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BACHELOR OF SCIENCE THESIS IN ARTIFICIAL INTELLIGENCE

Exploration and Testing of the Multilink Model

Simulating the Word Translation Process

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Abstract

In the field of language, word translation is a particular interesting process that comprises multiple complex processes such as word recognition, meaning retrieval and word production. To learn the underlying processes in word translation in bilinguals and explain the seeming contradicting and ambiguous empirical results in this field, this study uses a computational mode, Multilink, to simulate the word translation process. This study used the stimulus material of Christoffels et al. (Christoffels, De Groot, & Kroll, 2006) and manipulated four variables: (1) translation direction (from L1 to L2 vs. from L2 to L1), (2) L2 proficiency, (3) frequency effects (high frequent words vs. low frequent words), and (4) cognate status. Language direction and cognate status seemed to may be causal factors. Complete cognate translation equivalents and false friends in the stimulus material showed to have a major influence on the mean translation times, and also leading to large language direction effects. Furthermore, erroneous translations from non-cognates showed that the direct link between orthography and phonology, as assumed in the Revised Hierarchical Model, only leads to more problems and mistranslation.

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1 Introduction

Communication is one of the basic human skills. Both spoken and written language are used extensively in everyday life. Unraveling these skills and their underlying processes is a major goal of psycholinguistics. In the past, most research in the psycholinguistic field has been done in monolingual settings, although there has been an increased interest in bilingual research in recent decades (De Groot & Kroll, 2014; Altarriba & Heredia, 2008; Bhatia & Ritchie, 2012). One would expect to see more multilingual research being done, because there are over 6800 languages in the world (Sutherland, 2003) and only about 200 countries. In other words, more often than not more than one language is used for communication in one country (Grosjean, 1982).

We are able to acquire multiple languages and translate between these languages with, seemingly, relative ease. This capability is of vital importance in regions or countries where more than one language is widely spoken. Word translation is arguably one of the most complex tasks a human can perform, because to achieve it several skills such as word recognition, meaning retrieval and word production must work together. However, although translation involves many concerted cognitive actions, all bilinguals, even children, are able to do it easily. How is it that bilinguals and multilinguals perform this complex task so easily and efficiently?

Translation can take place via two routes. These two routes, Concept Mediation and Word Association, are depicted in figure 1 for how a Dutch-English bilingual might translate the English word *bike* to the Dutch word *fiets*. Translation via the Concept Mediation route is indirect translation using the meaning of the word. For example, reading the English word *bike*, look up the meaning of *bike* and generate the Dutch spoken word *fiets*. Another possibility is that the word form in one language directly activates its translation equivalent in the other language. Using the same example as before, written and spoken words forms for *fiets* are directly linked to the written and spoken word forms of *bike*. This is called Word Association. A word translation model that combines these two routes is the Revised Hierarchical Model (RHM) (Kroll & Stewart, 1994).

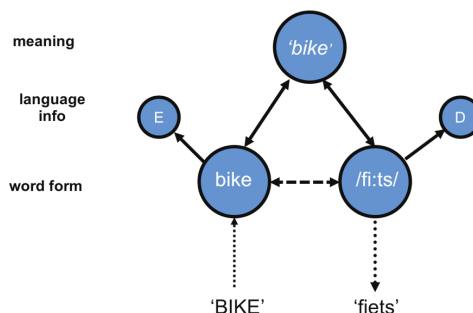


Figure 1: A general symbolic framework for word translation (T. Dijkstra & Rekké, 2010).

A verbal model, the RHM, will be described in detail in the next section. Three empirical studies concerning word translation will be discussed to explain the use of implemented models. In later sections, the Bilingual Interactive Activation Plus model, the WEAVER++ model, and the Multilink model will be described which are all implemented models. Multilink is an implemented model for word translation and combines aspects of the other models. Finally, computer simulations using the Multilink model will be described and compared to empirical data to clarify the cognitive mechanisms that underlie word translation in bilinguals who are more or less proficient in their languages.

1.1 The Revised Hierarchical Model

The RHM assumes that words in a bilingual's languages have separate word form representations but shared conceptual representations. Figure 2 depicts how the English word *bike* will be translated to the Dutch word *fiets* for a Dutch-English bilingual. L1 refers to the first, native language of the bilingual and L2 refers to the second, foreign language. The Dutch word *fiets* in figure 2 is from the native language of the speaker (L1), which means that Dutch is considered the mother tongue in this example. L2 contains the English word *bike*, thus this is a Dutch-English bilingual.

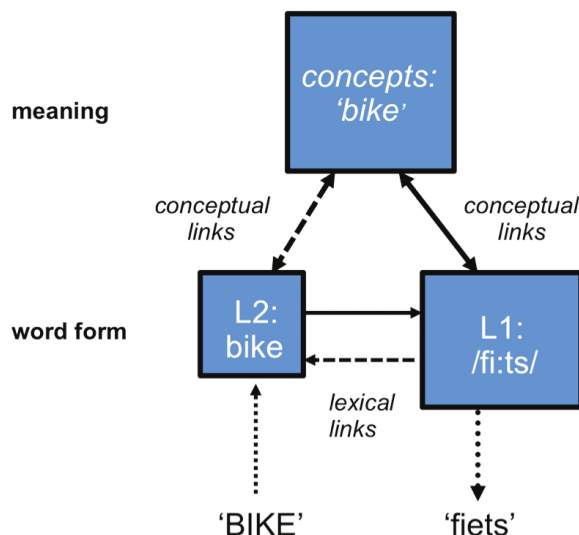


Figure 2: The Revised Hierarchical Model for word translation (Kroll & Stewart, 1994).

