Development in the

Bilingual Interactive Activation Model:

Simulations of L1 and L2 Acquisition

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Abstract

The word learning performance of monolinguals and early and late bilinguals was simulated using the Bilingual Interactive Activation (BIA) model by Dijkstra and Van Heuven (2002), a model for visual word recognition. Increasingly large lexicons with increasing frequencies were used to simulate language acquisition in seven discrete developmental steps. When a particular word from a second language (L2) was assumed to be learned in a particular developmental step, it was incorporated in a lexicon shared with words of the first language (L1). For all words in the integrated lexicon, the word recognition time cycles were simulated. Five simulation studies were done, compared to each other, and statistically analyzed. The languages for simulations were Dutch and English. It was found that learning an L2 had an influence on the word recognition performance of the already known L1. Learning English as L2 had a negative effect on processing Dutch as L1, but learning Dutch as L2 had a positive effect on processing English as L1. Knowing an L1 had a negative influence on acquiring a L2; and learning an L2 early was more efficient than learning it later. However, the observed influences were surprisingly small.

Keywords: Bilingual Interactive Activation (BIA) model; visual word recognition; L1 and L2 acquisition; simulations; monolingual; early bilingual; late bilingual.

1. Introduction

In 2005, a special issue of *Science* was published to celebrate the journal's 125th anniversary. *Science* came up with 125 important questions to which scientists do not know the answer yet. In the next 25 years these questions should be answered or it must be known how to answer the questions (Kennedy & Norman, 2005, p. 75). One of those questions is: "Why are there critical periods for language learning?" (Kennedy et al., 2005, p. 92). In times of globalization, learning a first or second language is a very important issue. It is still not known why children pick up languages more easily than adults, and how this affects the acquisition of the first language (L1) relative to the second (L2). More research into learning a language is clearly needed.

The usual moment to learn your native language (L1) is as a child. What the best age would be for learning a second language (L2) has been topic of discussion for many years (Zhang, 2009). It is believed that learning an L2 as early as possible is preferable, but this point is not a certainty yet. To learn an L2 early could also be a disadvantage, as it might affect and change the use of the L1 (Bialystok, 1997). Or it could be the other way around: Already knowing a language might influence the learning of an L2. The many differences between languages can also play a role in this. Various aspects of these issues can be clarified with a simulation model for language learning. Such a model would allow researchers and theorists to test the consequences of potential theoretical mechanisms and assumptions of language learning, even when these cannot be tested in real life situations due to ethical or practical reasons (see Dijkstra & De Smedt, 1996, for a discussion of the advantages of implemented models).

However, language learning is a very broad topic, relating to speed sounds, words, syntax, semantics, and so forth. Words are the basic building blocks of sentences and therefore for a language. So, an important part of learning a language lies in the acquisition of its vocabulary and the process of word recognition. Dijkstra and Van Heuven (2002) built a computer model for visual word recognition for bilingual adults, called the Bilingual Interactive Activation (BIA) model (Grainger & Dijkstra, 1992; Heuven, Dijkstra, & Gainger, 1998), shown in Figure 1. The BIA model is based on the monolingual Interactive Activation model of McClelland & Rumelhart (1981, 1986). This IA model has feature, letter, and word levels, which are connected with each other. "Each network node receives inhibitory and excitatory input from other connected nodes, and previous and current input establish the node's activation state, which can be transformed in an output value. Word recognition takes place if the target word node's activation meets an absolute or relative activation criterion. IA models are characterized by lateral inhibition (between nodes at the same level) and top down feedback (from nodes at a higher level downward)" (Dijkstra, 2006). Dijkstra and Van Heuven (2002) extended the IA model to the BIA model. On top of the word level, an additional level was implemented, that of the language nodes. There are two language nodes, one for each of the languages of a bilingual. In other respects, the model functions like the IA model.

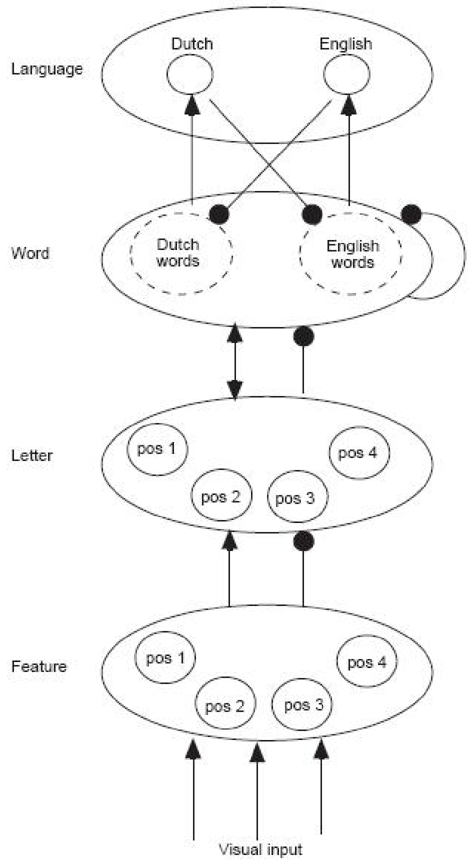

Figure 1. The Bilingual Interactive Activation (BIA) model for bilingual word recognition developed by Dijkstra and Van Heuven (2002). Arrowheads indicate excitatory connections; black filled circles indicate inhibitory connections.

The BIA model can simulate empirical effects like the word frequency effect, list context effects, and neighborhood effects. In the present simulation study, words are presented separately, so there is no context. The frequency effect implies that words with high frequencies of usage are generally recognized sooner than words with lower frequencies of usage, because they have a higher resting level activation. “During recognition, this results in a head start plus extra inhibitory power for higher frequency items” (Dijkstra, 2006). The neighborhood effect will also play a role in our research. Orthographic neighbors are words that share three letters with a four-letter target word. These words become active, because they get excitatory input from the three activated letter units. “These words subsequently inhibit other less activated words and over time, they start to affect each other’s activation and that of the target word negatively through lateral inhibition” (Dijkstra, 2006). Neighbors with a high frequency are stronger competitors, than neighbors with a low frequency (Brysbaert, & Dijkstra, 2006).

Some words cannot be recognized directly in the BIA model, because it does not yet represent semantic representations (only orthographic representations): cognates and false friends. Cognates are pairs of words in two languages that are written the same and have the same meaning. False friends are pairs of words in two languages that are written the same, but have different meanings.

In some research (e.g., Jacquet and French, 2002) the BIA model is criticized, because it did not simulate language development. However, as I will show, given particular assumptions, the model *can* be made to simulate language acquisition.

Another well-known model, the Revised Hierarchical Model (RHM) developed by Kroll and Stewart (1994), shown in Figure 2, does provide a verbal account of language development in adults. The L1 words, the L2 words, and their corresponding concepts are represented in the model. The strongest link is between the concepts and the L1 words. When an L2 word is learned, a link between the L2 word and the corresponding L1 word is formed. When the bilingual becomes fluent, direct links arise also between the L2 words and the concepts. This model assumed that the languages are represented separately in our mind.

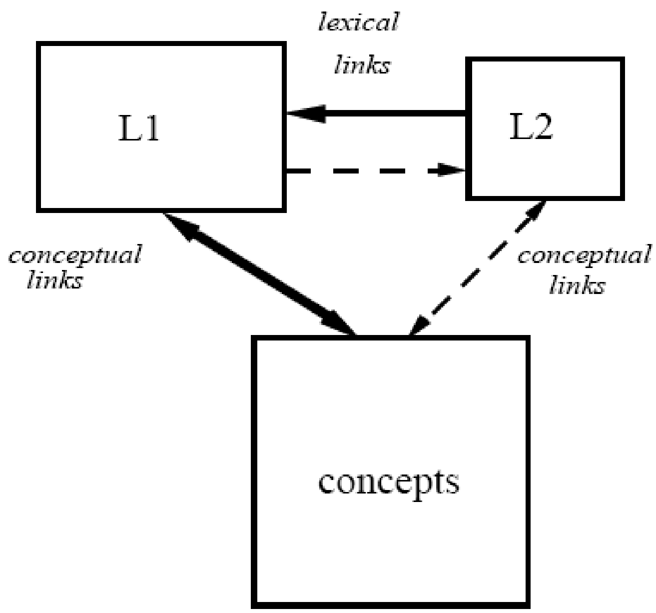

Figure 2. The Revised Hierarchical Model developed by Kroll & Stewart (1994).

Since 1994, the RHM dominated the thinking on bilingual language processing. However, the model has been criticized. Some assumptions from the model are no longer believed to be valid and are questioned. For example, it is not very likely anymore that the known languages are represented separately in our mind. Furthermore, the RHM is hard to adapt, and the model is not implemented and it is not easy to do so, because this model is underspecified (Brysbaert and Duyck, 2010). All these are reasons to examine the possibilities for the BIA model to simulate language development in the present study.

Grainger, Midgley, and Holcomb (2010) also considered how to simulate language development in the BIA model. They combined the BIA model with RHM to a developmental BIA model (BIA-d). A semantics level is added to the language level. When the first L2 words are learned, there is no link between these words and the associated semantics. The semantics are learned via the L1 words. After been exposed more often to the L2 words, a direct link to the semantics level arises. This special mechanism is needed to recognize the L2 words. The study in this paper does not follow this approach by Grainger et al., but will apply a different method, presented in section 2.1, without using a semantic level.

Talamas, Kroll, and Dufour (1999) investigated why adult learners make frequent errors of lexical form during early stages of second language acquisition. They performed a translation recognition task with more and less fluent English-Spanish bilinguals. In this experiment, the bilinguals had to determine if the second of two shown words was the correct translation of the first word. In the crucial part of the experiment, incorrect translations were presented that had to be rejected. Instead of correct translations they were related by lexical form, like man-hambre (hunger) instead of man-hombre, or by meaning, like man-mujer (woman) instead of man-hombre. The less fluent bilinguals experienced more interference for form-related than for meaning-related words. Meanwhile, the more fluent bilinguals experienced more interference for meaning-related words than for form-related words. It can be concluded that while learning a language, in early stages the lexical word form is more important than semantics, in the last stages semantics are more important.

When a new language is learned, people tend to learn the most frequent words first. At first, these words do not have a high frequency yet, because they have not occurred very often. However, after been exposed more often to these words, later in the learning process, these words become the most frequent words. In each stage of learning, one learns new words and the known words become more frequent (Harley, 2001, p. 147). I will use this principle to simulate learning, or more specifically, the acquisition of a language by the BIA model.

