

INVITED ADDRESS

**WHAT NUMBER TRANSLATION STUDIES  
CAN TEACH US ABOUT  
THE LEXICO-SEMANTIC ORGANISATION IN BILINGUALS**

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This article starts with a review of the major findings about the representation of written language in bilinguals, both at the level of word forms (lexical level) and at the level of word meanings (semantic level). Then, the most important model of bilingual word translation is described, followed by some recent findings on number translation that are problematic for the model. Finally, a new masked priming experiment is presented, in which Dutch-French bilinguals had to name Arabic digits (e.g., 5), number words of their first language (e.g., vijf), and number words of their second language (e.g., cinq) both in their first and second language. The targets were preceded by a masked Arabic prime numeral, which had a value ranging from Target minus three (e.g., prime 2 – target 5/vijf/cinq) to Target plus three (prime 8 – target 5/vijf/cinq). Previous research with monolinguals had shown that the priming effect of Arabic numerals depends on the difference in magnitude between prime and target (e.g., the target 5 is primed most by 5 and least by 2 and 8). This effect was repeated in the present study and extended to the translation conditions. Regression analyses revealed strong priming effects in both forward (from first to second language) and backward translation. Based on these findings, we argue that future models of bilingual memory should see all translation processes as the result of the summed activation from a semantically mediated route and a direct, lexical route.

According to Grosjean (1982, pp. vii), about half of the world's population has reasonable knowledge of more than one language and, thus, can be considered bilingual. This estimate further increases if one sees significant differences between home dialects and standard languages as another form of bilingualism. Indeed, the fact that most dialects are not treated as separate languages is politically motivated rather than scientifically based (Fabbro, 1999). Finally, widespread bilingualism is not a privilege of Western coun-

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tries. For example, the three main languages of Cameroon are mastered by more than half of the population (Bamgbose, 1994).

In contrast to the omnipresence of bilingualism, psycholinguistic research on the phenomenon has been relatively rare. Reasons for this scarcity are the assumption that one first has to understand the processing of a single language before one starts to tackle the mastery of several languages, and the conviction that one can study the mother tongue of a bilingual as if there were no other language. Only recently has it become clear that both assumptions may be wrong and that studies of multilingual processing are likely to contribute to the understanding of monolingual language processing as well (e.g., Brysbaert, *in press*; Dijkstra & Van Heuven, *in press*; De Bot, 1992). In the first part of this article, we present a short review of the major psycholinguistic findings related to bilingualism, followed by some relevant new empirical findings on number translation. The review of the literature is confined to the processing of visually presented words.

#### A Lexical and a Semantic Level of Word Representations

Essentially, to become bilingual, one must acquire the capacity to derive meaning from second language word forms (for listening and reading), and the capacity to produce meaning with these new forms (for speaking and writing). In addition, the meaning expressed by words from the second language (L2) is likely to be closely related to the meaning that otherwise would be conveyed with words from the first language (L1), even though the word forms of both languages may be very different. The fact that in bilinguals two different word forms are mapped on the same semantic concept, is one of the reasons why researchers have started to think of visual word recognition as a process involving two different kinds of representations. The first representation has to do with the word forms and is generally called the lexical level (because the "dictionary" of known words is referred to as the mental lexicon). The second representation is related to the meaning of the words and is called the semantic level<sup>1</sup>.

As noted by Kroll (1993), the fact that researchers of bilingualism in the beginning did not make a clear distinction between lexical and semantic word representations, was the origin of many contradictory findings about

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<sup>1</sup> Note that the distinction between lexical and semantic information does not imply serial processing, in which a word form must first be identified before meaning can be attached. Most current models of word recognition see lexical activation as a competition process that takes some time and during which activation continuously dissipates from the lexicon to the semantic system (and according to some models returns due to top-down connections).

the organisation of the bilingual language system. Studies that emphasised word meanings mostly produced evidence for a single language system shared by both languages, whereas studies that primarily addressed lexical processes seemed to provide support for two distinct, language-specific systems. In the sections below, we will first review the evidence in favour of a single semantic system accessed by L1 and L2 words, and then address the issue of how the lexical level of a bilingual should be thought of.

