Nature's distributional-learning experiment: Infants' input, infants' perception, and computational modeling

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SUMMARY IN ENGLISH: LEARNING SOUNDS FROM THE CLOUDS?

For many parents, their baby's language development really takes off with the production of the first word, even if the proud parents are the only ones that recognize a word in what others still perceive as a meaningless babble. In the months preceding this first word, the baby has already been a dedicated language learner. Much of the baby’s efforts have been spent on a challenge that parents often do not even realize to be a part of language acquisition: The acquisition of language-specific sound perception. Luckily, the parents do not need to be aware of their baby’s learning task to be excellent teachers. As long as they talk with their baby, their baby receives enough information to learn the language-specific properties of their language. This dissertation investigates how infants could learn language-specific sound perception from the speech they hear from their parents.

LEARNING ABOUT *man* and *maan*

What is language-specific sound perception? Native speakers of Dutch find it very easy to hear the difference between the words *man* and *maan* because these words have a different meaning in their language. One could object that speakers of Dutch hear the difference between the words *man* and *maan* simply because the vowels in the words sound different. However, the difference between the words *man* and *maan* is very difficult to hear for native speakers of Spanish because Spanish does not use this sound difference to signal a difference in meaning. That babies acquire language-specific sound perception implies that they learn which sound differences are important in their language (the *man*-vowel sound and the *maan*-vowel sound for a Dutch baby) and which sound differences they can ignore (the *man*-vowel sound and the *maan*-vowel sound for a Spanish baby).

The vowels in the words *man* and *maan* differ in vowel duration: The *man*-vowel is short and the *maan*-vowel is long. These vowels differ also in vowel quality: The *man*-vowel has a darker vowel quality and the *maan*-vowel has a more open vowel quality. In school, many native speakers of Dutch have learned to refer to the *man*-vowel as the ‘short a’ and to the *maan*-vowel as the ‘long a’. In perception, however, most native speakers of Dutch pay more attention to vowel quality to determine whether vowel sounds that fall somewhere in between these two typical sounds are more likely to be the *man*-vowel or the *maan*-vowel. This relative attention to the properties of the sound has been tested in speech perception experiments in laboratory settings.

Try this at home: Pronounce the *man*-vowel and the *maan*-vowel in front of the mirror. Do you see the different mouth shapes? Those determine the vowel quality.
and can also be tested at home. If you lengthen the word *man*, the vowel keeps the vowel quality of the *man*-vowel but gets the duration of the *maan*-vowel. Most native speakers of Dutch recognize such a lengthened *man* as the word *man* and do not think that the lengthening of the vowel changes the word to *maan*. This simple at-home experiment illustrates that Dutch listeners find vowel quality more important than vowel duration to determine whether they hear the *man*-vowel or the *maan*-vowel. This at-home experiment also highlights a second learning task for babies. They do not only need to learn which sound differences are important in their language but also which properties of the sounds are most important.

How do babies learn which sound differences are important in their language and how do they learn which properties of these sounds are most important? Babies cannot solve this learning task on the basis of word pairs such as *man* and *maan*, because they hardly know any words that only differ in one sound. Babies are endowed with a learning mechanism that can learn about sounds without any word knowledge. In combination with the properties of the sounds that babies hear, this learning mechanism explains that babies learn about the sounds of their native language very early in life. In my dissertation I have tested and found support for this idea in three closely integrated parts:

1. What are the sound properties of the *man*-vowel and the *maan*-vowel if Dutch mothers pronounce them to their baby?

2. Do Dutch babies hear the difference between the *man*-vowel and the *maan*-vowel and which sound properties do they use to hear it?

3. Can a computer baby with the learning mechanism that real babies are supposed to have learn about the *man*-vowel and the *maan*-vowel from the speech of real Dutch mothers and then hear the difference between the *man*-vowel and the *maan*-vowel in the same way as real Dutch babies do?

In the remainder of this summary, I will describe the research into these three research questions of my dissertation. When all three parts have been described, we know how Dutch infants learn that they need to hear the difference between the *man*-vowel and the *maan*-vowel.

**Part I: What are the sound properties of the *man*-vowel and the *maan*-vowel if Dutch mothers pronounce them to their baby?**

Even though I have been speaking of the *man*-vowel and the *maan*-vowel as some kind of constant entities, they actually sound different every time we hear them. To some extent, speakers can choose...
how they pronounce sounds. It has often been claimed that mothers choose to pronounce sounds very clearly to their baby, to highlight which sound differences are important in the language and help their baby’s acquisition of language-specific sound perception.

To test whether Dutch mothers highlight the difference between the man-vowel and the maan-vowel when they talk to their baby, I invited eighteen mothers to the Taallab in the Bungehuis. The mothers were asked to first play with their infant and then talk to an adult experimenter. The results of this study are reported in Chapter 2. Interestingly, these Dutch mothers did not pronounce speech sounds, such as the man-vowel and the maan-vowel, more clearly to their infant. On the contrary, they spoke more clearly to the adult experimenter! Fine analyses of the speech sounds showed that Dutch mothers smile a lot to their baby and when you are constantly smiling, it becomes difficult to articulate clearly. Dutch mothers adapt their speech to their baby in many ways, but they do not seem to help their baby to discover that the difference between the man-vowel and the maan-vowel is important in Dutch.

