argue that the meaning that is best expressed with a certain form from the *speaker's perspective* not necessarily is the correct interpretation for that form from the *hearer's perspective*. In the OT grammar, this asymmetry between production and comprehension can be accounted for by the presence of markedness constraints, which are direction-sensitive. As a result, they can have different effects in the speaker's direction and the hearer's direction of optimization. The pattern of forms and meanings defining the DPBE arises from two constraints in the OT grammar, namely PRINCIPLE A and REFERENTIAL ECONOMY:

(2) PRINCIPLE A: a reflexive must be bound in the local domain.

(3) REFERENTIAL ECONOMY:
Avoid full NPs » Avoid Pronouns » Avoid Reflexives

PRINCIPLE A is the violable version of Principle A of Binding Theory. REFERENTIAL ECONOMY is actually a constraint sub-hierarchy, which consists of several constraints. This hierarchy reflects a preference for less referential content. Since we will limit ourselves to pronouns and reflexives, and not discuss NPs, we can ignore the other two constraints and only consider AVOID PRONOUNS. This constraint expresses a preference for reflexives over pronouns. Importantly, AVOID PRONOUNS is direction-sensitive and is only effective in production. In comprehension, the form is already given and AVOID PRONOUNS does not distinguish between potential interpretations for this input form. PRINCIPLE A is direction-insensitive, because it determines that a reflexive should have a coreferential meaning and that a coreferential meaning should be expressed with a reflexive. Hence, this constraint has the same effect in production and comprehension.

In OT, the grammar consists of a set of violable constraints rather than inviolable rules. The candidate output that commits the least severe violations of the constraints is marked as the optimal candidate. A violation of a higher ranked constraint is more severe than several violations of lower ranked constraints. In the OT tableaux 1 and 2, children's interpretation of reflexives and pronouns is represented as a function of the two constraints in (2) and (3). In the tableaux, the constraints are ranked according to strength from left to right. In these tableaux, the symbol * means a violation of the constraint that is given at the top of the column and the symbol *! denotes a fatal violation. When children encounter a reflexive, they will assign it a coreferential interpretation, because a disjoint meaning violates PRINCIPLE A (illustrated in Tableau 1).

Tableau 1. Children's comprehension of reflexives
(☞ indicates an optimal candidate)

input: *reflexive*	PRINCIPLE A	AVOID PRONOUNS
a. ☞ coreferential		
b. disjoint	*!	

However, when children encounter a pronoun, PRINCIPLE A cannot differentiate between a coreferential and a disjoint interpretation. Furthermore, the constraint AVOID PRONOUNS does not have an effect in comprehension. As a consequence, both candidates are marked as optimal and guessing behavior is predicted for children, because pronouns are ambiguous (illustrated in Tableau 2).

Tableau 2. Children's comprehension of pronouns

input: *pronoun*	PRINCIPLE A	AVOID PRONOUNS
a. ☞ coreferential		
b. ☞ disjoint		

If children want to express a coreferential meaning, PRINCIPLE A is not violated by any of the candidate forms (see Tableau 3). However, AVOID PRONOUNS is violated by the use of a pronoun. As a result, a reflexive is the optimal form to express a coreferential meaning.

Tableau 3. Children's production of a coreferential meaning

input: *coreferential*	PRINCIPLE A	AVOID PRONOUNS
a. ☞ reflexive		
b. pronoun		*!

If children want to express a disjoint meaning with a reflexive, PRINCIPLE A is violated, but if they want to express a disjoint meaning with a pronoun, AVOID PRONOUNS is violated (see Tableau 4). In languages such as English and Dutch, PRINCIPLE A is higher ranked than AVOID PRONOUNS. Therefore, a pronoun must be used for expressing a coreferential meaning, although this form violates AVOID PRONOUNS.

Tableau 4. Children's production of a disjoint meaning

input: *disjoint*	PRINCIPLE A	AVOID PRONOUNS
a. reflexive	*!	
b. ☞ pronoun		*

To summarize, children only have knowledge of Principle A, which is a constraint of the grammar. Children do not have any knowledge of Principle B. Therefore, pronouns are ambiguous. However, children are able to produce pronouns correctly because of a general preference for forms with less referential content.