### The Organisation of the Semantic System in Bilinguals

There are several sources of evidence that L1 and L2 words access a common conceptual system. First, studies of interference effects, such as the Stroop-effect and the negative priming effect, have repeatedly shown that processing in one language interferes with processing in the other language (see Francis, 1999, for a review). For instance, Fox (1996) presented English-French bilinguals with two displays per trial. On the first display, an Arabic digit was shown with the same word printed above and beneath the numeral (e.g., the digit 5 between the words "pepper" and "pepper"). Participants were asked to indicate whether the digit represented an odd or an even number and to ignore the flanking words. On the second display, a single string of letters was presented and participants had to indicate whether the string formed a legal word or not (lexical decision). Fox found that lexical decision to L2 words was slowed down when these target words were semantically related to L1 words that had been presented as flankers on the previous display (i.e., participants needed more time to indicate that "SEL" [salt] was a French word when on the previous display the word "pepper" had been used as flankers). Negative priming was also observed from L2 flanking words on L1 targets if both words were translation equivalents (i.e., "sel" used as flanker and "salt" as target).

Second, primed lexical decision tasks have shown that processing of a word is facilitated about 75% as much when it is immediately preceded by a semantic associate in the other language as when it is preceded by a semantic associate in the same language (Francis, 1999). Thus, de Groot and Nas (1991) found that for Dutch-English bilinguals, lexical decision to the word "girl" was faster not only after the prime "boy" but also after the prime "jongen" (the Dutch word for boy). Similarly, Grainger and Frenck-Mestre (1998) observed that English-French bilinguals were faster to decide that the letter sequence "tree" formed a legal English word when it followed the French translation prime "arbre" than when it followed the unrelated prime "balle" [ball]. The effect was found despite the fact that primes were presented for 43 ms only and could not be reported by the participants. The

translation priming effect was reliably stronger when participants were asked to perform a semantic categorisation task rather than a lexical decision task, yielding further evidence that the origin of the effect was semantic.

Third, semantic comparisons between words from different languages have been shown to take no longer than comparisons between words of the same language, again suggesting the integration of semantic information between languages (for a review, see Francis, 1999).

Fourth, Dijkstra and colleagues (Dijkstra, Grainger, & Van Heuven, 1999; Dijkstra, Van Jaarsveld, & Ten Brinke, 1998) found that lexical decisions are faster for cognates than for interlingual homographs and language-unique words of the same frequency. Cognates are words in two languages that have the same meaning and a large overlap in orthography and phonology (e.g., "apple-appel" in English and Dutch). Interlingual homographs also share phonology and orthography but not meaning (e.g., "room" is a word both in English and in Dutch, but means *cream* in Dutch). Language unique words are words that only exist in one language. The faster reaction times to the cognates than to the other two types of words can only be explained if one accepts that they are due to the similarity in meaning in L1 and L2. Such a facilitative effect should not occur if semantic representations (at least for cognates) are not shared across languages.

Finally, using FMRI, Illes et al. (1999) measured the brain activity of proficient bilinguals performing a semantic categorisation task (abstract vs. concrete word) in L1 and L2. These authors were unable to find significant differences in brain activity between both language conditions. In L2 as well as in L1, there was enhanced activation in the left inferior prefrontal cortex, in line with previous monolingual studies.

Although few researchers still doubt that multilinguals have a single central semantic system, accessed by all the languages known, this does not imply that the meaning of all words in the different languages must be the same. Indeed, bilinguals often have the feeling that for a word (or expression) in one language there is no word in the other language with exactly the same meaning. To capture this aspect of bilingualism, de Groot and colleagues developed the conceptual feature model (de Groot, 1992a; de Groot, 1992b; de Groot, 1993; de Groot, Dannenburg, & van Hell, 1994). In this model, semantic concepts are not represented by single nodes but by a bundle of feature nodes. Each word activates a number of feature nodes and if two words in L1 and L2 have exactly the same meaning (which may be the case for the words "appel" and "apple"), they will activate the same pattern of features. However, words with slightly different meanings (such as "groot" in Dutch and "great" in English) will result in slightly different patterns of activation. de Groot argued that concrete words tend to have more similar meanings across languages than abstract words, and therefore will

show a larger feature overlap. Consequently, if translation requires semantic mediation, one can predict that it will be easier to translate concrete words than abstract words. This is indeed what De Groot et al. (1994) found. However, Tokowicz and Kroll (2002) recently criticised this finding and argued that it may be due to the number of translation equivalents for a given concept. Abstract words tend to have a wider meaning than concrete words and this meaning can often be expressed with several synonyms, leading to the activation of more candidate words for the translation of an abstract word and, hence, to greater lexical competition (and slower RTs). We will talk more about the possible influence of word concreteness on L2 semantic representations in the General Discussion.