The two lexicons of a bilingual are, according to the RHM, bi-directionally connected via lexical links and differ in size. The link from the word form of L1, the native language, to the concept is stronger than the L2 link. Also, the lexical link from L2 to L1 word form is stronger than the other way around. This asymmetry was proposed by Kroll and Stewart (Kroll & Stewart, 1994) and can also be seen in figure 2 where strong links are represented by solid lines and weak links by broken lines. The asymmetry only holds for unbalanced bilinguals. It plays a role during the acquisition of L2 when bilinguals learn to associate an L2 word form with its L1 translation equivalent. This implies that, until a sufficient level of L2 proficiency is achieved, words in L2 are likely to require mediation via the translation equivalent in L1 to reach the concept. Therefore, forward translation, from L1 to L2, is more probable to involve Concept Mediation, while backward translation, from L2 to L1, is achieved via Word Association (Kroll & Stewart, 1994). The RHM predicts that translation via Concept Mediation takes longer than via Word Association (because it requires one cognitive step more) and was proposed to account for the asymmetric translation performance. Furthermore, translation time is also affected by the L2 proficiency level of the bilingual, and certain features of the translation equivalents (e.g., frequency of the words and cognate status). Contrary to what is assumed in the RHM, several studies have shown that word forms for two languages are likely to be stored together, much like the semantic system, instead of being in separated stores (French & Jacquet, 2004; Fabbro, 2001; Abutaleb, Cappa, & Perani, 2001).

Three empirical studies that applied the translation production paradigm will be discussed and compared now.

1.2 Empirical Studies

An empirical task that has often been used to test the RHM and obtain information about word translation more generally, is the word translation production task. The task has often been used to study how L2 word forms are mapped onto meaning (De Groot et al., 2011). In the present study, we consider it with respect to the more general aspects of the word translation: to study if the L1/L2 word translation process is asymmetrical in nature, as described in the RHM, the influence of cognate status (i.e., whether cross-language words have similar form and meaning) of the translation equivalents on translation correctness, and the influence of word frequency on translation speed.

In two experiments, De Groot et al. (De Groot, Dannenburg, & Vanhell, 1994) found significant cognate facilitation effects (faster translation times for cognates compared to non-cognates) for both forward translation and backward translation (see table 1). Also, more proficient bilinguals had shorter translation times than the less proficient bilinguals. However, experiment 1 (in which the subjects were slightly less proficient than in experiment 2) showed faster translation times for backward translation for non-cognates than forward translation, whereas experiment 2 showed the opposite effect. For cognates, the language effect was the same for both experiments with forward translation having faster response latencies.

In another study that used word translation production, Kroll et al. (Kroll, Michael, Tokowicz, & Dufour, 2002) replicated the cognate facilitation effects that had been found in earlier studies (Costa, Caramazza, & Sebastian-Galles, 2000; De Groot et al., 1994; Kroll & Stewart, 1994) with a larger effect for less fluent bilinguals. Moreover, more fluent bilinguals produced significant short translation latencies than less fluent bilinguals. Interestingly, a significant positive language effect, where backward translation is faster than forward translation, was found for all bilinguals.

Christoffels et al. (Christoffels et al., 2006) compared the word translation production performance of trained interpreters to that of bilingual university students and highly proficient English teachers. Interpreters translated faster than students and made less errors. Students, but not translators or teachers, were significantly faster in forward translation than backward translation. Cognates were translated significantly faster than non-cognates by all three groups. However, the cognate facilitation effect tended to be smaller for high-frequency words than for low-frequency words.

As can be seen from these three studies, empirical results are ambiguous and conflicting: Asymmetric and symmetric effects have been found for both forward and backward translation production. Without a better understanding of the underlying process of word translation, it is unclear why different result patterns were observed across studies.

1.3 Computational Models

It is important to note that although this model inspired many studies, is a non-implemented symbolic model. A verbal model (e.g., the RHM), in contrary to the Bilingual Interactive Activation Plus model, the WEAVER++ model and the Multilink model, often underspecifies and is incomplete. Although this makes verbal models flexible and adaptable, it also leads to vagueness and problems regarding model interpretations. On the other hand, although the RHM is a pre-quantitative model (i.e. a ‘verbal-boxology’ model), it has been tested, extended, and applied more broadly. This shows the inspirational use of this model, its ‘research generability’. However, several of the obtained empirical results are ambiguous and the RHM has been subject to various kinds of

Christoffels et al.				
Group		L2 \rightarrow L1	L1 \rightarrow L2	Language effect
<i>HP bilinguals</i>				
	Cognates	705	701	
	Non-cognates	929	933	
Average		817	817	0
<i>LP bilinguals</i>				
	Cognates	864	811	
	Non-cognates	1092	1016	
Average		978	912	66
De Groot et al.				
Group		L2 \rightarrow L1	L1 \rightarrow L2	Language effect
<i>LP bilinguals (experiment 1)</i>				
	Cognates	1111	1099	
	Non-cognates	1390	1463	
Average		1251	1281	-30
<i>LP bilinguals (experiment 2)</i>				
	Cognates	1044	1008	
	Non-cognates	1328	1315	
Average		1186	1162	20
Kroll et al.				
Group		L2 \rightarrow L1	L1 \rightarrow L2	Language effect
<i>HP bilinguals</i>		964	1104	-140
<i>LP bilinguals</i>		1223	1511	-288

Table 1: Mean word translation latencies for different proficiency groups (high proficient (HP) and low proficient (LP) for three empirical studies.

criticism (Brysbaert & Duyck, 2010).