Adult language users do not show the same difficulties with pronoun comprehension that children have. So the crucial question is: how do children acquire their knowledge of Principle B? Hendriks and

Spenader (2005/2006) argue that adults show knowledge of Principle B because they can take into account the speaker's perspective, whereas children only consider their own perspective. Children's non-adult comprehension is modeled in OT as *unidirectional optimization*, that is optimization from form to meaning in comprehension and from meaning to form in production. In contrast, adults take into account both the perspective of the hearer and that of the speaker, which is formalized in OT as bidirectional optimization (Blutner, 2000). Using bidirectional optimization, a language user checks for every form-meaning pair *<f,m>* whether no other form-meaning pair exists with a better meaning for the same form *<f, m'>*, or a better form for the same meaning *<f', m>*. A form-meaning pair is marked as bidirectionally optimal if there does not exist a better form for the meaning of the pair or a better meaning for the form of the pair. Tableau 5 is a bidirectional OT tableau that describes the adult pattern of pronouns and reflexives. Adults are assumed to possessthe same grammar as children do, and therefore use the same constraints under the same ranking.

Tableau 5. Bidirectional optimization used for pronouns and reflexives

form-meaning pairs:	PRINCIPLE A	AVOID PRONOUNS
a. ☞ <reflexive, coreferential>		
b. <reflexive, disjoint>	*!	
c. <pronoun, coreferential>		*
d. ☞ <pronoun, disjoint>		*

Tableau 5 shows that the pair *<reflexive, coreferential>* is the only form-meaning pair that does not violate a constraint. As a consequence, *<reflexive, coreferential>* is marked as bidirectionally optimal, because there is no other form-meaning pair that satisfies the constraints better: the pair *<reflexive, disjoint>* violates PRINCIPLE A and the pair *<pronoun, coreferential>* violates REFERENTIAL ECONOMY. In addition, the pair *<pronoun, disjoint>* is also marked as bidirectionally optimal, because no other form-meaning pair exists with a better meaning for a pronoun, or with a better form to express a disjoint meaning: the pair *<pronoun, coreferential>* violates the same constraint, therefore this pair is equally good; and the pair *<reflexive, disjoint>* violates PRINCIPLE A, therefore this pair is less good. So bidirectional optimization blocks the coreferential meaning as the interpretation of a pronoun, because there is a better way to express a coreferential meaning, namely by using a reflexive. As a consequence, pronouns are not ambiguous for adults.

In summary, the OT account of the DPBE explains children's pattern of comprehension and production as resulting from unidirectional optimization, which is a formalization of the idea that children only consider their own perspective. The adult pattern can be explained by bidirectional optimization, which formalizes the idea that adults take into account the opposite perspective in addition to their own perspective. In this account, Principle B is a derived effect, resulting from bidirectional optimization.

3.2. Cognitive model of the DPBE

Although the OT account of the DPBE provides an adequate description of the DPBE, it does not explain what prevents children from using bidirectional optimization. To investigate the acquisition of adult-like behavior with respect to pronoun comprehension, the OT account of Hendriks and Spenader (2005/2006) is implemented in a computational cognitive model. This computational model is built in the cognitive architecture ACT-R (Adaptive Control of Thought-Rational; Anderson et al., 2004). ACT-R is both a theory of cognition and a modeling environment. As a theory of cognition, its aim is to explain human cognition and to account for a broad range of data from psychological and neurocognitive experiments. ACT-R also is a modeling environment that can be used to implement a computational simulation of a specific task. The architecture constrains these simulation models to ensure psychological plausibility. The constraints imposed on the models are based on experimental data and define how information is processed, stored and retrieved within modules, and how information is communicated between modules (Anderson, 2007). ACT-R distinguishes several modules that are involved in different aspects of human cognitive functioning. The two main modules of ACT-R are declarative memory and the central production system. Declarative memory contains chunks of factual information. The central production system contains IF-THEN rules. At each time step, the central production system applies the production rule of which all constraints in the IF-part are satisfied. If there are multiple production rules that match the current state, the most active rule is selected. The THEN-clause typically contains instructions to the modules to perform certain actions, for example, retrieve a chunk from memory, or initiate a key press (Anderson et al., 2004; Taatgen, Lebiere, & Anderson, 2006).