In summary, there is a large consensus that the semantic representations of translation equivalents are shared across languages. For a more detailed discussion of this topic, we refer to Kroll (1993), Kroll and de Groot (1997) and Tokowicz and Kroll (2002).

### The Organisation of the Mental Lexicon in Bilinguals

Because equivalent words in different languages usually have different forms (except for cognates; see above), the intuitively most appealing theory about the lexical organisation of a bilingual person is that there are two different lexicons: one for L1 and one for L2. In addition, it seems to make sense that if a person is reading in one language, only the lexicon of this language is active and the other is temporarily inhibited. As indicated by Dijkstra, Van Heuven, and Grainger (1998) this is a model with language-dependent storage and language selective access.

There is increasing evidence that both the idea of language-selective access and the idea of language-dependent storage are wrong. Here, we will only present some of the more recent findings, as Brysbaert (1998) already published a review of the literature in this journal.

Most of the evidence against language-selective access in visual word recognition comes from Dijkstra and colleagues. For instance, in an experiment on L2 visual word recognition with Dutch-English bilinguals, Van Heuven, Dijkstra and Grainger (1998) manipulated the number of orthographically similar words in L1 and L2. An English word like *left*, for example, has quite some English neighbours that differ from the word in only one letter position (e.g., *deft*, *heft*, *lift*, *loft*, *lent*, *lest*); it also has many Dutch neighbours of this type (e.g., *heft*, *lift*, *lest*, *leut*). Other words have few neighbours both in English and in Dutch (e.g., *deny*), few neighbours in English but many in Dutch (e.g., *keen*), or many neighbours in English but few in Dutch (e.g., *coin*). Previous monolingual research has indicated that

word recognition depends on the neighbourhood size of the word: The more orthographically similar words a target word has, the easier it is to process the word. Van Heuven et al. presented the above four types of English words to native Dutch speakers and found that reaction times not only depended on the number of orthographic neighbours in English but also on the number of orthographic neighbours in Dutch. This indicates that Dutch word forms were activated in the process of English word recognition, even though the Dutch language was irrelevant for the task.

A year later, Dijkstra, Grainger and Van Heuven (1999) ran a similar study with target words that varied in terms of orthographic (O), phonological (P) and semantic (S) overlap between English and Dutch. For instance, the word "film" overlaps on all three dimension, because it is written the same in English and Dutch, is pronounced very much the same, and has the same meaning. In contrast, "wild" is written the same and means the same but is pronounced differently (i.e., overlaps less on the P dimension). Dijkstra et al. found that the speed of word recognition was a function of the cross-lingual overlap of all three codes, again suggesting that during visual word recognition in one language similar word forms in the other language are not suppressed but contribute to the recognition process.

Other evidence for non-selective lexical access in visual word recognition comes from Brysbaert, Van Dyck, and Van de Poel (1999), and Van Wijnendaele and Brysbaert (2002). These authors started from the finding in monolingual word recognition that a target word is more easily processed when it is preceded by a tachistoscopically presented word that sounds the same (e.g., the target word "made" preceded by the prime "maid") than when it is preceded by a tachistoscopically presented word that does not sound the same (e.g., "mark"). Brysbaert et al. (1999) wondered whether the same finding would be observed when an L2 target word (e.g., "oui" (meaning *yes* in French) is preceded by an L1 prime that sounds the same (e.g., "wie" (meaning *who* in Dutch). They indeed found such a cross-lingual phonological prime effect (which was also observed when the primes were non-words). Van Wijnendaele and Brysbaert (2002) further showed that the cross-talk between languages was not limited to the influence of L1 primes on the processing of L2 words, but could also be observed the other way around (i.e., "wie" primed "oui" not only in Dutch-French bilinguals but also in French-Dutch bilinguals).