Here computational models can help to better understand the intricate process of translation by means of simulating that process. Computational models require a precise implementation of specific assumptions, and the clarity and consistency of these assumptions must be accounted for to make the model functional. This ensures that the interactions of the underlying mechanisms are clarified in detail. Moreover, computational models lead to fast and accurate simulations of both quantitative and qualitative nature.

In the coming sections, three computational models are discussed that are important for understanding the translation process. It has been suggested that the verbal RHM should be abandoned in favor of an implemented model such as the Bilingual Interactive Activation Plus (BIA+) model (A. Dijkstra & Van Heuven, 2002). However, even though the BIA+ model is useful as a symbolic connectionist model, it is not a word translation model but a word recognition model. As such, it only implements the recognition part of word translation.

1.3.1 The BIA(+) Model

The Bilingual Interactive Activation Plus (BIA+) model is a, partly implemented, localist-connectionist model that simulates the word recognition process in monolinguals and bilinguals (T. Dijkstra & Van Heuven, 1998; A. Dijkstra & Van Heuven, 2002). The BIA(+) model extends the Interactive Activation model (McClelland & Rumelhart, 1981), which is one of the best-known monolingual word recognition models, to the bilingual domain. Words are activated language non-selectively in a bottom-up fashion. This means that recognition begins with an identification of letters that then activate possible words in both languages. Language nodes associated with the words serve as language membership representations in order to differentiate words from different languages, for instance Dutch and English. These nodes are special to the BIA model. However, the BIA model, just as the Interactive Activation model, suffers from a restriction in word length due to position-specific coding of the letters.

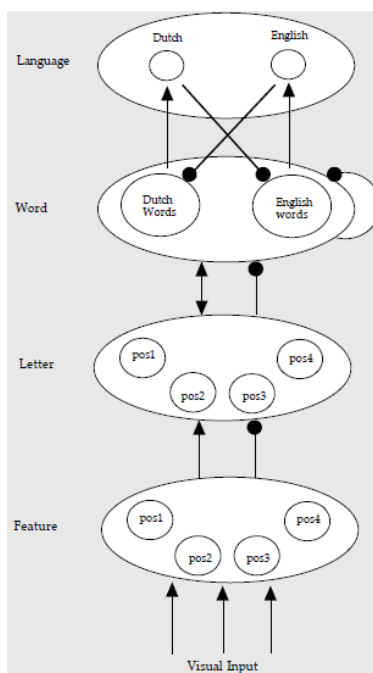


Figure 3: The Bilingual Interactive Activation model. Excitatory connections are indicated by normal arrows and inhibitory connections by round-headed arrows.

Whereas the BIA model implemented only the language membership and orthographic representations for words (figure 3), the BIA+ also includes phonological and semantic representations (figure 4) as well as a task/decision system to perform different tasks. In order to extend the BIA+ model from word recognition to word translation a number of problems must be overcome, as is clear by considering figure 1 and figure 4. First, it is important to implement a control process to ensure the correct translation is chosen. Second, a solution has to be found for the difficult implementation of the lexical phonological and semantic representations. Third, a mediating semantic representation must be implemented between the orthographic (input) and the phonological (output) representation.

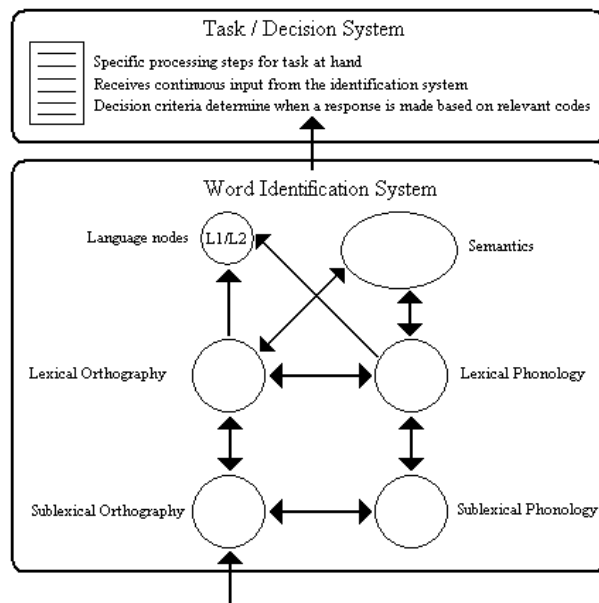


Figure 4: The Bilingual Interactive Activation Plus (BIA+) model for bilingual word recognition (A. Dijkstra & Van Heuven, 2002).

1.3.2 WEAVER++

WEAVER++ (Word Encoding by Activation and VERification) is a computational model designed to explain how humans plan and attentionally control the production of spoken words (Roelofs, 1997). It has been applied predominantly to the monolingual field; however, in a more recent study it has been applied to bilingual issues as well (Roelofs, 2003). This model is a ‘hybrid’ model in the sense that it combines a declarative associative network (“knowing what”) and a procedural rule system (“knowing how”). This model is important for the translation process, because it models the language production step, from ‘S’ to ‘P’. Thus, the present study assumes a translation from an orthographic representation (‘O’) to a phonological representation (‘P’) via a semantic representation (‘S’).