The DPBE/ACT-R model simulates production as an optimization process from the input meaning to the optimal form to express that meaning, and it simulates comprehension as an optimization process from the input form to the optimal meaning of that form. This way, the model simulates both comprehension and production. Chunks in declarative memory represent the constraints PRINCIPLE A and REFERENTIAL ECONOMY and the candidates (i.e., the forms and their possible meanings). In an optimization process, the model first retrieves two candidates on the basis of the input form or meaning and then retrieves a constraint to evaluate these candidates. The two candidates are first evaluated by the highest ranked constraint, PRINCIPLE A. If one of the candidates violates this constraint, another candidate is retrieved from declarative memory to replace this candidate, and another evaluation process is started. If there is no other candidate, the remaining candidate will be selected as the optimal meaning. Only when PRINCIPLE A cannot distinguish between two candidates, REFERENTIAL ECONOMY is retrieved as the next constraint, and the candidates are evaluated on the basis of this constraint. The output of the optimization process is the optimal candidate. If no unique candidate has been found, the model randomly selects one of the optimal candidates as the output.

Bidirectional optimization is implemented as two serial processes of unidirectional optimization, illustrated schematically for comprehension in Figure 1:

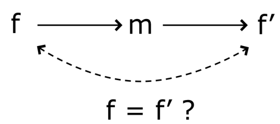

Figure 1. Bidirectional optimization in comprehension: taking into account the speaker's perspective.

In comprehension, the DPBE/ACT-R model first uses unidirectional optimization for optimizing from form to meaning, and then uses another step of unidirectional optimization for optimizing in the opposite direction, from meaning to form. If the model determines in the second step that another form *f'* is a better form for expressing the selected meaning *m* than is the original input form *f*, then the form-meaning pair <*f*, *m*> is not bidirectionally optimal and a new optimization process is started. By using this bidirectional optimization process, pronouns are disambiguated. When the model encounters a pronoun while simulating a hearer, first the optimal meaning for a pronoun is determined using unidirectional optimization. Because a pronoun is ambiguous, randomly one of the two optimal interpretations is selected and marked as the optimal candidate interpretation. If a coreferential meaning is selected for the pronoun, the model discovers in the second step that a reflexive is the optimal form for expressing a coreferential interpretation. So the resulting form (a reflexive) is different from the encountered form (a pronoun). As a consequence, the model will conclude that the speaker could not have intended a coreferential meaning by using the pronoun. In this way the coreferential meaning is blocked for pronouns. On the other hand, if a disjoint meaning is selected as the optimal interpretation of a pronoun, the model discovers in the second step that a disjoint meaning is expressed with a pronoun, validating the disjoint meaning as the optimal interpretation for a pronoun. Note that bidirectional optimization can also be used in production. In that case, the first step would consist of optimization from meaning to form and the second step of optimization from form to meaning (i.e., the two processes in Figure 1 in opposite order). However, when producing a pronoun or reflexive, bidirectional optimization does not lead to different behavior, because of the effects of the two constraints. This is also true for reflexive comprehension.

3.3. Predictions of the DPBE/ACT-R model

The main prediction of the DPBE/ACT-R model is that children, although they already know how to optimize bidirectionally, lack the processing efficiency to perform bidirectional optimization in the allotted time. This prediction of the DPBE/ACT-R model follows from the fact that in the model bidirectional optimization initially takes more time than unidirectional optimization, because bidirectional optimization is simulated as two consecutive processes of unidirectional optimization. An assumption of ACT-R that is important for this study is the assumption that every cognitive operation takes a certain amount of time. The amount of time available for bidirectional optimization is limited, because the speaker determines the speed of the speech directed to children. If children's speed of processing is not fast enough to perform two processes of unidirectional optimization within the given amount of time, pronouns remain ambiguous and a guessing pattern emerges. This is illustrated schematically in Figure 2a.