The early interactions of L1 and L2 word forms also call into question the language-dependent storage assumption (i.e., that L1 and L2 words are represented in different lexicons), although they do not completely rule out this possibility. Strong neuropsychological evidence for separate lexicons would be provided if a double dissociation were reported between a bilingual patient who due to brain damage was dyslexic in L1 but not in L2 (provid-

ed there are no obvious differences between the languages; e.g., that both make use of the same alphabet) and another patient who for the same language pair was dyslexic in L2 but not in L1. This would be evidence for the fact that both lexicons are not only functionally independent but also localised in different parts of the brain. Although such a dissociation has not yet been reported (and indeed is likely never to be reported), a comparable finding in the aphasia literature has been used to argue that L1 and L2 may occupy non-overlapping structures in the brain. This finding is the observation that after brain damage, the ability to speak may be affected differently in L1 and L2. In one of the best controlled studies, Fabbro (2001b) documented language recovery of 20 bilingual aphasics. Of these patients, thirteen (65%) showed a similar impairment in both languages (parallel recovery), four patients (20%) showed a greater impairment of L2, while three patients (15%) showed a greater impairment of L1. In particular, the fact that the native language may be affected more than the second language, has been used by some researchers as an argument that this cannot be explained unless one is willing to accept partly different localisations of L1 and L2 in the brain. Proposals have been that L1 may be stored largely in implicit –procedural– memory (because it was acquired spontaneously) whereas L2 would depend more on explicit –declarative– memory (because it has been studied), or that L2 may make use more of right hemisphere tissue than L1. The majority of authors, however, believe that the failure of a language to recover is not due to its loss, but rather to pathological inhibition. This inhibition is likely to be related to the control mechanisms that normally help with language switching and prevent unnecessary language mixing, pathological excesses of which are also sometimes observed in aphasia (see Fabbro, 2001a; and Gollan & Kroll, 2001, for reviews).

The ambiguity about the storage issue (language-dependent vs. language-independent) is still clearly visible in the psycholinguistic literature, where both views co-exist next to one another. On the one hand, there is the Bilingual Interactive Activation (BIA) model of Dijkstra and Van Heuven (Dijkstra & Van Heuven, 1998; Dijkstra, Van Heuven, *in press*; Dijkstra et al., 1998; Van Heuven et al., 1998), which is based on the idea of a single lexicon shared by L1 and L2 and which can explain the majority of results reported by Dijkstra and colleagues, but which is limited to visual word form recognition and does not address the issues of semantic access or word translation. On the other hand, there are the BIMOLA model of Grosjean (1997) and the revised hierarchical model of Kroll (see below) which deal more with the issues of language control and word translation, and which assume two separate lexicons for L1 and L2.

Irrespective of the issue of one vs. two lexicons, each comprehensive theory of bilingual word processing additionally has to deal with the question

of how bilinguals prevent language confusions, given that access to the lexicon(s) is not language-specific (see above). Why do Dutch-English and French-English readers not experience one confusion after the other while reading English texts, given that many of the English words could have a Dutch/French reading? (In the last sentence alone, the words "do, even, of, and have" exist in Dutch mostly with a different pronunciation and meaning; the words "do, expérience, and confusion" also exist in French). Apparently, at the lexical level there is a mechanism that prevents the words of the "wrong" language to become activated enough so that the reader is aware of them. There is currently a debate going on to what extent this mechanism is susceptible to top-down influences. According to Grosjean (1997; 1998), context factors (i.e., high-level factors) induce a "language mode" in bilinguals which help them to avoid the wrong readings. In contrast, Dijkstra (Dijkstra, *in press*; Dijkstra, Van Heuven, *in press*) believes that the language control mechanism is largely input-driven and cannot easily be influenced by the expectations of the participants.

### Translating Words

In the preceding sections, we have summarised the major findings about the lexical and semantic representations in bilinguals. Now we can look at how these representations interact when a word in one language is translated into a word of the other language. If the translation goes from L1 to L2, we talk about forward translation; the other direction is known as backward translation. Probably the most influential model of word translation is the revised hierarchical model of Kroll and Stewart (1994; see also Kroll & de Groot, 1997).

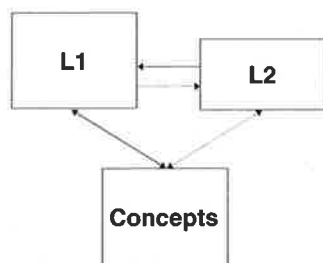
Some of the features of the revised hierarchical model can be traced back to Weinreich (1953) who 50 years ago already proposed three possible models of bilingualism. The first model, the co-ordinate model, consisted of two language-specific lexicons and two semantic systems. As we have seen above, this model is now refuted (it wasn't Weinreich's favourite either). The second model, the compound model, contained two separate lexicons each connected to the same semantic system. Finally, the third model, the subordinate model, also had two lexicons and one semantic system but assumed that word forms in the L2 lexicon only had access to the semantic system through their translation in the L1 lexicon. Weinreich further assumed that bilinguals made a shift from the subordinate model to the compound model when their L2 proficiency increased.