Frequencies, neighbors, and lexicon size will all affect word recognition time. Addition of a second language will also affect the word recognition of the first language, because the lexicon size and the number of neighbors will grow. We will test to what extent this is so. Ransdell and Fischler (1987, p. 400) concluded that "becoming fluent in a second language appears to have only slight impact on the ability to process the first". English monolinguals made lexical decisions in 700 - 900 ms, whereas bilinguals were only 125 ms slower, but performed equally well.

I will model the word recognition of a child who learns its first language; an early bilingual and a late bilingual. Because I am Dutch, and the number one language to learn in The Netherlands is English, I will use the languages Dutch and English. Brysbaert and Dijkstra (2006) mention that in English there are more 3, 4, and 5 letter words than in Dutch: 3600 versus 2600 words to be exact. They calculated that each Dutch word has 4.5 orthographic neighbors in Dutch and 2.7 in English. The influence of this aspect on word identification and simulations will be clarified in this study.

The development of a language was simulated by using increasingly large lexicons in the computer model. In seven discrete steps (stages of learning) the vocabulary of the new language was acquired. In the first stage, a small number of words of the new language was included in the lexicon used by the model; in the last stage, the complete lexicon was included. Words of a second language and the native language were put together in one lexicon. Four-letter words from the CELEX database (Max Planck Institute for Psycholinguistics, 2001) were used. These words all have a corresponding frequency of how often they occur in a language, in terms of occurrences per million (opm). During the simulations these frequencies were also adjusted. Low frequencies were used during early stages and higher frequencies during later stages (reflecting the subjective frequency of usage of each word by the developing bilingual). When a word is presented to the model, it takes a number of time steps before the word is recognized by the model. These time steps are called cycles by the BIA model and it is assumed that 1 cycle simulation time would correspond to about 25 ms reaction time. The number of cycles the model needs to identify a word is comparable to the average word recognition time by human participants. A batch job was used to obtain the number of cycles of all the words of the lexicon. The average number of cycles per stage is used to show the progress in acquiring a language.

Five simulations and eight comparisons will be done and statistically analyzed to answer my research questions, which can be summarized as follows.

Summary of the research questions

- Can the BIA model simulate the acquisition of a new vocabulary?
- What is the difference between learning Dutch and English?
- What is the influence of learning a second language (L2), English, on the word recognition of a native language (L1), Dutch? And what is the influence if English is L1 and Dutch L2?
- What is the influence of knowing a L1 vocabulary on learning a L2 vocabulary?
- Is it more efficient to learn both languages at the same time, like an early bilingual, instead of learning the second language later, like a late bilingual?

2. Simulations and comparisons

Five simulation studies were performed with the BIA model to simulate L1-acquisition and late and early L2-acquisition. Two languages were used: Dutch and English. The learning processes were simulated of a person who became (1) a Dutch monolingual, (2) an English monolingual, (3) a late Dutch-English bilingual, (4) a late English-Dutch bilingual or (5) an early Dutch-English bilingual. These simulation studies are followed by theoretically relevant and statistically supported comparisons of the simulations. First, I will describe the general method for simulating the acquisition of a language.

2.1. General Method

2.1.1. The lexicons

The BIA model can only handle words of the same length in one lexicon. For this study, two lists of four-letter Dutch and English words extracted from the CELEX database were used. These words all have a corresponding frequency of how often they occur in a language, in terms of occurrences per million (opm). The rarest words, with a frequency less than 2 opm, were removed from the lexicons. Cognates and false friends cannot be recognized, therefore they are also removed from the lexicons. The remaining lexicons are called the complete lexicons.

To simulate the word identification performance of a person who becomes a monolingual, seven increasingly large lexicons were made. The complete lexicon with the original frequencies was put in lexicon seven, which was used to simulate the last stage of learning, the stage where all the words of the new language were learned. In the other stages the following method was used to determine which words were put in the lexicon. First, the frequencies of the original lexicon were divided by a number belonging to that stage, see Table 1. Then all words with a frequency less than 2 opm were removed. The remaining words were included in the lexicon. At last, the frequencies were rounded up or down to the nearest integer. In this way, the words with the highest frequencies in the complete lexicon were learned first in stage one. The frequency range including words with little bit lower frequencies was learned next in stage two, and so on. Table 1 shows which frequency range of words is added per stage. The number of Dutch or English words added and used in each stage can also be found. To clarify Table 1: For example, in stage two the original frequencies were divided by 32, this led to the addition of words with an original frequency between 64 opm and 127 opm to the lexicon, which already contained the words added in stage one.

Table 1
The Seven Stages of Acquiring a New Language.

Stage	Added frequency range (opm)	Frequencies divided by	Number of added Dutch words	Known Dutch words	Number of added English words	Known English words
1	128 +	64	90	90	133	133
2	64-127	32	61	151	101	234
3	32-63	16	87	238	119	353
4	16-31	8	77	315	147	500
5	8-15	4	115	430	175	675
6	4-7	2	152	582	183	858
7	2-3	1	174	756	239	1097

When learning Dutch, 61 Dutch words were added in stage two to the 90 already known Dutch words, resulting in knowing 151 Dutch words after stage two. When learning English, 101 English words were added in stage two to the 130 already known English words, resulting in knowing 234 English words after stage two.

This method was also used for second language learning. Words from the second language were gradually added to the lexicon with the first language. To simulate that the first language was already known before the learning of the second language is started, a stage zero was added. In stage zero, the complete L1 lexicon was used for simulations without any L2 words. In the seven learning stages, the increasingly large L2 lexicons were added to the complete L1 lexicon. In stage seven, the lexicon contained the complete vocabularies of both languages. In other words, they simulate the word recognition performance of a balanced bilingual.

The complete English lexicon of four-letter words contains 1097 words, whereas the Dutch lexicon only contains 756 words. One could argue that that it is preferable to have a last stage with an equal number of Dutch and English words to get a better comparison. This raises the question which words should be deleted from the English lexicon. I decided to use the whole lexicon, because first of all, it seemed quite realistic that the English lexicon really is bigger. So in real life a truly balanced bilingual might really know more English (four-letter) words than Dutch words. And, secondly, the total size of the lexicon might have not such a big effect on processing at all.

2.1.2. The batch job

A batch job is a program on a computer which can execute many steps without manual intervention. In this study, a batch job was used to calculate the number of cycles (NCs) needed until recognition for all the words in the given lexicon.

The BIA model, originally written in the computer language C, was re-programmed by P. Gerke and L. Dijkstra in Java and adapted to handle simulations per word and per lexicon.

A lexicon and a file with test words were used as input. In this study, all the words of the lexicon were used as test words. The batch job simulated the recognition of every word in the lexicon. The NCs were counted with continuous values by interpolating the interval where the threshold 0.7 was passed. For example, when the activation after 18 cycles was 0.6 and after 19 cycles it was 0.8, the NCs until recognition became 18.5. The needed NCs were saved in an output file. With these data, the mean NCs per language or per stage can be calculated.

For more details about the program and the batch job, see Appendix A.

2.1.3. The output

For all words of an input lexicon, the NCs until recognition are produced as output. In this study, one lexicon contained 90 to 1853 words. Because the BIA software reads in one lexicon at a time, the procedure is repeated for each of the seven or eight lexicons belonging to one simulation study. The NCs are used next for further analysis.

2.2. Simulations

2.2.1. Simulation study 1: Acquisition of Dutch as a native language

Goal

To gain more insight on how a native language is acquired, we simulated how the words of this new language are recognized by a learner. Our hypothesis is that the more often a word is seen, the faster it is recognized. However, on average it may take longer to recognize a word in a particular learning stage, because in each stage of learning more neighbors are added that compete for recognition. Said differently, if you take the average recognition time of all words in each developmental stage, you will see an upward trend. The results can be used in later comparisons, see section 2.3.

Method

We increased the lexicon used in the BIA model in seven steps, from knowing a few 4-lettered Dutch words to knowing all 4-lettered Dutch words. The same procedure as in the general method was used to determine the number of Dutch words used per stage and their frequencies. The numbers used in simulation study 1 can be found in Table 1. For all words we will measure the number of cycles needed until word recognition.

Results

The mean number of cycles until recognition (mean NCs) in each stage of learning a Dutch vocabulary and associated standard deviations can be found in Table 2 and are visualized in Figure 3. A clear upward trend was found. In stage 1, the mean NCs is 18.504, this rises to 19.116 in stage 7. The difference between stage 1 and stage 7 is 0.612 cycles, this is equal to 15 ms recognition time.

Table 2

The Number of Dutch Words Used, the Mean Number of Cycles until Recognition and Their Standard Deviations in each Stage of Learning a Dutch Vocabulary.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
Dutch								
N	90	151	238	315	430	582	756	
Mean number of cycles	18.504	18.661	18.868	18.935	19.046	19.101	19.116	+ 0.612
Std. Deviation	1.186	1.231	1.055	0.963	0.877	0.833	0.821	

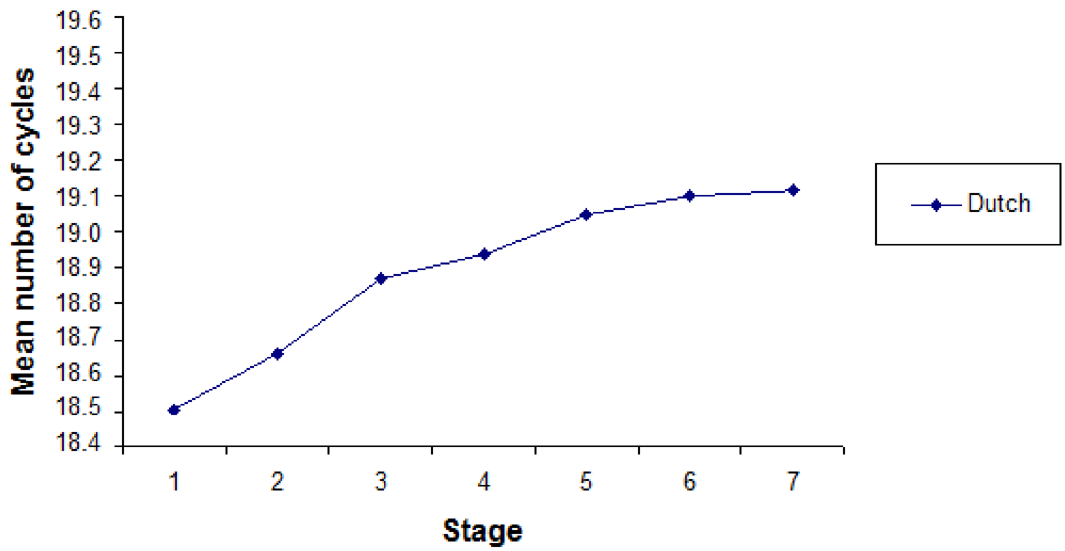

Figure 3. The mean number of cycles until recognition in each stage of learning a Dutch vocabulary.