Or do they? In Chapter 3, I investigated the man-vowels and the maan-vowels of the mothers in some more detail to understand how infants might nevertheless learn something about these vowels. Of the over 700 man-vowels and maan-vowels that the 18 mothers together spoke to their baby, no two were identical. Of course, there are slight differences between speakers. On top of that it is impossible for a speaker to say exactly the same sound twice. All these man-vowels

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1 For the sake of comparability with previous research, only mothers were included in the present study. This choice does not imply that only mothers would provide valuable speech input to their baby.
and *maan*-vowels together are shown in figure A. In the left of these two figures, there is one cloud of *man*-vowels, which all have a relatively dark vowel quality and a relatively short duration. The second cloud in this figure is of the *maan*-vowels, which all have a relatively open vowel quality and a relatively long duration. Even in the figure on the right, which does not tell you which dots are *man*-vowels and which dots are *maan*-vowels, it is possible to squint your eyes and still see two clouds, a *man*-cloud and a *maan*-cloud.

Babies in laboratory experiments can learn from the clouds: They can listen to speech sounds that are all slightly different and discover how these can be grouped into clouds. Babies that have learned from the clouds ignore differences between speech sounds that belong to the same cloud and are extra sensitive to differences between speech sounds that belong to two different clouds. If infants indeed learn from the clouds in practice, they can discover the *man*-vowel and the *maan*-vowel by just listening to their smiling Dutch mother.

**Part II: Do Dutch babies hear the difference between the *man*-vowel and the *maan*-vowel and which sound properties do they use to hear it?**

Now that we know that Dutch infants could learn about the difference between the *man*-vowel and the *maan*-vowel by learning from the clouds of their mother, it is important to know what Dutch infants actually know about the difference between these two vowels.

![Figure B. The sound properties of the stimuli used in the experiments.](image-url)
To test this in speech perception experiments with infants, four vowel sounds were created. These vowel sounds can be seen in figure B, where they can be compared to the \textit{man}-vowels and the \textit{maan}-vowels that the mothers produced. The first vowel sound was a typical \textit{man}-vowel, with a dark vowel quality and a short duration. The second was a typical \textit{maan}-vowel, with an open vowel quality and a long duration. The third was an in-between vowel, with the dark vowel quality of the \textit{man}-vowel and the long duration of the \textit{maan}-vowel (the sound you get when you lengthen the word \textit{man}). The fourth was the opposite in-between vowel, with the open vowel quality of the \textit{maan}-vowel and the short duration of the \textit{man}-vowel (the sound you get when you say \textit{maan} with the shortest possible vowel).

**Figure C.** The explanation of the first listening task. The baby sits in front of a screen. She sees a checkerboard pattern and hears series of sounds. In some series the same sound is repeated (\textit{man}...\textit{man}...\textit{man}...) and other sound series are an alternation between two different sounds (\textit{man}...\textit{maan}...\textit{man}...\textit{maan}...). Babies enjoy change. Therefore, if they perceive the difference between \textit{man} and \textit{maan}, they look longer to the checkerboard during this series of sounds than during the series of repeated sounds. If they do not perceive the difference between \textit{man} and \textit{maan}, they look just as long to the checkerboard for the alternating sound series as for the repeated series. In order to find out whether babies perceive differences in vowel duration, they are played series of sounds in which only the vowel duration is changed (\textit{man}...lengthened-\textit{man}...\textit{man}...lengthened-\textit{man}). To find out whether babies perceive differences in vowel quality, I play them series of sounds in which only the vowel quality is changed (\textit{man}...shortened-\textit{maan}...\textit{man}...shortened-\textit{maan}). The results of this experiment showed that babies were interested in the alternation between typical \textit{man} and \textit{maan}, but not really in the sound series that alternated only one sound property. The conclusion from this result is that Dutch babies know that \textit{man} and \textit{maan} need to differ in two sound properties, vowel quality and duration.

In the first listening experiment, which is described in Chapter 3, I asked Dutch babies whether they heard the difference between one of...
the typical vowel sounds (the typical man-vowel or the typical maan-vowel) and the three other vowel sounds. Simply asking did not work, so I made use of a test to find out which sound differences the babies did and did not hear. This test is described in figure C.

The Dutch babies found it easy to hear the difference between the typical man-vowel and the typical maan-vowel. The babies did not really know what to do with the atypical vowel sounds (the lengthened man-vowel and the shortened maan-vowel). They seemed to think that these atypical vowel sounds could just as well belong to the man-cloud as to the maan-cloud. The babies did not seem to favour vowel quality or duration when listening to the man-vowel and the maan-vowel. When we look back at the specific values with which Dutch mothers say man-vowels and maan-vowels to their baby, we must conclude that the babies are completely right: The atypical vowel sounds from the experiment could belong to either cloud. The way in which Dutch babies hear the difference between the man-vowel and the maan-vowel is thus completely in agreement with the clouds of man-vowels and maan-vowels that Dutch mothers produce.