The first study that empirically addressed the question whether word translation requires concept mediation or not was reported by Potter, So, Von Eckardt and Feldman (1984). They started from the finding that pictures



always require semantic mediation to be named (e.g., Potter & Faulconer, 1975), and hypothesised that if translation is semantically mediated, then it would take roughly as long to translate a word from L1 to L2 as to name a picture in L2. In contrast, if word translations are based on direct word-word associations, translation times could be significantly faster than picture naming times. Potter et al. found that the two tasks were performed in approximately the same amount of time, supporting the concept mediation hypothesis. In addition, the effect was obtained both for very fluent and less fluent bilingual participants, questioning Weinreich's developmental hypothesis. Later studies, however, examining second language learners at still earlier stages of acquisition, found faster translation times than picture naming times, in line with Weinreich's predictions (e.g., Kroll & Curley, 1988).

Similar to Weinreich's compound and subordinate model, the revised hierarchical model of Kroll and colleagues (Kroll & Stewart, 1994; Kroll & de Groot, 1997) consists of two language-specific lexical stores<sup>2</sup>, and one common semantic system (see Figure 1). Unlike the earlier models, however, it contains all possible links between the lexical and the semantic components. The only parameter that varies is the strength of the connections. The connections between word forms in L1 and their meanings are assumed to be stronger than those between L2 word forms and their meanings. Similarly, the word-word connections are thought to be stronger from L2 to L1 than the other way around. This is because L2 words are initially learned by associating them with L1 translations. As a consequence, forward translation (from L1 to L2) is more likely to engage conceptual mediation than backward translation, certainly at the first stages of language acquisition. Only when L2 words have been encountered in many meaningful contexts, do the lexico-semantic connections become strong enough for this language too.



*Figure 1.* The revised hierarchical model of bilingual memory (as published in Kroll & de Groot, 1997). Solid lines represent stronger links than dotted lines.

<sup>2</sup> Note that the storage-dependent assumption is not an essential element of the model. The model would also work if the L1 and L2 lexical items were part of a single, combined lexicon, in which translations had direct lexical connections.

Sholl, Sankaranarayanan, and Kroll (1995) reported support for the asymmetry assumption of the revised hierarchical model by showing that forward translation, but not backward translation, was subject to semantic priming. The priming was achieved by presenting pictures related to some of the words prior to the translation task. Similarly, Kroll and Stewart (1994) manipulated the semantic relatedness of the stimuli within a word list: Half of the lists contained words from a single semantic category, half contained words from different categories. This manipulation of context did not affect word naming and backward translation, but did have an effect on forward translation. It was more difficult to translate words in the blocked lists (presumably due to increased competition at the semantic level) than in the mixed lists. Furthermore, backward translation was faster than forward translation, in line with the strong lexical connections postulated from L2 words to L1 words. Similar effects have been reported by other authors (Sánchez-Casas, Davis, & Garcia-Albea, 1992; Cheung & Chen, 1998; Keatley, Spinks, & Degelder, 1994; Fox, 1996).

As for the developmental hypothesis, Talamas, Kroll and Dufour (1999) found greater interference of semantically related false translations in a translation recognition task when participants were highly proficient in L2, whereas less proficient bilinguals suffered more from form-related distractors. Other evidence was reported by Dufour, Kroll and Sholl (1996) who observed that although cognates always are translated faster than matched non-cognates, the effect is particularly strong in beginning bilinguals, suggesting that the overlap in the lexical representations is more important in the early stages of second language acquisition than in later stages. For a more detailed review of the various findings supporting the different assumptions of Kroll's model, we refer to Kroll and de Groot (1997).