When I looked closer to stage 7, I found that words with higher frequencies were recognized faster than words with lower frequencies as shown in Figure 3. The used frequency ranges can be found in Table 1. The mean NCs was 18.365 for frequency range 1, which contained the highest frequencies; the mean NCs for frequency range 7 was 19.528. On average, words in frequency range 1 were recognized 1.163 cycles (= 29 ms) faster than words in frequency range 7.

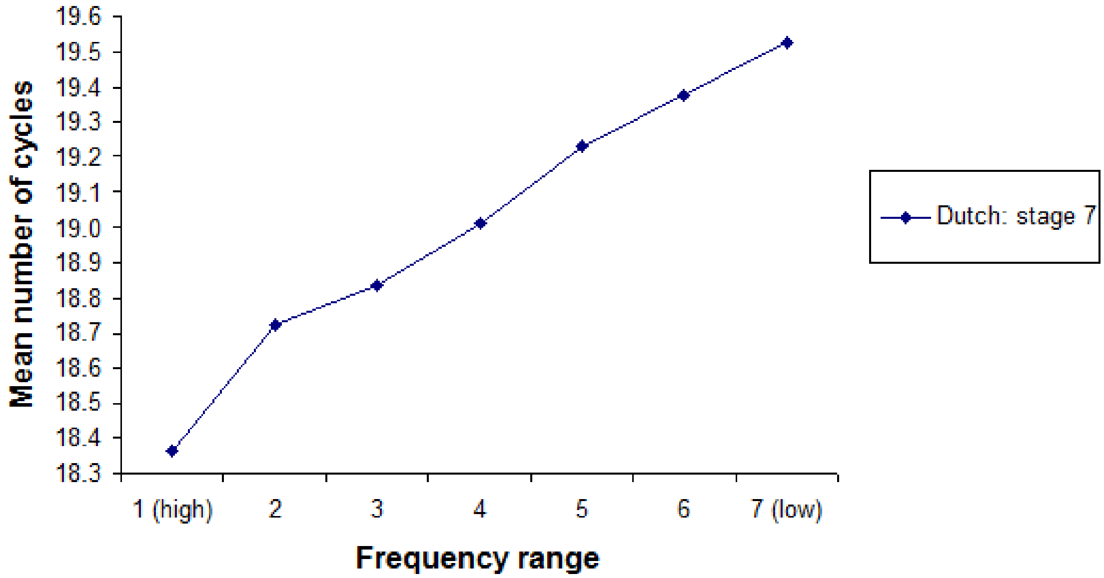

Figure 4. Words with higher frequencies are recognized faster than words with lower frequencies in the Dutch vocabulary in stage 7.

Conclusion

Words with higher frequencies were recognized faster than words with lower frequencies. During the acquisition of a vocabulary not only the frequencies became higher, but also the number of known words increased. This led to a large neighborhood size for every word, which also influenced the mean word recognition time. On average, the mean NCs increased per stage. Thus, the more words were known, the slower one word was recognized.

2.2.2. Simulation study 2: Acquisition of English as a native language

Goal

The goal of simulating the acquisition of English as a native language is the same as in simulation study 1. In section 2.3.1., the results of this simulation study are compared to simulation study 1, to see the difference between learning Dutch and learning English.

Method

The same method as in simulation study 1 was used. The numbers used in simulation study 2 can be found in Table 1.

Results

The mean NCs in each stage of learning an English vocabulary and associated standard deviations can be found in Table 3 and are visualized in Figure 5. In stage 1, the mean NCs is 18.459, this rises to 19.199 in stage 7. The difference between stage 1 and stage 7 is 0.740 cycles, this is equal to 11 ms recognition time.

Table 3
The Number of English Words Used, the Mean Number of Cycles until Recognition and Their Standard Deviations in each Stage of Learning a English Vocabulary.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
English								
N	133	234	353	500	675	858	1097	
Mean number of cycles	18.459	18.816	19.011	19.059	19.127	19.165	19.199	+ 0.740
Std. Deviation	1.328	1.208	1.084	0.996	0.924	0.878	0.854	

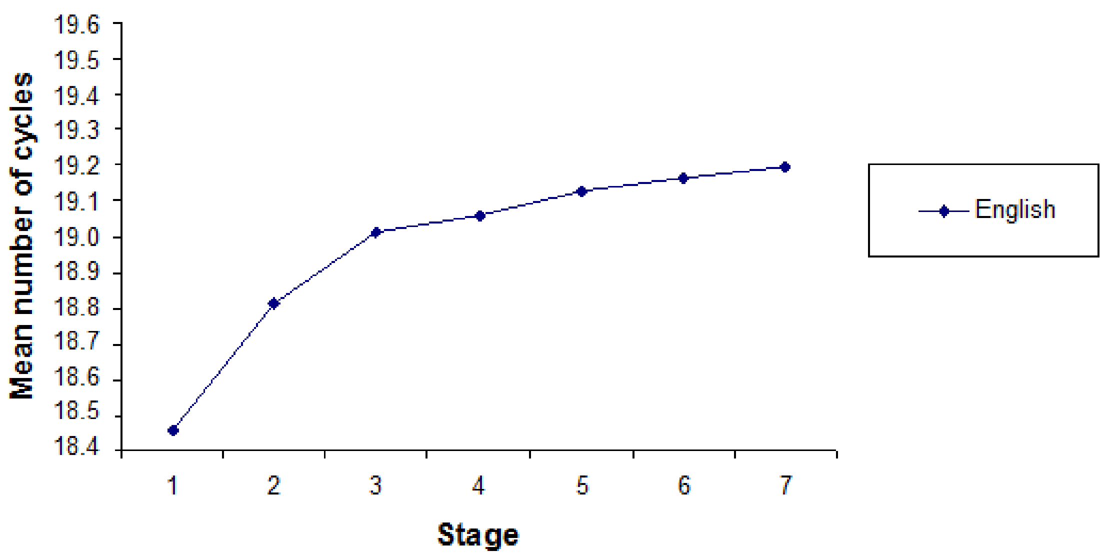

Figure 5. The mean number of cycles until recognition in each stage of learning a English vocabulary.

Conclusion

The same kind of results as in simulation study 1 was found, so the same can be concluded. The increase of vocabulary had as effect that the recognition time per word increased, this means that on average words are recognized slower. In other words, it appears that our conclusions can be generalized across language.

2.2.3. Simulation study 3: Late Dutch-English bilingual

Goal

Because the BIA model was especially developed to simulate the word recognition process by bilinguals, I want to test if the BIA model can simulate the acquisition of a second language. I begin with sequential learning of a second language: having a native language and then learning a second language.

In this simulation study, I will use Dutch as L1 and English as L2. This simulation study shows how Dutch is affected by English in different stages of learning English. My hypotheses are that learning a second language, English, has some influence on the word recognition of the native language, Dutch. I want to obtain a detailed view of the effect and find the possible differences for different frequency ranges.

Method

Initially, only all Dutch words were known, which are presented in stage zero, and then the learning begins. In stage 1, some English words re added to the Dutch lexicon. Then in six more steps, a complete English vocabulary was added, as described in the general method.

Results

The mean NCs per stage and per language and associated standard deviations can be found in Table 4. No clear trend was found, as also shown in Figure 6. The mean NCs fluctuated during the learning process, and this applied to both languages.

To know if learning English has any influence on the recognition of Dutch words, further analyses are needed.

Table 4
The Number of Dutch and English Words Used, the Mean Number of Cycles until Recognition and Their Standard Deviations in each Stage of Learning an English Vocabulary, Next to Having a Dutch Vocabulary.

	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
Dutch									
N	756	756	756	756	756	756	756	756	
Mean number of cycles	19.116	19.102	19.105	19.097	19.098	19.112	19.137	19.184	+ 0.068
Std. Deviation	0.821	0.801	0.781	0.776	0.762	0.749	0.734	0.720	
English									
N	--	133	234	353	500	675	858	1097	
Mean number of cycles	--	19.127	19.138	19.110	19.087	19.084	19.108	19.161	+ 0.034
Std. Deviation	--	0.840	0.776	0.686	0.643	0.641	0.659	0.692	

Note. The absence of data for English in stage 0 is due to the fact that there are no English words in stage 0.

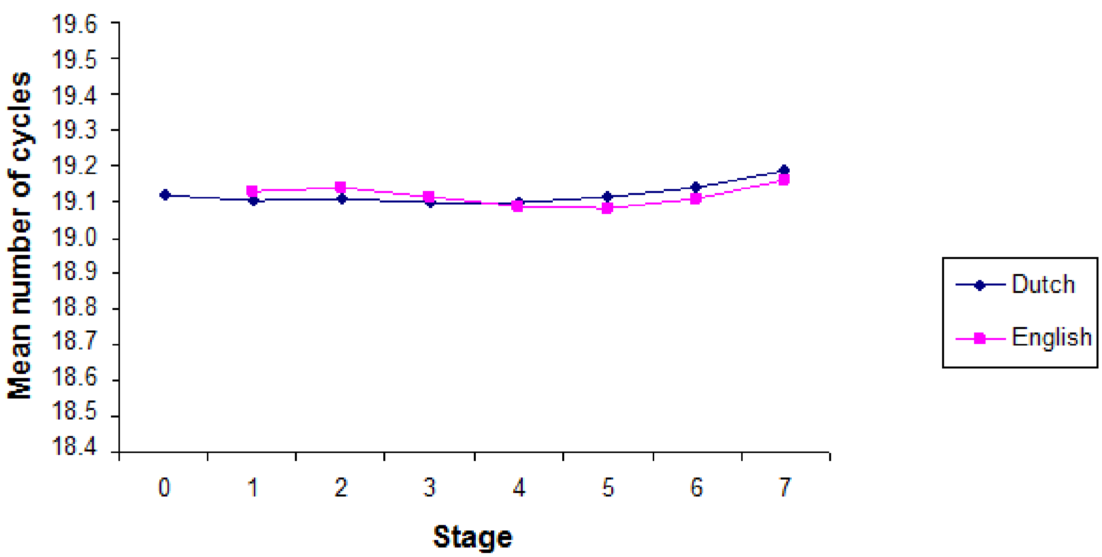

Figure 6. The mean number of cycles until recognition in each stage of learning an English vocabulary, next to having a Dutch vocabulary.