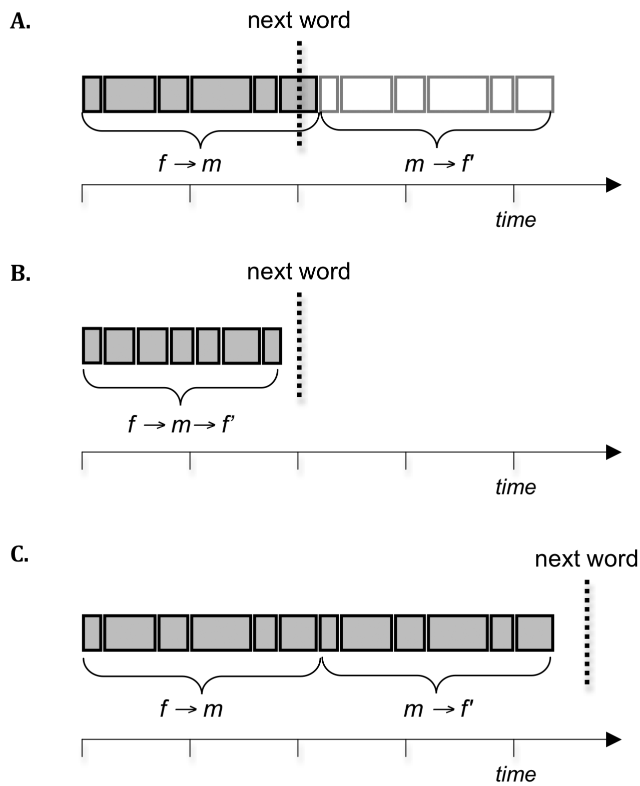

Figure 2. Schematic illustration of the predictions of the DPBE/ACT-R model: a.) Children do not have sufficient time to complete bidirectional optimization; b.) Adults can complete bidirectional optimization within the limited amount of time, because their processing is more efficient; c.) Children can complete bidirectional optimization if they have more time for interpretation. The blocks represent the cognitive operations involved in pronoun interpretation.

In contrast, the model predicts that adults are able to complete bidirectional optimization, because their processing has become more efficient. In ACT-R, higher processing efficiency can be obtained through the production compilation mechanism (Taatgen & Anderson, 2002). Production compilation is a learning mechanism that makes a process more efficient when it is repeatedly performed. Eventually, children's unidirectional optimization processes are performed fast enough so that two unidirectional processes can be completed in the given time, resulting in bidirectional optimization. As soon as this is achieved, pronouns are correctly disambiguated (see Figure 2b).

So the DPBE/ACT-R model assumes that children have the ability to optimize bidirectionally, but just lack the processing efficiency to do so. As a result, the model predicts that when children who show the DPBE are given more time, their performance on pronoun interpretation will improve (see Figure 2c). However, children who do not show a DPBE anymore are not expected to benefit from slowed-down speech, because they are already able to interpret pronouns correctly. In conclusion, the model predicts that children's speed of processing is the factor that determines whether children show the DPBE.

4. Experimental design

In this study we investigate the prediction that children's performance on pronoun interpretation will increase when they are given more time for interpretation. We hypothesize that the performance of children who show the DPBE will increase as an effect of slowed-down speech, while the performance on reflexive interpretation will remain the same.

4.1. Methods and materials

To test the comprehension of pronouns and reflexives, a Truth Value Judgment Task was used, in which the Dutch children had to judge whether a presented sentence is a correct description of a picture that is shown on the computer screen. An example of a test sentence is presented in (4).

(4) Kijk, een pinguïn en een schaap zijn op de stoep.
De pinguïn slaat hem / zichzel met een pan.
'Look, a penguin and a sheep are on the sidewalk.
The penguin is hitting him / himself with a pan.'

The verbs that were used are *bijten* (to bite), *kietelen* (to tickle), *schminken* (to make up), *wijzen naar* (to point at), *slaan* (to hit) and *vastbinden* (to tie up). All verbs are more likely to be used to describe an other-directed action, thus avoiding a bias towards a coreferential interpretation (Spenader et al., 2009). In the two speech rate conditions of the experiment the same verbs were used, but the sentences differed between conditions in the choice of actors and instruments.