Although the revised hierarchical model clearly is the dominant model of word translation, it should be noted that it is by no means the only model. Jiang (in press; 2000), for example, proposed a model in which each lexical entry contains semantic and syntactic information in a lemma component, and morphological and form-related information in a lexeme component (see Kempen & Huijbers (1983) and Levelt (1989) for the origin of word processing models that distinguish between lemmas and lexemes). He conjectured that in the first stage of second language acquisition, L2 words only exist as lexemes with a pointer to the corresponding L1 lexeme. Hence, L2 words initially are not mapped directly onto lemma information (meaning and syntax), but only via their L1 counterpart. Gradually, the lexeme pointer to the L1 word is deactivated, because it does not assist in L2 word use, and a link is established between the L2 lexeme and the lemma of the L1 translation. When this process is finished, lemma copying takes place and L2 words are mapped directly onto meaning. Needless to say, the learning part

of the model closely resembles the developmental aspect of the revised hierarchical model.

### Semantic Mediation in Number Translation

Although the support for the developmental and the asymmetry hypotheses of the revised hierarchical model is quite compelling, there are also a number of findings that are less easy to integrate. Instead of reviewing this part of the literature (see Kroll & de Groot, 1997; see also the General Discussion), we will summarise some of our own recent findings on number translation, which suggest that, at least for some types of stimuli, the connections between L2 word forms and concepts may be stronger and created more rapidly in the L2 acquisition process than indicated by the model.

Brysbaert (1995) found that processing times of Arabic numerals increase when the magnitude of the numeral increases. People need more time to read the number 72 than the number 27. Brysbaert argued that this is because the semantic representation of small numbers can be accessed more rapidly than the representation of large numbers. Based on this finding, Duyck and Brysbaert (2002) reasoned that the issue of semantic mediation in translation could be investigated by looking at the time it takes to translate numbers. If semantic mediation is involved in number translation, then it must take longer to translate the number 8 than the number 2. In contrast, if the translation is based on word-word associations, one would expect that the translation time is fairly constant for all numbers below 20 (assuming that the learning of these L2 number words took place roughly at the same time and with the same frequency). In addition, according to the revised hierarchical model, the number magnitude effect should be significantly larger in forward than in backward translation (unless the bilinguals are highly proficient), since forward translation is assumed to be more semantically mediated than backward translation. Also, backward translation should be faster than forward translation, because it is based on direct word – word associations at the lexical level.

In their first experiment Duyck and Brysbaert (2002, Experiment 1) tested these predictions directly with less proficient and highly proficient (balanced) Dutch-French bilinguals using a translation task with numbers ranging from 1 to 12. Numbers were randomly presented as Arabic numerals (e.g., “5”), verbal L1 numerals (“vijf”), or verbal L2 numerals (“cinq”). Participants had to name the numbers either in L1 or in L2 (blocked conditions). The main findings of the experiment are plotted in Figure 2.

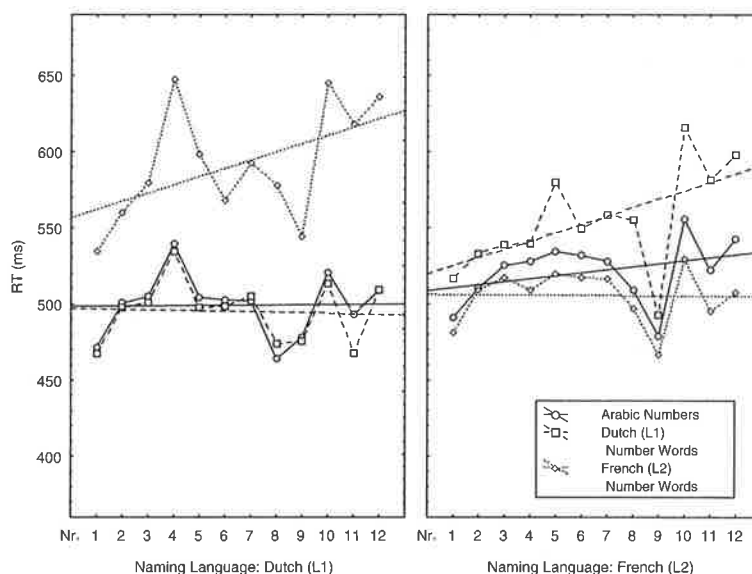


Figure 2. Mean naming RTs across L2 proficiency levels by naming language, target format and number size (from Duyck & Brysbaert, 2002, Experiment 1). Straight lines represent best linear fit according to a least squares criterion.