A repeated-measures-MANOVA was conducted with Group (treatment: knowing Dutch, learning English / control: knowing Dutch) as between-subject factor and Stage (0/1/2/3/4/5/6/7) as within-subject factor. The dependent variable was the recognition time of Dutch words, measured with the number of cycles. Learning an English vocabulary had a significant effect on the recognition time of the Dutch words ($F(7,1504) = 8.045$, $p < .001$), but this effect was weak ($eta^2 = .036$). Only the within-subject contrast between stage 0 and stage 7 was significant ($F(1,1510) = 1.767$, $p < .001$) and this effect was also weak ($eta^2 = .008$). The averages showed that initially the treatment group recognized the Dutch words as fast as the control groups (M = 19.116), but in stage 7 the treatment group recognized the Dutch words more slowly than the control group (M = 19.184 and 19.116). The difference was 0.068 cycles, which is equal to 2 ms.

I also considered the mean NCs per frequency range; the results can be found in Table 5. In each frequency range, the Dutch words showed a slightly upward trend, which can also be seen in Figure 7. In Figure 8, the results of the English words are shown, the mean NCs were decreasing.

Table 5

The Number of Dutch and English Words Used, the Mean Number of Cycles until Recognition Per Frequency Range and Their Standard Deviations in each Stage of Learning an English Vocabulary, Next to Having a Dutch Vocabulary.

Mean number of cycles per frequency range	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
Dutch									
1 (128+)	18.365	18.344	18.378	18.367	18.368	18.376	18.388	18.429	+ 0.064
2 (64-127)	18.724	18.705	18.700	18.688	18.708	18.741	18.754	18.783	+ 0.059
3 (32-63)	18.836	18.828	18.833	18.822	18.828	18.826	18.833	18.876	+ 0.041
4 (16-31)	19.011	18.971	18.952	18.947	18.965	19.005	19.031	19.077	+ 0.066
5 (8-15)	19.228	19.218	19.205	19.198	19.186	19.205	19.217	19.243	+ 0.015
6 (4-7)	19.375	19.358	19.370	19.350	19.338	19.356	19.409	19.469	+ 0.094
7 (2-3)	19.528	19.527	19.530	19.535	19.540	19.539	19.569	19.630	+ 0.102
English									
1 (128+)	--	19.127	18.924	18.776	18.670	18.526	18.441	18.360	- 0.767
2 (64-127)	--	--	19,420	19,272	19,102	18,980	18,869	18,789	- 0.631
3 (32-63)	--	--	--	19,346	19,172	19,042	18,945	18,876	- 0.470
4 (16-31)	--	--	--	--	19,386	19,232	19,140	19,061	- 0.325
5 (8-15)	--	--	--	--	--	19,471	19,334	19,242	- 0.229
6 (4-7)	--	--	--	--	--	--	19,589	19,495	- 0.094
7 (2-3)	--	--	--	--	--	--	--	19,651	0

Note. The absence of data is due to the fact that there are no English words of some frequency ranges in some stages.

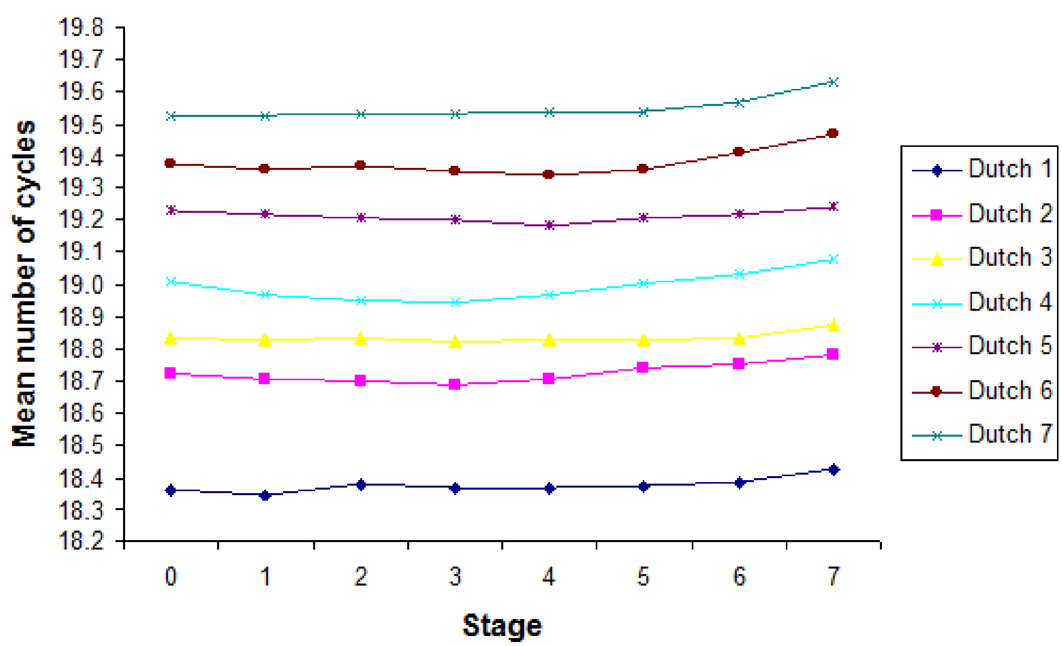

Figure 7. The mean number of cycles until recognition in each stage of learning an English vocabulary, next to having a Dutch vocabulary, per frequency range, only for Dutch words.

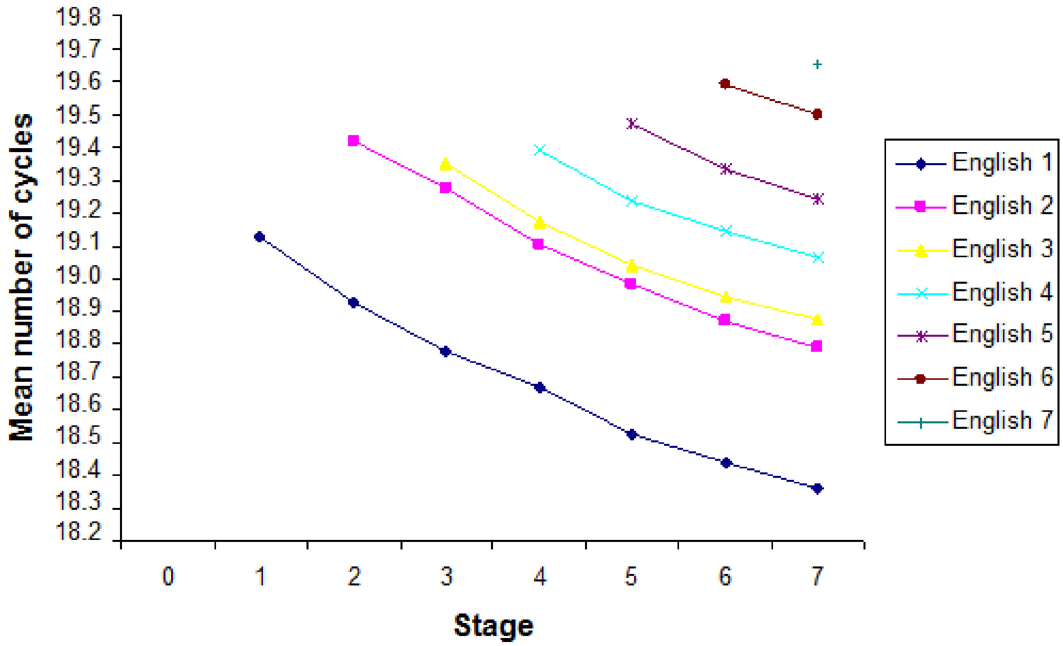

Figure 8. The mean number of cycles until recognition in each stage of learning an English vocabulary, next to having a Dutch vocabulary, per frequency range, only for English words.

Conclusion

This simulation showed how Dutch was affected by English in different stages of learning English. Dutch words were significantly slower recognized, however only 2 ms, after English was learned than without it. It can be concluded that learning an English vocabulary has a little, negative influence on the recognition of Dutch words.

On average, the English words in each stage were recognized in the same NCs, but there were differences when looking per frequency range. In each frequency range, the same words were involved, but their frequencies are increasing each time a next stage of learning is reached. The decreasing lines are due to the increased frequencies. When the first points of each frequency range, the words with the highest frequencies per stage, are connected to each other, a rising line would appear. This is due to the fact that these words gained more neighbors throughout the stages. The frequency and neighborhood effects cancel each other, which caused that on average an almost straight line appears.

In both languages, it can be found that words with frequencies from frequency range two were relatively much slower recognized than words with frequencies from frequency range one, this is because the frequencies from frequency range one are relatively much higher than the frequencies from frequency range two.

2.2.4. Simulation study 4: Late English-Dutch bilingual

Goal

The learning process of Dutch by a person with English as native language was simulated. This simulation shows how English is affected by Dutch in different stages of learning Dutch. My hypotheses are that learning a Dutch has a small effect on the word recognition of the native language, English.

Method

Initially, only all the English words were known, which are presented in stage zero, and then the learning begins. In stage 1 some Dutch words were added to the English lexicon. Then in six more steps a complete Dutch vocabulary was added, as described in the general method.

Results

The mean NCs per stage and per language and associated standard deviations can be found in Table 6. Regarding the Dutch words a clear decreasing line is seen. The difference between stage 7 and 1 is 0.285 cycles, which is 7 ms faster recognition. No clear trend was found regarding the English words, as also shown in Figure 9. To know if learning Dutch has influence on the recognition of English words, further analyses are needed.

Table 6

The Number of English and Dutch Words Used, the Mean Number of Cycles Until Recognition and Their Standard Deviations in Each Stage by Learning a Dutch Vocabulary as second language.