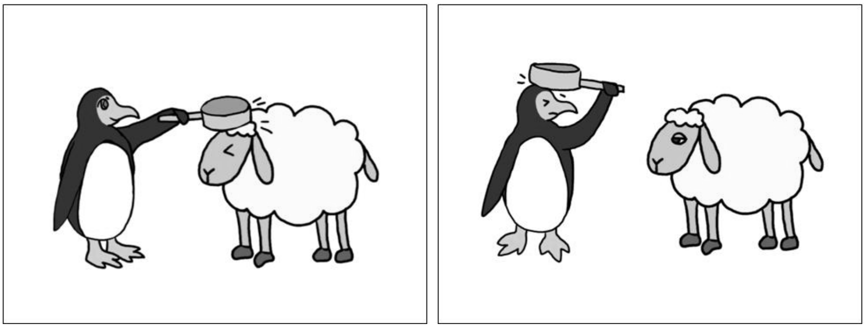

Figure 3. The pictures that were presented with the sentences in (4).

Half of the sentences were combined with a matching picture and the other half were presented with a non-matching picture (see Figure 3). Each picture showed two cartoon-like characters. Both animals were drawn in approximately the same size, to avoid a difference in saliency present in some earlier experiments (see Elbourne, 2005, for a discussion).

The sentences were prerecorded at a normal speech rate. Sentences for the slow speech rate condition were digitally slowed-down using the software Adobe Audition 1.5, while keeping the pitch constant. The mean speech rate of the normal speech rate sentences was 4.0 syllables per second. The slow speech rate sentences were stretched 1.5 times, resulting in a mean speech rate of 2.7 syllables per second. These speech rates are comparable with the normal and slow speech rates reported for English (e.g., Montgomery, 2004; Weismer & Hesketh, 1996). Every participant was tested in both who speech rate conditions. Each condition contained 8 pronoun sentences and 8 reflexive sentences. In addition to the test sentences four control sentences per condition were used.

4.2. Participants

Seventy-five children between 4;1 and 6;3 years from a Dutch local elementary school were tested. From these children, 13 were excluded from further analysis because they were not monolingual Dutch speakers, did not finish the task or answered more than two out of eight control items incorrectly. The data of the remaining 62 children (35 boys and 27 girls), ranging in age from 4;1 to 6;2, was used for statistical analysis.

5. Results

Figure 4 shows the percentage of correct interpretations of reflexives and pronouns for all 62 participants.

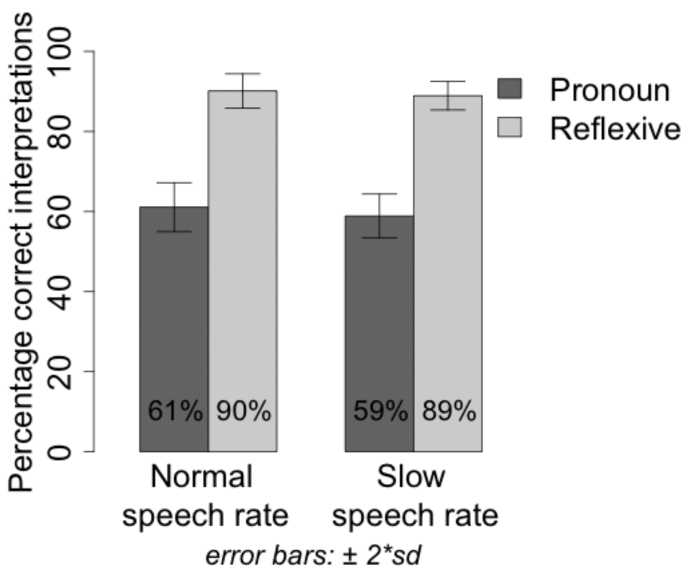

Figure 4. Mean percentage correct interpretations on pronoun and reflexive sentences in the two speech rate conditions. Data of 62 participants.