1.3.3 Multilink

The Multilink model (T. Dijkstra & Rekké, 2010) is a recent computational model for multilingual word translation and is implemented in a localist-connectionist fashion. Because the translation process includes aspects of word recognition, meaning retrieval, and word production, the Multilink model combines aspects of RHM, BIA+, and WEAVER++ to model this whole process as effectively as possible. For example, the representational framework for word translation consists of an integrated multi-language lexicosemantic system as proposed by BIA/BIA+ and WEAVER++, containing orthographic, semantic, and phonological representations for multiple languages. Similarly, this model assumes a task/decision system in a similar fashion as both models. Similar to the RHM, it shares the notion of conceptual mediation and the different sizes of the L1 and L2 lexicons. A number of other assumptions made by Multilink are similar to those by La Heij et al. (La Heij, Hooglander, Kerling, & Van Der Velden, 1996).

1.3.3.1 Activation Process

A word presented to the Multilink model, of any length, results in the activation of the orthographic representation of the input word and of other words similar to the input, irrespective of their language. The orthographic representations lead to activation of semantic representations. For example, take the English word *fork* as input. The activation of *fork* leads to activation of the lexical-orthographic representations of the Dutch word *vork*, the English word *work* and the semantic representation for *fork* (see figure 5). The level of activation depends on (1) the similarity with the input and (2) the words' frequency. The similarity with the input is determined by the Levenshtein distance between the two strings. Activation of candidates with different lengths is computed by normalizing the Levenshtein distance for length. The word frequency determines the resting level for that representation with a more frequent word having a higher resting level activation. The basic activation functions are equal to those used in the IA model (McClelland & Rumelhart, 1981) and the BIA model (T. Dijkstra & Van Heuven, 1998). The level of activation is calculated each time step via the sum of the activation on the previous time step and the input from all connected nodes (including the presented word). When (1) the activation level of a lexical-phonological representation exceeds a certain threshold, and (2) the representation represents a spoken word for which the language is different from the input word, the associated lexical-phonological representation will be produced as output. Using the same example as before with the English word *fork* as input, the output word cannot be English. Considering a Dutch-English bilingual, the output word can only be the Dutch word that has exceeded the threshold first. Because the model does not check if the output is the correct translation, some mistakes may still be made.

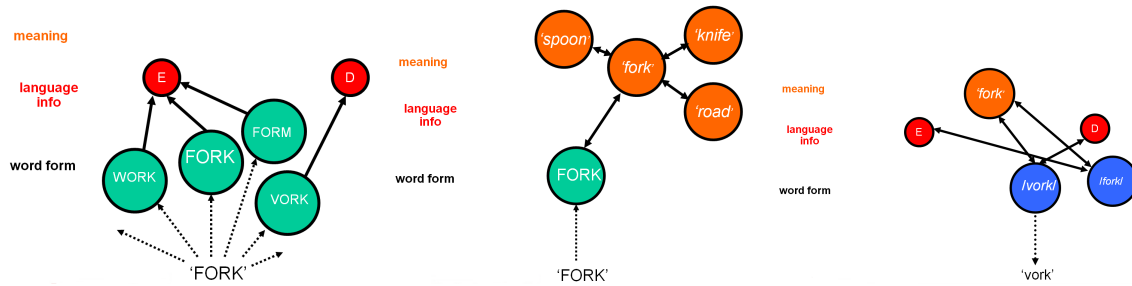


Figure 5: Activation process for the input word *fork*.

As proposed by the RHM, there are two possible routes for word translation. In beginning bilinguals, the Word Association route is especially important. This means that the lexical-orthographic representation of the input word is linked to the lexical-phonological representation of its translation equivalent without mediation of the semantic layer. This connectivity can be achieved in one of two ways: (1) The orthographic representation of the input word activates the orthographic representation of the translation equivalent, which will activate the phonological representation of the output word; (b) the orthographic representation of the translation equivalent is activated, which activates the phonological representation of the output word. Since Multilink concentrated thus far on adult performance, the Concept Mediation route is the only possible route. Therefore, activation of a phonological presentation cannot can only directly be achieved via the semantic representation.

1.4 Research Questions

The research questions addressed by this study are:

- Is it possible to simulate word translation using the Multilink model?
- Can Multilink explain the diversity in empirical data regarding word translation?
- Can Multilink account for the following effects in word translation:
 1. Direction of language effect: $L1 \rightarrow L2$ vs. $L2 \rightarrow L1$
 2. Proficiency of the second language (L2)
 3. Frequency effects: high vs. low frequency
 4. Cognate status: cognates vs. non-cognates

Because the empirical data of Christoffels et al. (Christoffels et al., 2006) are the most extensive and the best documented, this study tries to replicate it using the Multilink model. More specifically, the following four variables will be explored and simulated:

1. Language effect
2. Proficiency of the second language, L2
3. Frequency effects
4. Cognate status

2 Method

2.1 Stimulus Materials

The study by Christoffels et al. used two sets of word stimuli for their translation task as depicted in appendix 2b in their paper (Christoffels et al., 2006). Both sets contain 72 English-Dutch translation equivalents. Set 1 was used for English to Dutch translation and set 2 vice versa. Appendix A, figure 10, shows the stimuli used in the translation task. In order to simulate the translation task, frequency ratings for all the selected words are needed. Dutch word frequency was taken from the CELEX database (Baayen, Piepenbrock, & van Rijn, 1993) and English word frequency was taken from the Kucera and Francis database (Kucera & Francis, n.d.), which is also a part of the CELEX database. All word frequencies are used as occurrences per million (ocm). This number reflects how many times a certain word is encountered when a million words are read. Not all words from Christoffels et al. could have been simulated, because some word frequencies were missing from the CELEX database. In addition, the identical cognate word pair *hand* - *hand* was not used for translation, because the identical orthographic representations result in simulation problems (i.e., what is the language membership of this input word?). The lexical characteristics of the remaining stimuli are given in figure 7.