	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
English									
N	1097	1097	1097	1097	1097	1097	1097	1097	
Mean number of cycles	19.199	19.198	19.197	19.199	19.201	19.179	19.178	19.161	- 0.038
Std. Deviation	0.854	0.840	0.830	0.823	0.816	0.777	0.755	0.692	
Dutch									
N	0	90	151	238	315	430	582	756	
Mean number of cycles	--	19.470	19.465	19.398	19.330	19.248	19.231	19.184	- 0.285
Std. Deviation	--	0.988	0.887	0.779	0.784	0.724	0.720	0.720	

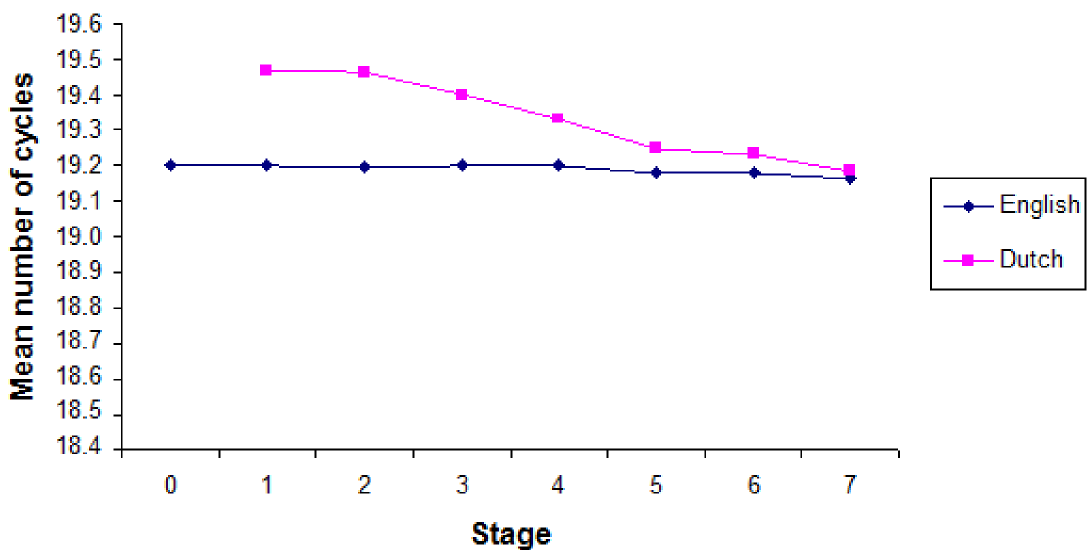

Figure 9. The mean number of cycles until recognition in each stage of learning a Dutch vocabulary.

A repeated-measures-MANOVA was conducted with Group (treatment: knowing English, learning Dutch / control: knowing English) as between-subject factor and Stage (0/1/2/3/4/5/6/7) as within-subject factor. The dependent variable was the recognition time of English words, measured with the number of cycles. Learning a Dutch vocabulary had a significant effect on the recognition time of the English words ($F(7,2186) = 7.457$, $p < .001$), but this effect was weak ($eta^2 = .023$). The within-subject contrast between stage 0 and stage 5 was significant ($F(1,2192) = 3.967$, $p < .05$), this effect was weak ($eta^2 = .002$). And the within-subject contrast between stage 0 and stage 7 was significant ($F(1,2192) = 7.416$, $p < .01$), this effect was weak ($eta^2 = .003$). The averages showed that initially the treatment group recognized the English words as fast as the control groups (M = 19.199), but in stage 7 the treatment group recognized the English words faster than the control group (M = 19.161 and 19.199). The difference was 0.038 cycles, which is equal to 1 ms.

Conclusion

English words were recognized significantly faster after Dutch was learned than without it, however the difference was only 1 ms. It can be concluded that learning a Dutch vocabulary has a positive influence on the recognition of English words, but only a little.

2.2.5. Simulation study 5: Early Dutch-English bilingual

Goal

After simulating sequential learning I also want to test if the BIA model can simulate the acquisition of two languages at the same time. A person with who learned Dutch and English at the same time was simulated. The results were compared to other results in section 2.3.

Method

The learning began in stage 1 where some Dutch and some English words were put in the lexicon. In the next stages, words of both languages were added to the lexicon, to end up with a lexicon with the complete Dutch and English vocabularies. The general simulation method described earlier was followed.

Results

The mean NCs per stage and per language, and the associated standard deviations can be found in Table 7 and are visualized in Figure 10. During the learning process, the mean NCs increased for both languages. However, on average, the English words were always recognized faster. The Dutch words were recognized in 18.675 cycles in stage 1, the recognition time increased with 0.509 cycles to 19.184 cycles in stage 7. The English words were recognized in 18.551 cycles in stage 1, the recognition time increased with 0.610 cycles to 19.161 cycles in stage 7. The lines run almost parallel to each other.

Table 7
The Number of Dutch and English Words Used, the Mean Number of Cycles Until Recognition and Their Standard Deviations in Each Stage of Learning both English and Dutch Vocabularies Simultaneously.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
Dutch								
N	90	151	238	315	430	582	756	
Mean number of cycles	18.675	18.951	19.079	19.137	19.149	19.168	19.184	+ 0.509
Std. Deviation	1.156	1.138	0.916	0.808	0.748	0.720	0.720	
English								
N	133	234	353	500	675	858	1097	
Mean number of cycles	18.551	18.878	19.001	19.061	19.090	19.112	19.161	+ 0.610
Std. Deviation	1.101	0.993	0.857	0.786	0.745	0.718	0.692	

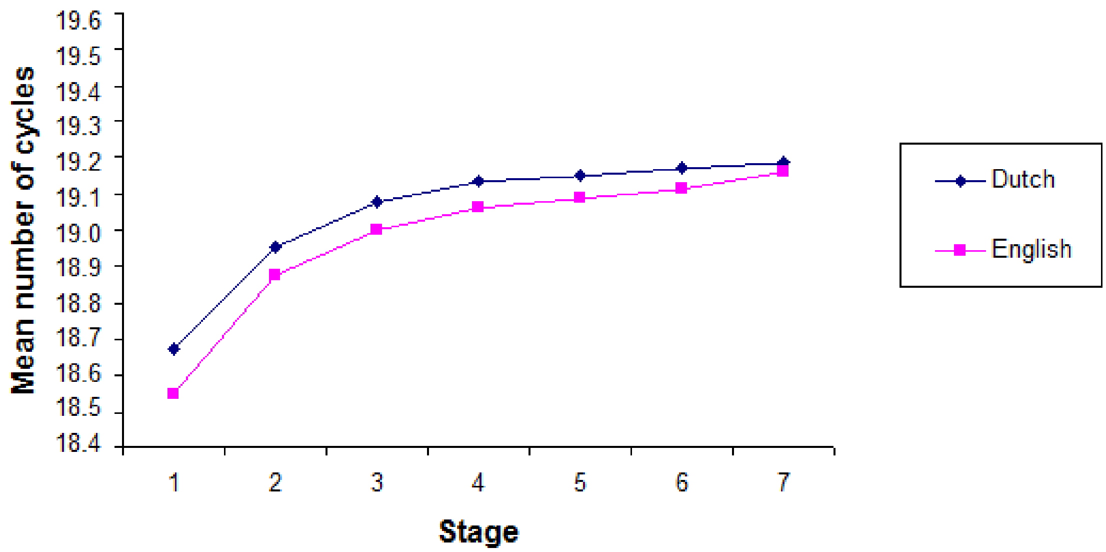

Figure 10. The mean number of cycles until recognition in each stage of learning both English and Dutch vocabularies simultaneously.

Conclusion

It can be concluded that the BIA model can also simulate the word recognition performance of an early bilingual. Further conclusions can be drawn after some additional simulation comparisons, described in section 2.3.

2.3. Comparisons of simulations

2.3.1. Comparison 1: Dutch monolingual vs. English monolingual

Simulation study 1 (acquisition of Dutch as a native language) can be compared to simulation study 2 (acquisition of English as a native language). The pattern of learning is the same: Words in the first stage were recognized faster than words in the last stage. Both showed an upward line. The English words in stage one were recognized a little bit faster than the Dutch words in that stage. In stage seven this difference was other way around: the Dutch words were recognized faster than the English words. The difference between the first and the last stage was bigger for English than for Dutch (0.740 vs. 0.612 cycles).

The differences between learning Dutch and learning English are probably due to the lexicon characteristics. The Dutch lexicon had fewer words, but more neighbors per word than the English lexicon. This can be the cause of that in the early stages the English words are recognized faster than the Dutch words. Further, the Dutch words with a frequency from frequency range one had on average higher frequencies than the English words with a frequency from frequency range one (825 vs. 534 ocm). This can be the cause of that in the last stage the Dutch words were recognized faster than the English words.

2.3.2. Comparison 2: English monolingual vs. late Dutch-English bilingual

English can be learned as a native language (simulation study 2; L1) and as a second language after already knowing Dutch (simulation study 3; L2). The cycle times of English as L1 can be compared to the cycle times of English as L2 with a t-test for independent samples. The differences between them must be due to the (not) knowing of Dutch words. This comparison shows the effect of knowing Dutch while learning English. How does the recognition time for English words develop when they become more frequent, under the influence of the ever-present Dutch words?

The results can be found in Table 8 and are visualized in Figure 11. The English words in stage one and two were recognized significantly slower when learned as L2 after Dutch instead as L1. In other stages they were equal to each other. So, at word form level, learning English is initially more difficult when Dutch is known.