Figure 4 shows a clear difference between the percentage of correct interpretations on pronoun and reflexive sentences in both speech rate conditions. Only a few errors are made on reflexive sentences (normal speech rate: 90%, slow speech rate: 89%), while the performance on pronoun interpretation is just above chance level (normal speech rate: 61%, slow speech rate: 59%). This difference in comprehension is found to be significant (normal speech rate: paired $t(61) = 8.9$, $p = .000$; slow speech rate: paired $t(61) = 9.5$, $p = .000$). However, from this figure almost no difference can be seen between the two speech rate conditions. Statistical analysis showed no significant effect of speech rate.

The main question of our experiment is whether children who show the DPBE will benefit from slowed-down speech in pronoun comprehension. Therefore, we should establish whether all children indeed show the DPBE. To this end, we classified the participants in different groups based on their task performance. For the details of this classification, see Van Rij, Hendriks, Spenader, and Van Rijn (2009). From the 62 participants, 34 children (19 boys and 15 girls; age 4;1-6;2, mean 4;11) were found to show the DPBE. From the children that did not show the DPBE, 14 children (9 boys and 5 girls; age 4;2-6;0, mean 5;5) showed (almost) correct performance on both pronoun and reflexive sentences. Furthermore, 5 children (3 boys, 2 girls; age 4;3-4;7; mean 4;5) not only showed incorrect performance on pronoun sentences (less than 80% correct interpretations), but alsomade as many or even more errors with reflexives. Finally, 9 children (3 boys, 6 girls; age 4;10-6;2; mean 5;7) showed incorrect performance on pronoun sentences by using the extra-grammatical strategy of answering ‘yes’ to all pronouns. We leave these three groups of children out of consideration in this paper and focus on the 34 children who show a typical DPBE pattern.

5.1. Pronoun comprehension of children that show the DPBE

Figure 5 displays the percentages of correct pronoun (left) and reflexive (right) interpretations of the children who show the DPBE in the two speech rate conditions.

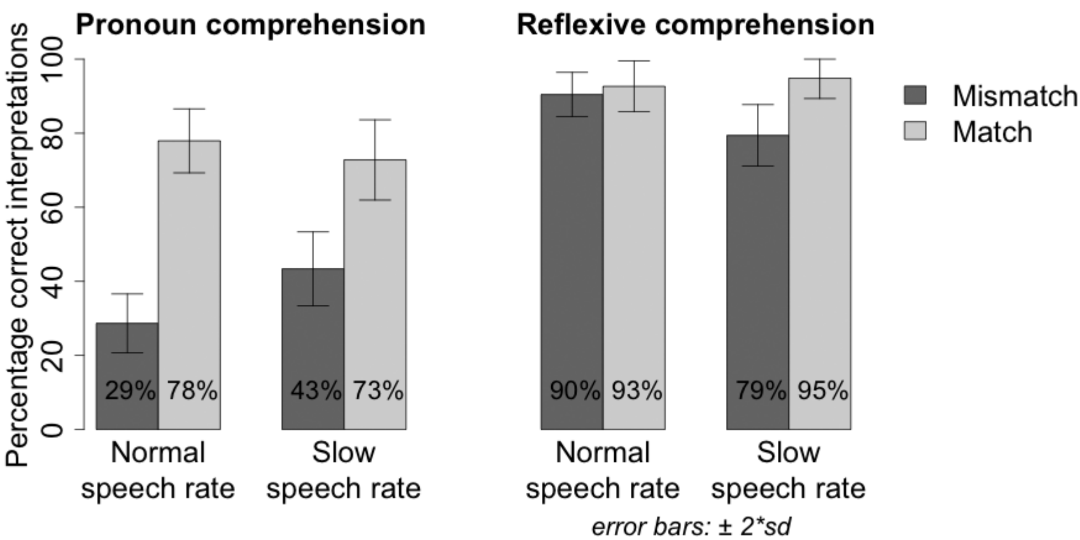

Figure 5. Mean percentage correct interpretations on pronoun sentences (left) and reflexive sentences (right) in the two speech rate conditions, divided in match and mismatch trials. Data of the 34 participants that show the DPBE.