Kolmogorov-Smirnov normality tests show that only the 10-log frequency distribution of the stimuli is normally distributed. Further statistical analyses indicate that the distributions of the 10-log frequency for low frequent, cognate words of the Dutch-English set differ significantly ($p \leq 0.03$).

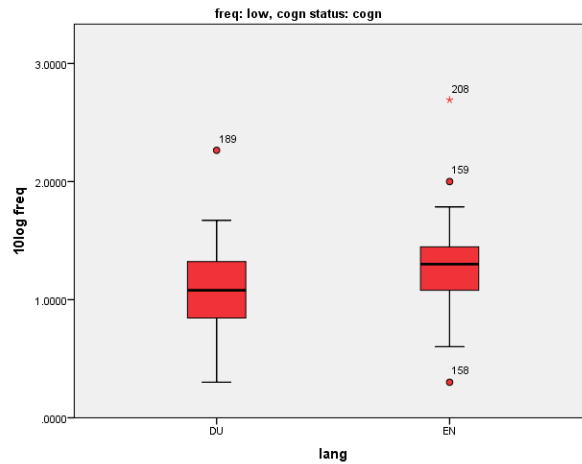


Figure 6: Boxplots of the distributions that differ significantly with the boxplot for Dutch left and for English right.

The boxplots of these distributions can be seen in figure 6. Although the rest of the distribution and medians are not significantly different, one must still be careful because the stimuli groups are small ($n \leq 18$). A small sample size is prone to show no statistical significance where a bigger sample size could conceivably indicate statistical significance.

2.2 Design

In order to test what variables can possibly explain the diversity in the empirical data, different simulations will be conducted. As mentioned before, the four variables are: (1) language effect, (2) proficiency of the second language, (3) frequency effects, and (4) cognate status. The simulation data was collected for three proficiency groups. The highest proficiency group replicates the *interpreters* group in Christoffels et al. and the lowest two proficiency groups try to replicate the *students* group. It is important to note that the L2 proficiency and word frequency both affect the same variable within in Multilink model, but in different ways.

2.3 Simulations

For the simulation process, subsets of the selected words by Christoffels et al. (Christoffels et al., 2006) were used. Set 1 contains 71 English-Dutch translation equivalents and set 2 65 Dutch-English translation equivalents. Word frequency, cognate status, and L2 proficiency were manipulated. L2 proficiency was manipulated by taking the standard, balanced bilingual (bilinguals with full proficiency in both languages), lexicon and dividing the word frequencies for L2 (in this case the English word frequencies) by four and ten to mimic the lexicon of an unbalanced Dutch-English bilingual. This resulted in three groups with different L2 proficiency: ‘complete bilinguals’, ‘students 4’ (English word frequencies divided by 4), and ‘students 10’ (English word frequencies divided by 10). The translation task with the balanced bilingual lexicon was simulated in both translation directions for all words to test the similarity of the two different sets. For both the unbalanced bilingual lexicons the translation task was simulated in both translation separately, from English into Dutch for the first set and from Dutch into English for the second set.

English-Dutch (group 1)				
Measure	High frequency		Low frequency	
	Cognates	Noncognates	Cognates	Noncognates
<i>Dutch stimuli</i>				
10 Log frequency	2.1	2.2	1	0.8
Length (# of letters)	5.4	4.9	5.5	5.8
<i>English stimuli</i>				
10 Log frequency	2.1	2.2	1.2	1
Length (# of letters)	5.3	5.1	5.3	5.3

Dutch-English (group 2)				
Measure	High frequency		Low frequency	
	Cognates	Noncognates	Cognates	Noncognates
<i>Dutch stimuli</i>				
10 Log frequency	2.2	2.1	1.1	1.1
Length (# of letters)	5.4	4.9	5.3	5.4
<i>English stimuli</i>				
10 Log frequency	2.3	2.2	1.3	1.3
Length (# of letters)	5.3	4.3	5.3	5.4

Figure 7: Properties of the stimuli used in the translation task.

3 Results

With the structure described by the RHM, a number of problems arose. The first simulations showed that complete cognate translation equivalents, e.g. *hand-hand*, could not be translated properly. Complete cognate translation equivalents are characterized by a similar orthographic representation in both languages and this resulted in a much faster word translation. The fact that the translation equivalent in such cases is receiving maximum activation from the first time step onwards, speeds up the translation process notably. More problems arose with false friends (e.g. *room*, which is both a Dutch and an English word). Translating the English word *room* to the Dutch word *kamer* resulted in an translation time increase of almost 50%. These two examples in the stimulus material have a remarkable influence on the mean translation times. These examples are deleted from the stimulus material.

Figure 8 shows the results for the first simulations including the complete cognate translation equivalents and false friends in the stimulus material. Forward translation (from L1 to L2) was for all three groups in this case faster than backward translation.

Also, some non-cognate words were translated into a pseudo-cognate that was an erroneous translation. For example, the English word *ant* was incorrectly translation into the Dutch word *tante* (the Dutch translation equivalent for *aunt*). Why this happened will be discussed in the next section. For all further simulation purposes, updated lexicons were used in which the complete orthographic cognate pairs were deleted to account for the empirically observed effects above as best as possible. Moreover, as explained before, not all words used by Christoffels et al. (Christoffels et al., 2006) could be simulated due to this structure.