Table 8

Mean Number of Cycles (With Associated Standard Deviations) Per Group (English as L1 / English as L2 after Dutch) and Their Differences Between Groups per Stage.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
English as L1								
Mean number of cycles	18.459	18.816	19.011	19.059	19.127	19.165	19.199	+ 0.740
Std. Deviation	1.328	1.208	1.084	0.996	0.924	0.878	0.854	
English as L2 after Dutch								
Mean number of cycles	19.127	19.138	19.110	19.087	19.084	19.108	19.161	+ 0.034
Std. Deviation	0.840	0.776	0.686	0.643	0.641	0.659	0.692	
Difference								
Mean number of cycles	- 0.668 ***	- 0.322 **	- 0.099	- 0.028	+ 0.044	+ 0.057	+ 0.038	

** p<.01. *** p<.001.

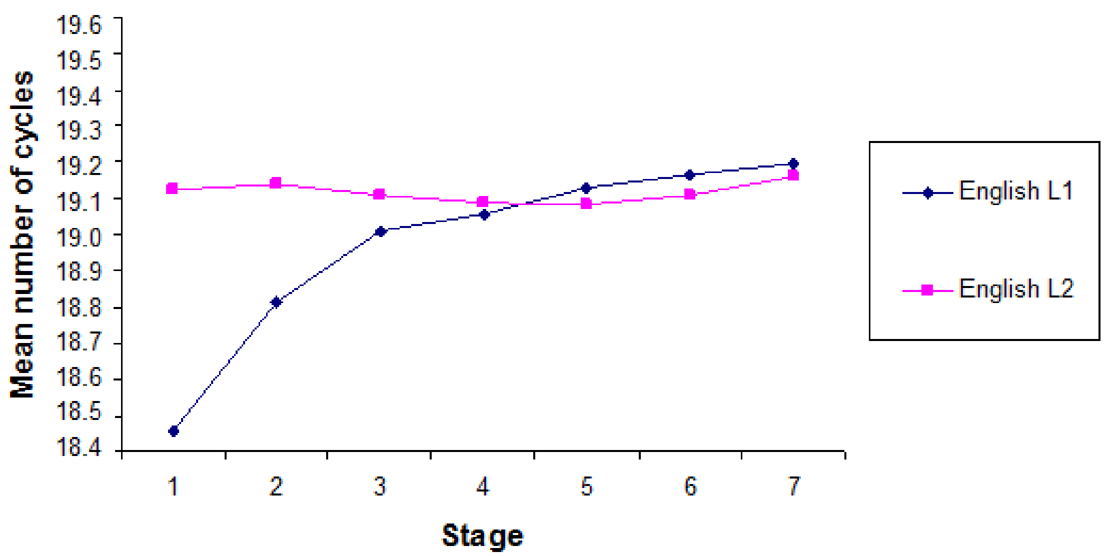

Figure 11. The mean number of cycles until recognition in each stage of learning English as a native language or as second language after already knowing Dutch.

2.3.3. Comparison 3: Dutch monolingual vs. late English-Dutch bilingual

Dutch can be learned as a native language (simulation study 1; L1) and as a second language after already knowing English (simulation study 4; L2). The cycle times of Dutch as L1 can be compared to the cycle times of Dutch as L2 with a t-test for independent samples.

The differences between them must be due to the (not) knowing of English words. This comparison shows the effect of knowing English while learning Dutch. How does the recognition time for Dutch words develop when they become more frequent, under the influence of the ever-present English words?

The results can be found in Table 9 and are visualized in Figure 12. The Dutch words in stage one to six were recognized significantly slower when learned as L2 after English instead as L1. Only in the last stage they were equal to each other. So, at word form level, learning Dutch is more difficult when English is known.

The largest difference between the recognition times for the Dutch words as L1 or as L2 was in stage 1. The Dutch words as L2 were recognized in 0.966 more cycles, which is equal to 24 more milliseconds, than the Dutch words as L1. Thus, the Dutch words as L2 were slower to be recognized, but most important is that they are recognized at all. The first Dutch words are not 'blown away' by the many, already known English words. No special protection for the first words is necessary to be recognized.

Table 9

Mean Number of Cycles (With Associated Standard Deviations) Per Group (Dutch as L1 / Dutch as L2 after English) and Their Differences Between Groups Per Stage.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
Dutch as L1								
Mean number of cycles	18.504	18.661	18.868	18.935	19.046	19.101	19.116	+ 0.612
Std. Deviation	1.186	1.231	1.055	0.963	0.877	0.833	0.821	
Dutch as L2 after English								
Mean number of cycles	19.470	19.465	19.398	19.330	19.248	19.231	19.184	- 0.285
Std. Deviation	0.988	0.887	0.779	0.784	0.724	0.720	0.720	
Difference								
Mean number of cycles	- 0.966	- 0.804	- 0.531	- 0.395	- 0.203	- 0.130	- 0.068	
	***	***	***	***	***	*		

* p<.05. *** p<.001.

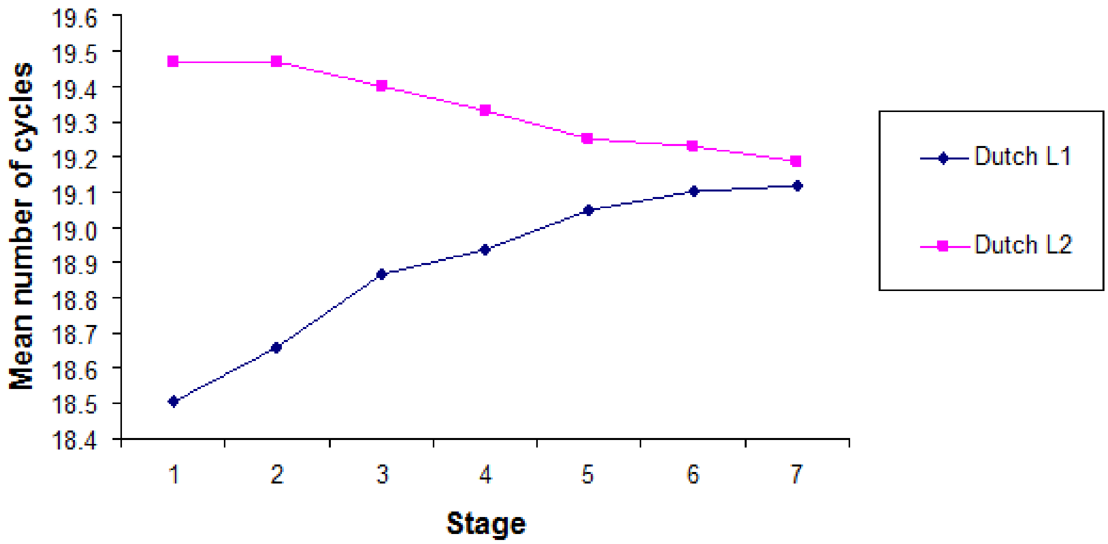

Figure 12. The mean number of cycles until recognition in each stage of learning Dutch as a native language or as second language after already knowing English.

2.3.4. Comparison 4: late Dutch-English bilingual vs. late English-Dutch bilingual

The acquisition of the second language was not the same for a late Dutch-English bilingual (simulation study 3) and a late English-Dutch bilingual (simulation study 4). Learning Dutch, while knowing English, was harder than learning English, while knowing Dutch. The Dutch words were affected more. This can be concluded because the Dutch words were slower recognized than the English words in the first stages in simulation study 4; and because the learned English vocabulary caused slower Dutch word recognition in simulation study 3. The English words are recognized faster in the end, when the Dutch words were learned. When learning English after knowing Dutch, the English words are recognized in the same time as the known Dutch words.

It seems the Dutch words were affected more, because the English vocabulary was larger than the Dutch vocabulary. Relative more English words are added to the lexicon in each stage too. For the specific number of words in each stage, see Table 1 again. The fact that English had a larger vocabulary in the simulations than Dutch does not seem to be a completely defensible simulations aspect, although it may be a ‘natural’ characteristic of these two languages.

To be sure that the used number of words in the lexicons is not the cause of the difference between a late Dutch-English bilingual and a late English-Dutch bilingual, I will re-test the stage one, because it displayed the largest differences. In stage one the first words of the second language were added to the first language. The Dutch words were recognized much slower than the known English words. This is quite different than in the knowing Dutch, learning English situation, where the English words were recognized as fast as the Dutch words.

In stage one for the late Dutch-English bilingual were 756 Dutch and 133 English words used, for the late English-Dutch bilingual were 1097 English and 90 Dutch words used. These numbers were equated to 756 L1 words and 90 L2 words. Thus, the effect of the difference in the used number of words on the simulations will be removed. The mean NCs with these numbers can be compared with the initial average number of cycles.

The new results can be found in Table 10. The mean number of cycles and associated standard deviations were presented for the first and second language in knowing Dutch and learning English, and in knowing English and learning Dutch. The differences in mean NCs were statistically analyzed with t-tests for independent samples.

The difference between the two first languages was not significant, but the difference between the two second languages was (t (178) = -2.033, p = .044). The Dutch words as L2 were recognized 0.285 cycles slower than the English words as L2.

The difference between the L1 and the L2 in knowing Dutch and learning English was not significant, but it was for knowing English, learning Dutch (t (844) = -2.212, p = .027). The Dutch words as L2 were recognized 0.225 cycles slower than the English words as L1.

Table 10
Mean Number of Cycles (With Associated Standard Deviations) for the First and Second Language in Knowing Dutch and Learning English, and in Knowing English and Learning Dutch. Stage One Was Done Over With an Equal Number of Words in the First (N=756) and in the Second (N=90) Language. Their Differences and Significance are Also Shown.

	Knowing Dutch, learning English: Stage 1	Knowing English, learning Dutch: Stage 1	Difference
First language (L1)			
Mean number of cycles	19.102	19.129	- 0.027
Std. Deviation	0.801	0.903	
Second language (L2)			
Mean number of cycles	19.068	19.353	- 0.285*
Std. Deviation	0.908	0.971	
Difference			
Mean number of cycles	+ 0.033	- 0.225*	

* p<.05.

Dutch is still recognized slower than English, even though the used number of words was the same. It can be concluded that it is harder to learn Dutch, when English is known than to learn English, when Dutch is known. The Dutch words were affected more by the English words than the English words were affected by the Dutch words.

2.3.5. Comparison 5: Dutch monolingual vs. early Dutch-English bilingual

The acquisition of Dutch by a monolingual (simulation study 1) can be compared with the acquisition of Dutch by an early Dutch-English bilingual (simulation study 5). The results can be found in Table 11 and are visualized in Figure 13. It can be seen how the mean NCs evolved through the stages and what the differences are between the two ways of learning Dutch.

The differences in mean NCs are statistically analyzed with t-tests for independent samples. The Dutch words in an early Dutch-English bilingual were significantly slower recognized in stage 2 and 3 than in a Dutch monolingual ($p < .05$ in both situations). But the difference was at most 0.290 cycles, which are only 7 milliseconds. In the other stages were the words recognized equally fast.

It can be concluded that it is a little bit harder to learn Dutch for the bilingual than for the monolingual.