For the children showing the DPBE, a difference is seen between their performance on pronoun and reflexive sentences (see Figure 5). Furthermore, Figure 5 shows that there is a clear difference in performance on pronoun sentences between match and mismatch trials. This difference is statistically significant in both conditions (normal speech rate: paired $t(33)=8.596$, $p<0.001$; slow speech rate: paired $t(33)=3.811$, $p<0.001$).

To investigate whether slowed-down speech has a significant positive effect on pronoun comprehension, a repeated measures ANOVA was performed on the arcsine transformation of the proportion correct interpretations. The included within-subject factors were: *Expected Answer* (type of test sentence: match or mismatch with picture), and *Speech Rate* (normal or slow). Because the sequence of the two speech rate conditions was counterbalanced across participants, the between-subjects factor *Block* was also included, specifying the sequence of the speech rate conditions (normal speech rate condition first versus slow speech rate condition first). The statistical analysis showed a marginal significant interaction between Expected Answer and Speech Rate ($F(1,33)=3.904$; $p=0.057$), and a significant main effect of Expected Answer ($F(1,33)=54.436$; $p<0.001$). The significant effect of Expected Answer reflects children’s yes-bias, a tendency to answer ‘yes’ over ‘no’ when the answer is not certain (e.g., Chien & Wexler, 1990). Because children are assumed to say ‘no’ only when they are highly certain about the answer, it makes sense to focus on the pronoun mismatch items. Figure 5 shows a difference in performance on pronoun mismatch items between the speech rate conditions (normal speech rate: 29%; slow speech rate: 43%). This difference is statistically significant (paired $t(33)=-2.512$; $p=0.017$). In contrast, no significant difference between the two speech rate conditions (normal speech rate: 78%; slow speech rate: 73%) was found on match items (paired $t(33)>0.1$). In general, it can be concluded that slowed-down speech has a significant beneficial effect on pronoun comprehension.

5.2. *Reflexive comprehension of children that show the DPBE*

Although the focus in this study is on the performance on pronoun interpretation, the performance on reflexive interpretation was analyzed too. A repeated measures ANOVA on the arcsine transformed data (within-subjects factors *Expected Answer* and *Speech Rate*, between-subjects factor *Block*) showed a marginal significant interaction between Expected Answer and Speech Rate ($F(1,32)=3.904$; $p=0.090$) and significant interaction effects of Expected Answer and Block ($F(1,32)=8.941$; $p=0.005$) and Speech Rate and Block ($F(1,32)=11.082$; $p=0.002$). Also a significant main effect of Expected Answer was found ($F(1,32)=8.941$; $p=0.005$). Figure 5 shows that the performance on the mismatch sentences decreases in the slow speech rate condition, while the performance on the match sentences remains the same. When we analyzed the mismatch reflexive sentences with a repeated measures ANOVA (within-subject variable *Speech Rate*, between-subject variable *Block*), we found a significant interaction effect of Speech Rate and Block ($F(1,32)=6.594$; $p=0.015$) and a significant main effect of Speech Rate ($F(1,32)=4.169$; $p=0.049$). So the decrease in performance is significant. We found no significant differences between the speech rate conditions, when analyzing the match sentences ($p > 0.1$).

To summarize, slowed-down speech has a significant beneficial effect on children's pronoun comprehension and a significant detrimental effect on reflexive interpretation. However, the latter effect is probably an experimental artifact, since the analysis showed a significant interaction effect with the sequence of the experimental conditions. Children who started the experiment with the Slow Speech Rate condition performed worse on reflexive comprehension in slowed-down speech than children who first participated in the Normal Speech Rate condition. So children have some difficulties with the slowed-down speech, but this effect disappeared when they got used to the task. In the pronoun comprehension data no significant effects of the order of the experimental conditions were found. Therefore we conclude that if the child displays the DPBE, slower speech rate has a beneficial effect on children's comprehension of pronouns, but not on children's comprehension of reflexives.