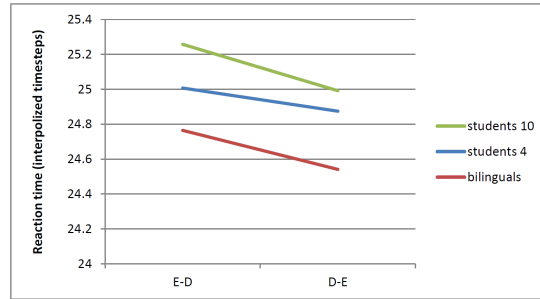


Figure 8: Mean translation times (in time steps) for the three different groups for both translation direction before the changed made to the stimulus material.

Using two different sets of words for the two translation directions is understandable from an empirical perspective but it also brings some complications with it. Section 2.1 discussed the stimulus material and found almost no significant differences between the two sets. However, in the light of the findings above, simulations in both translation directions for both sets have been conducted and depicted in table 2. No difference has been found between the two sets when compared in both translation directions for the complete bilingual group.

	L1 → L2	L2 → L1
Set 1	24.61	24.61
Set 2	24.62	24.63

Table 2: Mean time steps (TS) for set 1 (English-Dutch words) and set 2 (Dutch-English words) in both translation directions for the complete bilingual group.

Simulations for all three groups were conducted on both set (in only one translation direction per set) using the updated stimulus material. A graph with the mean time steps can be found in figure 9. For the complete bilingual group there was no difference found between the translation directions (see also table 2), but the other two groups were faster in backward translation (L2 to L1) in comparison to forward translation (L1 to L2), contradicting the findings for students by Christoffels et al. (Christoffels et al., 2006). Correlations of 94% for the complete bilinguals, 85% for the ‘students 4’, and 82% for the ‘students 10’ with their respective counterparts in the study by Christoffels et al. have been found.

It can also be observed that the difference between the complete bilingual group and ‘students 4’ is much bigger than the difference between ‘students 4’ and ‘students 10’. This indicates that dividing the English word frequencies by a bigger number to replicate the unbalanced bilingual has not much effect. This is because the high frequency words are affected much more than the low frequency words, but after dividing all English word frequencies by 10 one end up with all low frequency words with small differences in word frequency.

A precise breakdown of all mean time steps and error percentages for the three groups is shown in table 3. The error percentages are for all three groups the same with the exception that ‘students 10’ made one less mistake the low frequency non-cognates. From table 3 can be observed that high frequency words, especially English high frequency words, are produced much slower when the L2 proficiency decreases. The language effect is calculated by subtracting the mean translation time

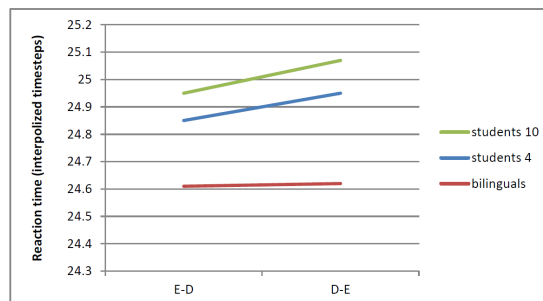


Figure 9: Mean translation times (in time steps) for the three different groups for both translation direction after the changed made to the stimulus material.

for the forward translation from the mean translation time for the backward translation. Thus, a negative language effect means a faster mean backward translation time. Also, the translation times from erroneous translation has been taken out.

4 Discussion

4.1 Direction of Language Effect

As has been shown in section 1.2, there are some inconsistencies between the empirical studies in the field of word translation, especially for direction of language effect. The first experiment by de Groot et al. (De Groot et al., 1994) and the study by Kroll et al. (Kroll et al., 2002) found a faster backward translation whereas the second experiment by de Groot et al. and the study by Christoffels et al. showed, in some cases, faster forward translation. As can be seen from figure 8, at first this study found a faster forward translation for all L2 proficiencies, but after some alterations to the stimulus material a faster backward translation was found for the lower proficiency groups (figure 9).

Interestingly, this study tried to replicate the experiment, and with that its findings, by Christoffels et al. and found similar results at first. This suggests that Multilink can be used to simulate the word translation process in bilinguals. However, after editing the stimulus material to account for a disproportionate influence some word translation pairs had on the mean translation times, a faster backward translation for the groups with a lower L2 proficiency, and no language effect for the complete bilinguals was found. The translation pairs taken out of the stimulus material were *room-kamer* (from set 1) and *hand-hand* (from set 2). *Room* is both a Dutch and a English word and therefore the model was significantly slower translating *room*. *Hand* was translated faster since its translation equivalent has a similar orthographic representation. The differences in translation times found before the editing and after indicate that good stimulus material is important and hard to make. Possibly, if Christoffels et al. used stimulus material without false friends and complete cognate translation equivalents, different results would have been found.

The stimulus materials used in the experiments by de Groot et al. (De Groot et al., 1994) is not readily available and it is therefore unknown whether it also used false friends and complete cognate translation equivalents, but it is a real possibility. This is not to say that faster forward translation is not possible, conceivably the stimulus materials used in the study by Kroll et al. (Kroll et al.,

Group	Language				Language effect	
	English-Dutch		Dutch-English			
	TS	%error	TS	%error		
<i>complete bilinguals</i>						
Cognates						
	HF	22.77	0	23.12	5.88	
	LF	24.03	0	24.19	0	
Non-cognates						
	HF	25.37	0	25.15	12.50	
	LF	26.60	11.11	26.50	7.14	
Average		24.61	2.82	24.62	6.15	-0.01
<i>students 4</i>						
Cognates						
	HF	23.09	0	23.69	5.88	
	LF	24.11	0	24.31	0	
Non-cognates						
	HF	25.84	0	25.69	12.50	
	LF	26.65	11.11	26.62	7.14	
Average		24.85	2.82	24.95	6.15	-0.1
<i>students 10</i>						
Cognates						
	HF	23.19	0	23.91	5.88	
	LF	24.12	0	24.33	0	
Non-cognates						
	HF	25.97	0	25.89	12.50	
	LF	26.73	5.56	26.64	7.14	
Average		24.95	1.41	25.07	6.15	-0.12

Table 3: Mean time steps (TS) and error percentages (%error) for high frequency (HF) and low frequency (LF) cognate and non-cognate words per language and per group, and the difference in time steps between the two language directions (language effect) for the complete bilinguals, the student 4 group (English lexicon divided by 4), and the students 10 group (English lexicon divided by 10).