Table 11

Mean Number of Cycles (With Associated Standard Deviations) Per Group (Dutch as L1 / Dutch in an early Dutch-English Bilingual) and Their Differences Between Groups Per Stage.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
Dutch as L1								
Mean number of cycles	18.504	18.661	18.868	18.935	19.046	19.101	19.116	+ 0.612
Std. Deviation	1.186	1.231	1.055	0.963	0.877	0.833	0.821	
Dutch in early Dutch-English bilingual								
Mean number of cycles	18.675	18.951	19.079	19.137	19.149	19.168	19.184	+ 0.509
Std. Deviation	1.156	1.138	0.916	0.808	0.748	0.720	0.720	
Difference								
Mean number of cycles	- 0.171	- 0.290 *	- 0.211 *	- 0.202	- 0.104	- 0.068	- 0.068	

* p<.05.

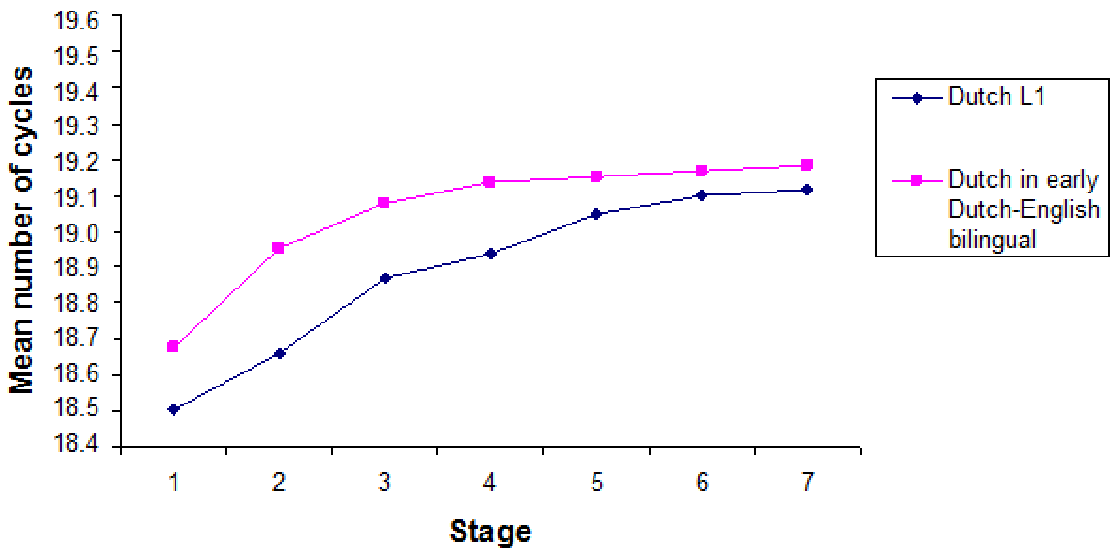

Figure 13. The mean number of cycles until recognition in each stage of learning Dutch as L1 and in an early Dutch-English bilingual.

2.3.6. Comparison 6: English monolingual vs. early Dutch-English bilingual

The acquisition of English by a monolingual (simulation study 2) can be compared with the acquisition of English by an early Dutch-English bilingual (simulation study 5). The results can be found in Table 12 and are visualized in Figure 14. The Table and Figure show the mean NCs evolved through the stages and what the differences are between the two ways of learning English.

The differences in mean NCs are statistically analyzed with t-tests for independent samples. None of the differences were significant; the English words in an early Dutch-English bilingual were recognized in the same time than in an English monolingual.

It can be concluded that the monolingual learns English not faster or slower than the bilingual.

Table 12
Mean Number of Cycles (With Associated Standard Deviations) Per Group (English as L1 / English in an early Dutch-English bilingual) and Their Differences Between Groups Per Stage.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
English as L1								
Mean number of cycles	18.459	18.816	19.011	19.059	19.127	19.165	19.199	+ 0.740
Std. Deviation	1.328	1.208	1.084	0.996	0.924	0.878	0.854	
English in early Dutch-English bilingual								
Mean number of cycles	18.551	18.878	19.001	19.061	19.090	19.112	19.161	+ 0.610
Std. Deviation	1.101	0.993	0.857	0.786	0.745	0.718	0.692	
Difference								
Mean number of cycles	- 0.092	- 0.062	+ 0.010	- 0.002	+ 0.037	+ 0.053	+ 0.033	

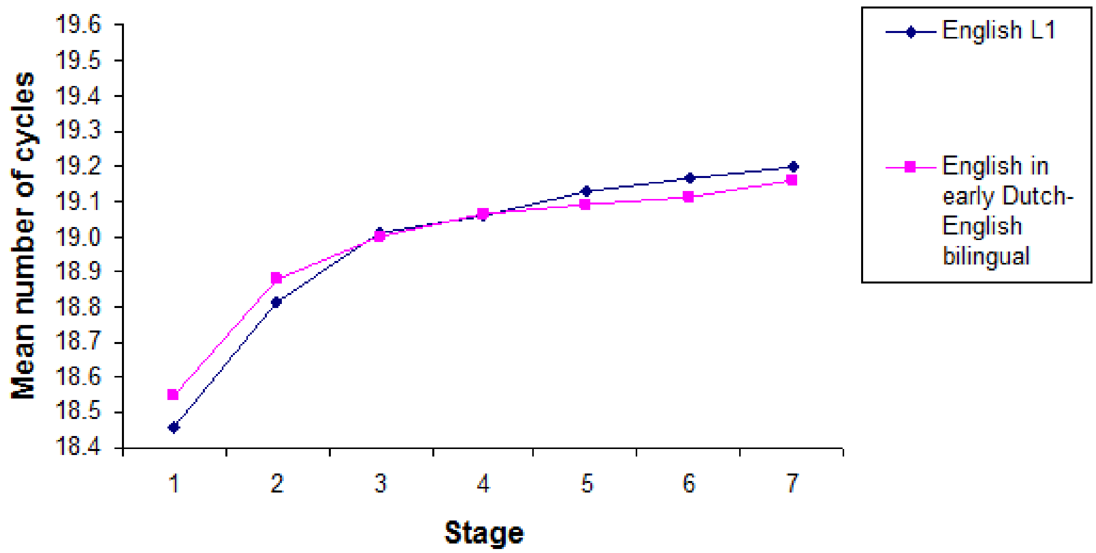

Figure 14. The mean number of cycles until recognition in each stage of learning English as native language and in early Dutch-English bilingual.

2.3.7. Comparison 7: early Dutch-English bilingual vs. late Dutch-English bilingual

There are two general ways to become a bilingual. You can learn both languages at the same time or sequentially. To find out if it is more efficient to learn Dutch and English at the same time, or first Dutch and then English, the acquisition of English by an early Dutch-English bilingual (simulation study 5) can be compared with the acquisition of English by a late Dutch-English bilingual (simulation study 3). Table 13 and Figure 15 show how the mean NCs evolved through the stages and what the differences are between the two ways of learning English. The lexicons used in stage seven were the same, so the final results are the same as well.

The differences in mean NCs were statistically analyzed with t-tests for independent samples. In stage one and two, the English words in an early Dutch-English bilingual were recognized significantly faster than in a late Dutch-English bilingual (respectively $p < .001$ and $p < .01$). In the other stages the words were recognized equally fast.

It can be concluded that it is initially harder to recognize English words when learned after Dutch than at the same time as Dutch.

Table 13

Mean Number of Cycles (With Associated Standard Deviations) Per Group (English in an early Dutch-English bilingual / English in a late Dutch-English bilingual) and Their Differences Between Groups Per Stage.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
English in early Dutch-English bilingual								
Mean number of cycles	18.551	18.878	19.001	19.061	19.090	19.112	19.161	+ 0.610
Std. Deviation	1.101	0.993	0.857	0.786	0.745	0.718	0.692	
English in late Dutch-English bilingual								
Mean number of cycles	19.127	19.138	19.110	19.087	19.084	19.108	19.161	+ 0.034
Std. Deviation	0.840	0.776	0.686	0.643	0.641	0.659	0.692	
Difference								
Mean number of cycles	- 0.576 ***	- 0.261 **	- 0.109	- 0.026	+ 0.006	+ 0.004	0.000	

** p<.01. *** p<.001.

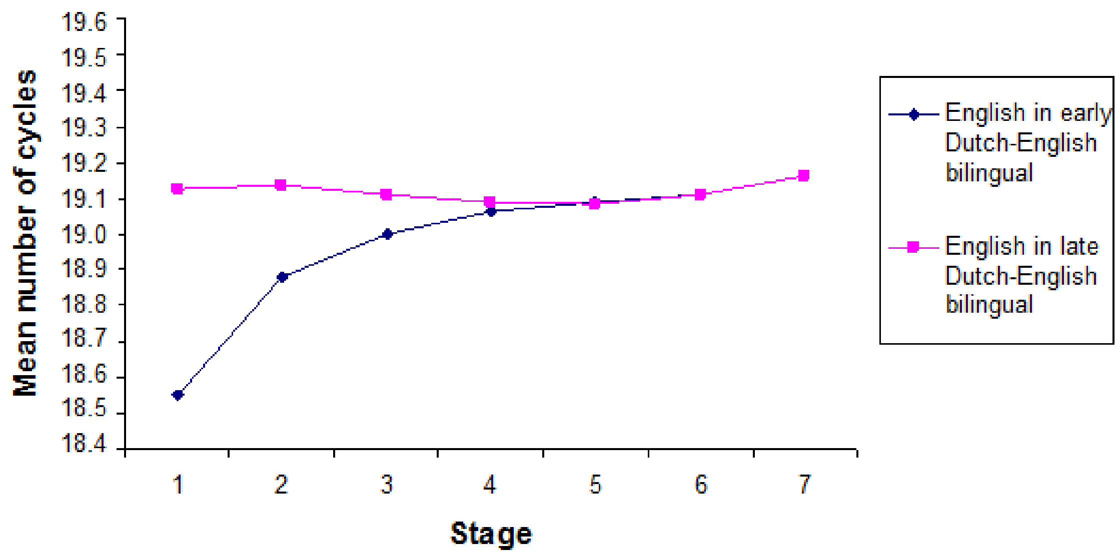

Figure 15. The mean number of cycles until recognition in each stage of learning English in early Dutch-English bilingual and in late Dutch-English bilingual.