Try this at home (because adults are able to do this task!)
Shorten the vowel in the word maan. Do you hear man or do you hear maan?

Figure D. The explanation of the second listening task. The baby sits in front of a screen. She sees two boxes moving horizontally apart from each other and hears a series of three sounds: man...man...man or maan...maan...maan. After the third sound, something fun appears. The fun happens on the left after man and on the right after maan. In this way, the baby can learn to look left in reaction to man and right for maan. If the baby has learned the side–sound combinations, her reaction to the atypical sounds is interesting. A baby that pays attention to vowel quality will expect something on the man side after lengthened man and something on the maan after shortened maan. A baby that pays more attention to vowel duration will look to the maan side after lengthened man and to the man side after shortened maan. Because the babies did not follow the correct box for the typical sounds, man and maan, it is impossible to draw conclusions about their use of the sound properties.
In the second experiment, which is described in Chapter 4, I tried to ask Dutch infants to tell me more explicitly whether they think that the lengthened man-vowel and the shortened maan-vowel belong to the man-cloud or to the maan-cloud. The task I used to ask them this question is described in figure D. That task was too difficult for them. But infants were very engaged in the task, so we could measure their general interest in the four vowel sounds. The older infants in the experiment, who were all around 15 months old, were especially interested in one of the atypical vowel sounds, the lengthened man-vowel. When we look back again at man-cloud and the maan-cloud in the speech of the Dutch mothers we must conclude that the babies are completely right again: Mothers almost never say sounds like the lengthened man-vowel, so it is no wonder that infants are surprised when they hear it. The fact that only the babies of 15 months old and not the 9-month-olds reacted surprised to the lengthened man-vowel shows that it takes infants quite some time to discover what happens at the boundaries of the clouds. At 15 months, Dutch babies have clearly learned a great deal about the specific shape of the man-cloud and the maan-cloud in the speech of their Dutch mothers.

Part III: Can a computer baby with the distributional-learning mechanism that real babies are supposed to have learn about the man-vowel and the maan-vowel from the speech of real Dutch mothers and then hear the difference between the man-vowel and the maan-vowel in the same way as real Dutch babies do?

As real Dutch babies learn from their real Dutch mothers about man-vowel and the maan-vowel, what are computer babies doing here? To motivate the third part of my dissertation, I need to convince you that the mechanism learning from the clouds not only answers questions about how infants could learn the difference between sounds, but also opens the way for many, many new questions. How exactly do infants observe the clouds? They cannot look at a picture of 700 sounds, but hear the sounds one by one. And how exactly do infants store the clouds in their memory? It would be inefficient for them to just remember all 700 words in the clouds, but that implies they do not store the clouds at all! Questions such as these, especially when they contain the word ‘exactly’, can be answered with the use of computer babies.
Try this at home: do you see the two curves in Gaussian brains and do you see the two stable reactions in the neural network brains?

**Figure E. The explanation of the computer babies.** Half of the computer babies were given Gaussian brains (on the left). Babies with Gaussian brains represent a vowel as a function that indicates for each possible value of the sound property how probable it is that the vowel has that specific value. Two such vowels in a Gaussian brain are the two curves in the figure. The other half of the computer babies were given neural network brains (on the right). Babies with neural network brains hear on the bottom row of network nodes the values of a sound property and react to those values with a pattern on the top row of nodes. The vowels are the stable reactions in the top row across slightly different values in the bottom row. Two such vowels in a neural network brain are the two top-row patterns in the figure. In this figure, the baby brains connect each vowel to only one sound property. To successfully learn the *man*-vowel and the *maan*-vowel, the baby brains had to connect each vowel to two sound properties, that is, to both vowel quality and duration.

Computer babies, by the virtue of having computer brains, can only learn from the clouds if they receive very exact instructions regarding the workings of this learning mechanism. In Chapter 5, two different types of computer babies were built, representing two ideas of how infants might actually go about learning from the clouds. Figure E shows an example of the two types of computer babies. Both types of computer babies were able to learn the *man*-vowel and the *maan*-vowel from the 700-or-so vowel sounds as spoken by the real Dutch mothers. And both types of computer babies reacted to the test sounds in largely the same way as the real Dutch infants did. These results from the exact computer babies confirm the idea that learning from the clouds helps babies to learn about the differences between speech sounds, such as the *man*-vowel and the *maan*-vowel. At the same time, we have gained a much more precise understanding of the idea learning from the clouds, as we have access to no fewer than two possible descriptions of this learning mechanism.
Conclusion and implications

In this dissertation, I have shown that Dutch infants can learn about the *man*-vowel and the *maan*-vowel by just listening to the vowel sounds that their mothers say. Dutch mothers do not pronounce the *man*-vowel and the *maan*-vowel very clearly for their language-learning baby, because they are too busy playing and smiling. And that is not a problem. The learning mechanism of the babies is sufficiently powerful that they do not need to be taught about the *man*-vowel and the *maan*-vowel. Babies take care of it themselves.