2002) contained some problematic translation equivalents as well, it is merely to show that stimulus materials should always be checked for these. A future study including both empirical data and computational data could explain better what the consequences are.

4.2 Proficiency of the Second Language

First, it is important to note that the L2 proficiency in this study is manipulated solely by changing the word frequency for English words. Variables such as lexicon size, knowledge of the grammar system, and syntax could have an impact as well, therefore it is unlikely to assume that L2 proficiency is influenced exclusively by the word frequency. However, the high correlations with the empirical data from Christoffels et al. (Christoffels et al., 2006), even though the language effect was reversed, suggest that for word translation the word frequency is a good predictor for L2 proficiency.

It was clearly visible in all three empirical studies that a lower L2 proficiency resulted in a

slower translation times in case of word translation, which has been replicated in this study as can be seen in figures 8 and 9. This is also to be expected from the model, because word frequency plays an important role in the amount of activation.

4.3 Frequency Effects

Frequency is highly related to L2 proficiency in Multilink since it both involved differences in word frequency and therefore leads to similar results. As was also found in the empirical data, high frequency words are translated faster than low frequency words with Multilink. In this study it was also found that high frequency words were more affected by changes in L2 proficiency than low frequency words where the results by Christoffels et al. indicate a opposite effect. This could suggest that the way L2 proficiency was manipulated in this study can be improved. Possibly, high frequent words in different proficiency groups are equally high frequent, because they are recognized and used by all groups equally where low frequency words are recognized but used less for lower L2 proficient. This could explain the differences in the results between this study and Christoffels et al. regarding frequency effects.

4.4 Cognate Status

In the empirical data was found that cognates are generally translated faster than non-cognates, because of their bigger orthographic overlap. In this study similar results were found with a smaller mean translation time for cognates than non-cognates in both language direction (see table 3). In the RHM, a direct link between input (orthography) and output (phonology) is assumed and could possibly explain the faster mean translation time for cognates. However, a direct activation spread from orthography to phonology, without the intervention of semantics, leads to problems as can be observed from the erroneous translation from the English word *ant* to the Dutch word *tante* (aunt) that Multilink made during simulations. Initially, *ant* is activated but, as explained in section 1.3.3.1, *aunt* gets partially activated as well due to the low Levenshtein distance. Activation spreads from *ant* to the semantic node for *ant*, but also orthographically similar words, for instance *tante*. Later on, *tante* also receives activation from *aunt* via the semantic node and the combination leads to the erroneous translation.

These errors were made, even though activation can only spread via a semantic node in Multilink. There is no direct link between input and output. Assuming a direct link from input to output, as in the RHM, would lead to more errors, because the output is less influenced by the activation it gets from the semantic level. Bilinguals making this type of error is highly unrealistic when they have obtained a certain level of L2 proficiency whereas this type of mistakes were made during all proficiency levels in Multilink. A possible solution to this problem is to let the model check whether the output word as input word result in the same word as the initial input word. For example, check if the translation for *tante* would result in *ant*. If not, then it is a erroneous translation and the model must look for another output. It is not sure whether this is also done by bilinguals, but this would lead to several problems. The translation time would be affected greatly, especially when errors are made. Also, in some cases, errors unlikely made by bilinguals could still be made by Multilink if the same translation mistake will be made in both translation directions. Another possible solution is to check in the lexicon whether the output word is indeed the translation equivalent of the input word, but this would be considered as cheating by the model and is implausible for bilinguals. It is also possible to implement a rule that only gives an output when

enough semantic activation has been reached for its related node. It is clear that a good solution to this problem has still to be found, but also other problems regarding cognate status should be considered (e.g., How to determine the cognate status between Chinese and English words?).

5 Future Research

Further research within the field of word translation could benefit from Multilink. This study shows some promising results regarding Multilink and simulating the word translation process, but the simulations can only be as good as the empirical data they are based on. A study which obtains better empirical data about word translation that is fine-tuned to the Multilink model, and simulates with the same stimulus material the translation process using the Multilink model is necessary. Also, it is not certain whether time steps in Multilink and translation times in empirical data are linear and can be treated as such. It is possible to manipulate the translation speed in Multilink to test what the relation is between these two ways.

A possible extension for Multilink is implementing relationships between semantic nodes. Orthographic nodes can activate each other, the same holds for phonological nodes, but semantic nodes can only activate orthographic or phonological nodes. Semantic relationships are extensive and difficult to implement, but could be a solution to the problem with certain erroneous translations such as *ant-tante* discussed in section 4.4. It should lead to a more fluent and human-like translation.

Section 4.3 suggests that the way L2 proficiency is manipulated in this study could be distinct from how varying levels of L2 proficiency differ in bilinguals. The results from Christoffels et al. indicate suggest that low frequency words should be more affected by the level of L2 proficiency than high frequency words. It is unclear how this holds for different empirical studies, so further research is necessary.