2.3.8. Comparison 8: late English-Dutch bilingual vs. early Dutch-English bilingual

To find out if it is more efficient to learn Dutch and English at the same time or first English and then Dutch, the acquisition of Dutch by an early Dutch-English bilingual (simulation study 5) can be compared with the acquisition of Dutch by a late English-Dutch bilingual (simulation study 4). The results can be found in Table 14 and are visualized in Figure 16. They indicate how the mean NCs evolved through the stages and what the differences are between the two ways of learning English. The lexicons used in stage seven were the same, so also the results are the same.

The differences in mean NCs are statistically analyzed with t-tests for independent samples. In stage one to five, the Dutch words in an early Dutch-English bilingual were recognized significantly faster than in a late Dutch-English bilingual (see Table 14 for the p-values). In the other two stages the words were recognized equally fast.

It can be concluded that it is harder to recognize Dutch words when learned after English than at the same time as English.

Table 14
Mean Number of Cycles (With Associated Standard Deviations) Per Group (Dutch in an early Dutch-English bilingual / Dutch in a late Dutch-English bilingual) and Their Differences Between Groups Per Stage.

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Difference last stage - first stage
Dutch in early Dutch-English bilingual								
Mean number of cycles	18.675	18.951	19.079	19.137	19.149	19.168	19.184	+ 0.509
Std. Deviation	1.156	1.138	0.916	0.808	0.748	0.720	0.720	
Dutch late English-Dutch bilingual								
Mean number of cycles	19.470	19.465	19.398	19.330	19.248	19.231	19.184	- 0.285
Std. Deviation	0.988	0.887	0.779	0.784	0.724	0.720	0.720	
Difference								
Mean number of cycles	- 0.795 ***	- 0.513 ***	- 0.319 ***	- 0.193 **	- 0.099 *	- 0.062	0.000	

* p<.05. ** p<.01. *** p<.001.

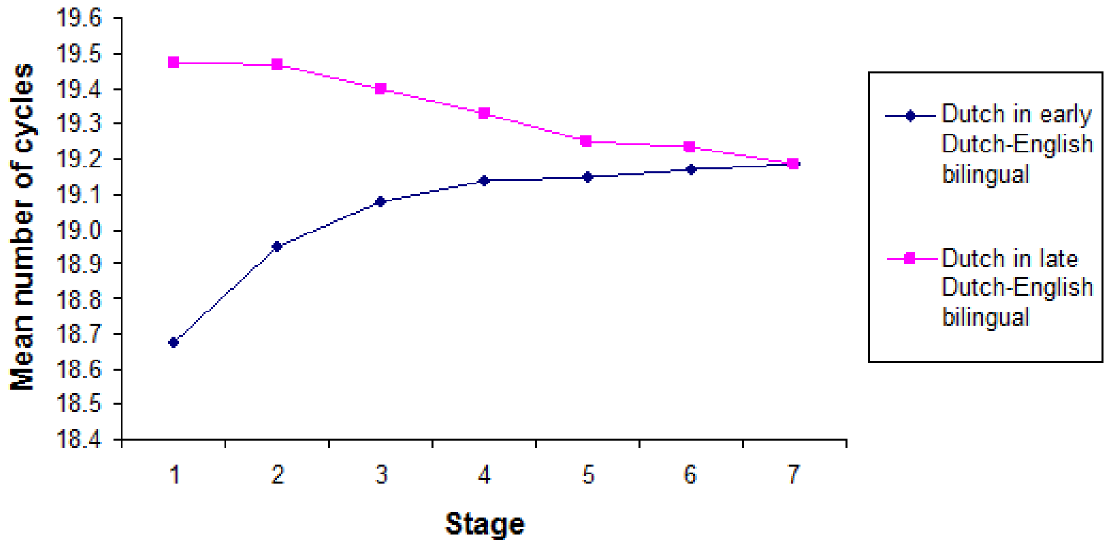

Figure 16. The mean number of cycles until recognition in each stage of learning Dutch in early Dutch-English bilingual and in late Dutch-English bilingual.

3. General Discussion

The learning process of a Dutch monolingual, an English monolingual, a late Dutch-English bilingual, a late English-Dutch bilingual, or an early Dutch-English bilingual was simulated with the BIA model of Dijkstra and Van Heuven (2002). The results of the simulations were compared to each other and statistically analyzed to answer the five research questions formulated in the introduction.

First of all, it can be concluded that, following the described method, the BIA model can simulate language development, in particular, the acquisition of a native (L1) and a second language (L2) vocabulary.

Secondly, it was found that learning Dutch was not very different than learning English. The small differences are probably due to differences in lexicon characteristics. It must be noted that the simulations were concerned only with the orthographic representations for words in an alphabetic writing system. Thus, the precise contribution of semantic and phonological representations and the recognition of words in non-alphabetic writing systems remains to be investigated.

Thirdly, it was found that L2 acquisition affected the word recognition process in the L1. Learning an English vocabulary had a negative effect on the recognition of Dutch words. In the end stages of learning, Dutch words are significantly slower recognized after English has been learned than without it. On the other hand, learning a Dutch vocabulary had a positive influence on the recognition of English words. Here, in the end stages, English was recognized significantly faster after Dutch has been learned than without it. In conclusion, known Dutch words experienced interference from the learned English, but learning Dutch words activated the English words. However, these effects were very small, the differences were on average at most 2 ms.

Fourthly, knowing an L1 affected the acquisition of an L2. In first stages of learning, L2 words were slower recognized. Knowing English had more effect on acquiring Dutch than vice versa. Even when the number of used words in the two languages was equal, the same conclusion could be drawn.

Finally, it can be concluded that it is more efficient to learn languages simultaneously (like an early bilingual), than sequentially (like a late bilingual). During the stages of acquisition an early bilingual recognized its L2 words faster than a late bilingual.

These conclusions provide an answer to the research questions. In evaluating the conclusions, the following aspects of the simulations are important to consider. For every word used in the simulations, a recognition time was calculated. The word recognition times were roughly between 16 and 22 cycles, which can be compared to empirically obtained response times of 400 to 550 ms. In a word naming task, Harley (2001) found reaction times which around 500 ms (p. 143), whereas reaction times in lexical decision are usually around 550 ms. Given these observations, we can link the cycle times in the simulations to reaction times in empirical studies by assuming that 1 cycle simulation time would correspond to about 25 ms reaction time. All words were recognized by the model, even the first words of a second language. The initially low frequency words were slower recognized than higher frequency words, but they were recognized correctly (rather than their high frequency competitors). In stage 1 of learning, the Dutch words as L2 were recognized 0.966 cycles slower than the same words as L1. This was the biggest difference found in the simulations and would correspond with 24 ms in behavioral data. On average, the Dutch words as L1 were recognized in 18.504 cycles (463 ms) and same words as L2 in 19.470 cycles (487 ms). This is a relative small difference, which would not change much with a somewhat different ratio between cycle times and reaction times. A link from L2 words to the translation equivalent L1 words, like Grainger et al. (2010) suggested, was not needed to be able to recognize the L2 words. (However, note that we are assuming that the lowest frequency of a word is 2 opm. Of course, the first encounter with a word cannot be compared to this.)

We may further note that the first words that children learn are probably different than those that adults learn. Children will acquire more concrete words for new objects and concepts that are directly important in their little world, whereas adults learn many words for known concepts that are more abstract. As a consequence, our approach needs an empirical check and can be developed in further research.

The program that we applied could not handle words that are represented twice in one lexicon, like interlingual cognates and false friends. Those words cannot be recognized, because both word forms would be activated, but not enough to be recognized (due to lateral inhibition). If a context is added, the language to which the word belongs would be known, and then it could be recognized.

Furthermore, only four-letter words were used in the simulations, because the program cannot directly handle words with different lengths in one lexicon. However, other versions of the model are available that can process three and five letter words (see Dijkstra, 2003) for simulations with such words). This research can be re-done with, for example, five-letter words. Only the parameters between the levels in the BIA model have to be adjusted. Then the new data can be compared with the data from this study. If the same results were found, it will be more plausible that the found results also apply in reality.

Our conclusions only apply to Dutch and English four-letter words. Dutch and English are orthographically quite similar to each other. Many letter combinations occur in both languages, leading to many interlingual neighbors. Therefore, Dutch and English experienced interference from each other. A new study with different languages might yield different results. Very dissimilar languages will experience less interference from each other and will affect each other less. This can be tested in further research.

On the basis of the present results, I would advise that one should start early with learning a second language. Learning a second language has influence on the word recognition of the first language, but this influence is surprisingly small. For English people, it may be hard to learn Dutch, but rewarding in the end. For Dutch people, it is easy to start learning English, but will be more difficult in the end. And for people who want to do research on language development, it is possible to use the BIA model.

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Appendix A

In this study, the BIA model re-written in Java by P. Gerke and L. Dijkstra was used. We wanted to determine the number of cycles (NCs) needed until recognition for several words and for several lexicons in stead of for one word at the time. A batch job, called BatchCycleTimes, was made and used to determine the NCs needed for all the words of one lexicon.

The batch job needs as input: a file with a feature lookup table for the alphabet; a lexicon with words and associated opm-values (CELEX occurrences per million); a file with test words; and an output file where the found NCs are printed.

For every word of the lexicon the NCs was calculated. The original model only had a function to cycle a particular number of times. As we needed the number of cycles until recognition, we adapted the cycle function. The program will proceed until one word has an activation of 70% or higher, then it is highly probable that the word you are reading is this word.

But we wanted to know what the NCs were when the word was exactly 70% activated. Therefore, we also adapted how the number of cycles is saved by the program. Continuous values were used instead of discrete cycles. The NCs were counted with continuous values by interpolating the interval where the threshold 0.7 was passed. For example, when the activation after 18 cycles was 0.6 and after 19 cycles it was 0.8, the NCs until recognition became 18.5. The activation after 18 cycles is used to calculate the exact NCs needed for recognition. The exact NCs = 18 + (0.7 – 0.6) / (0.8 – 0.6). With continues cycles you can save more details. Now for example, ‘book’ can be recognized in 18.568 cycles, in stead of in 19 cycles.

The re-written Java program already changes the frequencies (opm) into so-called resting level activations (RLAs). In the past for every new lexicon these RLAs had to be calculated first, using the formula described by McClelland and Rumelhart (1986, p. 216). The word with the highest frequency received the highest RLA, this caused that words with higher frequencies were recognized faster. RLAs have typically values between 0 and -0.92.