6. Discussion

The aim of this study was to investigate the predictions that followed from the DPBE/ACT-R model. According to the model, the DPBE arises because children do not have sufficient time to take into account the perspective of the speaker. It is predicted that if these children are given more time, their performance will improve. In our study, we found that a slower speech rate indeed has a beneficial effect on children's comprehension of pronouns, but only if the child displays a DPBE. Furthermore, the beneficial effect of slowed-down speech is only found for pronoun comprehension, and not for reflexive comprehension. The results of the experiment support the predictions of our DPBE/ACT-R model. If children do not display a DPBE anymore, no improvement is expected because children's processing is expected to already be fast enough. Furthermore, bidirectional optimization is not necessary for correct performance on reflexive comprehension. Therefore, even if little time is available (as in the normal speech rate condition), children will already be able to interpret reflexives correctly.

From the results of this study, it can be concluded that children in principle know how to interpret pronouns. However, due to their processing limitations they are unable to do so. It is difficult to explain these findings within other accounts of the DPBE. If the DPBE is caused by a lack of pragmatic skills, as proposed by Thornton and Wexler (1999), it remains unexplained how slowing down the speech rate would provide children with the necessary pragmatic skills or the ability to use these skills to interpret pronouns correctly. Another account that attributes the DPBE to processing limitations is proposed by Reinhart (2006). She argues that children are unable to comprehend pronouns correctly due to working memory limitations. However, it is difficult to determine what the effect of slowed-down speech is on working memory. So it remains unclear whether Reinhart's (2006) account would predict an increase or decrease in performance on pronoun comprehension due to slowed-down speech.

In addition, this study illustrates that combining assumptions and predictions of the OT framework with assumptions and predictions of the cognitive architecture ACT-R gives rise to very specific and testable claims with respect to language development. The OT account of the DPBE (Hendriks & Spenader, 2005/2006) assumes that the DPBE is caused by direction-sensitive constraints, which have different effects on production and comprehension. As a result, pronouns are ambiguous for children. In contrast, pronouns are not ambiguous for adults, because adults take into account the speaker's perspective and thus are able to block one of the meanings. By combining the OT account with assumptions about cognitive processes and the time they take to perform, it is possible to test this theoretical OT account empirically. The cognitive architecture ACT-R imposes additional restrictions on the explanation of the DPBE because the proposed explanation also has to satisfy the cognitive constraints that ACT-R imposes on cognitive models. For example, in bidirectional Optimality Theory, bidirectional optimization is generally defined as a condition on bidirectional optimal pairs (bidirectionally optimal form-meaning pairs are those pairs for which there does not exist a bidirectionally optimal pair with either a better form or a better meaning, cf., Blutner, 2000), not as a procedure to obtain these bidirectionally optimal pairs. Because ACT-R assumes that central processing is serial (i.e., the production system can perform only one action at a time), in our DPBE/ACT-R model bidirectional optimization is simulated as two serial processes of unidirectional optimization. The result is a cognitively plausible procedure for determining whether a particular form or meaning is part of a bidirectionally optimal pair. From this procedure, but not from bidirectional optimization per se, it follows that bidirectional optimization takes more time to perform than unidirectional optimization. As a consequence, the interpretation of pronouns is predicted to take more time than the interpretation of reflexives.

7. Conclusion

In this study we investigated the effects of slowed-down speech on pronoun comprehension. Research has shown that children are able to comprehend reflexive sentences correctly from the age of 3;0 on, but show difficulties on the interpretation of pronoun sentences until the age of 6;6 (e.g., Chien & Wexler, 1990). Hendriks and Spenader (2005/2006) attributed this Delay of Principle B Effect (DPBE) to a direction-sensitive grammar in combination with children's inability to take into account the speakers perspective (bidirectional optimization). A computational cognitive model of the acquisition of pronoun comprehension, (based on Hendriks et al., 2007), predicts that children are unable to complete bidirectional optimization because of their limited speed of processing. In a psycholinguistic study we tested whether children's performance on pronoun comprehension increases when they have sufficient time for interpretation. We gave children more time for interpretation by slowing down the speech rate. Children's performance on pronoun comprehension at a normal speech rate was compared with their pronoun comprehension at a slower speech rate. We found that slower speech rate has a significant beneficial effect on children's comprehension of pronouns, but only if the child displays a DPBE. No beneficial effect of slowed-down was found on their reflexive comprehension. This supports the hypothesis of our cognitive model that the DPBE is caused by children's insufficient speed of processing.

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