6 Conclusion

Multilink has shown its potential in the field of word translation and this study shows that it is possible to simulate the word translation using the Multilink model. It shows insight in what humans do during translation, because it is not a theoretical model but a computational model. Multilink shows to be a powerful tool, especially when some extensions are implemented.

The aim of this study was to explain the differences in empirical data in the field of word translation in terms of (1) language effect, (2) L2 proficiency, (3) frequency effects, and (4) cognate status. Three empirical studies have been compared and discussed. Multilink showed that, in principle, it can account for these variables in the word translation process. Although it is not possible to be definitive, language direction and cognate status may be causal factors for why the empirical studies are ambiguous and contradictory. The effect from language direction was mostly due to the initial stimulus material and the problems that came with it. Complete cognate translation equivalents showed to be much faster translated than others and false friends resulted in much slower latencies. Including or excluding these instances resulted in a significant change, leading to large translation direction effects. Also, non-cognates were sometimes erroneously translated into a pseudo-cognate, i.e. a word in the other language that orthographically and/or phonologically is similar to the input word but is not the translation. These problems show that the structure assumed by the RHM is debatable. Especially the direct link between an orthographical and

phonological representation cannot exist without mediation from the semantics layer. Even though this direct link is not implemented in Multilink, and every translation has to pass through the semantics layer, these problems still arose in the simulations. A direct link between orthography and phonology would only lead to more mistranslations.

It is important to note that simulations can only be as good as the empirical data they are based upon. Therefore, better empirical data are necessary that are fine-tuned to the Multilink model to replicate the findings from this study.

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A Words used in Simulations

Cognates				Non-cognates			
High frequency		Low frequency		High frequency		Low frequency	
Stim.	Transl.	Stim.	Transl.	Stim.	Transl.	Stim.	Transl.
<i>English - Dutch</i>							
EAR	OOR	INSECT	INSEKT	WOMAN	VROUW	SHARK	HAAI
CULTURE	CULTUUR	MURDERER	MOORDENAAR	QUESTION	VRAAG	PEACH	PERZIK
GROUND	GROND	SCANDAL	SCHANDAAL	SCIENCE	WETENSCHAP	GARLIC	KNOFLOOK
TASK	TAAK	CALF	KALF	GARDEN	TUIN	STOMACH	MAAG
COFFEE	KOFFIE	SLAVE	SLAAF	CARE	ZORG	JUICE	SAP
QUALITY	KWALITEIT	HEATHEN	HEIDEN	DOG	HOND	SCAR	LITTEKEN
CHANCE	KANS	HEAT	HITTE	TOWN	STAD	ROPE	TOUW
MOTHER	MOEDER	PIRATE	PIRAAT	TREE	BOOM	SLEEVE	MOUW
MOUTH	MOND	DOMAIN	DOMEIN	DANGER	GEVAAR	ANT	MIER
POLICE	POLITIE	SHEEP	SCHAAP	VILLAGE	DORP	QUARREL	RUZIE
FINGER	VINGER	RICE	RIJST	MONEY	GELD	PENCIL	POTLOOD
FOOT	VOET	FOX	VOS	LAW	WET	TREATY	VERDRAG
HAIR	HAAR	FLAME	VLAM	WALL	MUUR	PIGEON	DUIF
WORD	WOORD	PANIC	PANIEK	FEELING	GEVOEL	COWARD	LAFKAARD
METHOD	METHODE	WARMTH	WARMTE	LADY	DAME	TENANT	HUURDER
NAME	NAAM	SAUCE	SAUS	STORY	VERHAAL	CURSE	VLOEK
WORLD	WERELD	THIEF	DIEF			PIG	VARKEN
FIGURE	FIGUUR	PIPE	PIJP			GLOVE	HANDSCHOEN
<i>Dutch - English</i>							
PRIJS	PRICE	NAALD	NEEDLE	OORLOG	WAR	KRAAN	TAP
DOCHTER	DAUGHTER	BAKKER	BAKER	GEZICHT	FACE	SPELD	PIN
SCHOUDE	SHOULDER	BIJBEL	BIBLE	TEKEN	SIGN	WROK	GRUDGE
NATUUR	NATURE	BRUID	BRIDE	KUNST	ART	STIER	BULL
MUZIEK	MUSIC	MUIS	MOUSE	VOLK	PEOPLE	GEDULD	PATIENCE
STRAAT	STREET	PAREL	PEARL	RAAM	WINDOW	LAWAAI	NOISE
NACHT	NIGHT	HONING	HONEY	BOER	FARMER	DEKEN	BLANKET
PUBLIEK	PUBLIC	ZILVER	SILVER	MEISJE	GIRL	PLAFOND	CEILING
ZOON	SON	KATOEN	COTTON	AUTO	CAR	STAART	TAIL
VRIEND	FRIEND	KLIMAAT	CLIMATE	TAAL	LANGUAGE	KOORTS	FEVER
VADER	FATHER	KROON	CROWN	OOG	EYE	DUIM	THUMB
ZEE	SEA	LAM	LAMB	JONGEN	BOY	VERF	PAINT
ZOMER	SUMMER	MOTIEF	MOTIVE	BEEN	LEG	HERFST	AUTUMN
STEEN	STONE	PEPER	PEPPER	LICHAAM	BODY	SLAGER	BUTCHER
EINDE	END	RITME	RHYTHM	HUID	SKIN		
JAAR	YEAR	TIJGER	TIGER	VOGEL	BIRD		
HUIS	HOUSE	ZEEP	SOAP				
		ZWEET	SWEAT				

Figure 10: Stimuli used in the translation task and their translation equivalents.