As hypothesised by Duyck and Brysbaert and in line with the findings of Potter et al. (1984), there was a clear effect of number magnitude in the translation conditions, both forward (Dutch number words, French naming) and backward (French number words, Dutch naming), indicating that the semantic representation had been activated. However, nearly all other details of study ran against the predictions of the revised hierarchical model: The effect was equally strong in backward translation as in forward translation, both for highly proficient *and* less proficient bilinguals (which is why Figure 2 displays the average data and not the data per proficiency group), and backward translation was significantly slower than forward translation. All these findings strongly suggest that semantic mediation was involved to the same extent in backward as in forward translation, already at a low proficiency level.

Because it might be argued that the previous study did not allow of optimal control of the level of proficiency (maybe all participants were too proficient already, even though their performance in L2 was not good) and the frequency of word-word pairings in L2 acquisition (maybe smaller number

words have been encountered more often in L2 than larger number words), Duyck and Brysbaert (2002) in a next experiment trained participants for less than half an hour on an unknown set of non-words called 'Estonian number words' ranging from one to fifteen. Thereafter, an 'Estonian'-Dutch translation task was given. Again, backward translation showed a clear effect of number magnitude, even though the participants had learned these words only twenty minutes before. This indicates that, at least for numbers, new L2 lexical representations are mapped very rapidly onto existing semantic representations. A similar conclusion was reached by Altarriba and Mathis (1997) who trained a group of monolinguals on a set of Spanish words for a limited period of time and presented English-Spanish word pairs in a translation recognition experiment ("are these two words translations?" yes/no). In this experiment, participants not only had problems with lexically related false translations (i.e., words that looked very much like the correct translation) but also with semantically related translations. The latter effect should not occur if new L2 word forms are not mapped onto existing semantic knowledge but simply are associated with the L1 word forms.

A possible objection against the number translation studies discussed so far, is that all stimuli came from the same semantic category and were presented repeatedly. This may have provided sufficient semantic context to boost the semantic mediation in backward translation and eliminated the translation asymmetry (Kroll & de Groot, 1997, pp. 183). To check this possibility, Duyck and Brysbaert (2002) in a final experiment presented the 12 number words only once within a list of 192 unrelated filler words. Again, the magnitude effect was significant for both directions of translation, although this time the size was slightly smaller in the backward translation condition. Once more, this suggests that, at least for some stimuli, semantic mediation in backward translation is more important than implied by the revised hierarchical model.

Below, we further examine the issue of semantic mediation in forward and backward translation of numbers, by looking at the semantic distance priming effect.

### Experiment

Brysbaert (1995) reported that an Arabic numeral was processed faster when it followed another numeral with a close magnitude than when it followed a numeral with a distant magnitude. So, the numeral 65 was recognised faster if on the previous trial the numeral 66 had been presented rather than the numeral 78. The priming effect was a linear function of the distance in magnitude between prime and target and continued up to a distance of 20.

Brysbaert ventured that the distance-related priming effect was due to the facts (1) that the semantic representations of numbers are part of an ordered number line, and (2) that spreading of activation occurs along this line. When a number on the line is activated, the activation does not stay confined to this number but dissipates upward and downward along the line, first to the numbers nearby, then to the next numbers, and so on. Reynvoet and Brysbaert (1999) showed that the distance-related priming effect also could be obtained with tachistoscopically presented primes and short SOAs (stimulus-onset asynchrony, the time between the onset of the prime and the onset of the target). The only difference between Reynvoet and Brysbaert's masked priming effect and Brysbaert's sequential stimulus processing effect was that the masked priming effect levelled off at a distance of plus or minus 3 between prime and target. In addition, Reynvoet and Brysbaert showed that there was a repetition priming effect over and above the distance-related priming. The repetition effect is observed when prime and target refer to the same quantity. Both the study of Brysbaert (1995) and that of Reynvoet and Brysbaert (1999) made use of Arabic primes and targets. Subsequently, Reynvoet, Brysbaert, and Fias (2002) reported that the distance-related priming effect was equally strong when prime and target were presented in different formats (e.g. "3 – five" or "three – 5") as when they were presented in the same format ("3 – 5" or "three – five"), providing further evidence that the priming effect is semantic in origin (i.e., related to the magnitude of the numbers rather than to co-occurrences of digits and number words). There was some evidence that the repetition effect is smaller in the inter-format condition than in the intra-format condition. Finally, Reynvoet (2002, Chapter 5) presented evidence that the priming is stronger for Arabic targets than for verbal targets.

In the present study, we used the distance-related priming paradigm in a number naming and a number translation task to see whether there are differences in the priming between number naming, forward translation, and backward translation. According to the asymmetry hypothesis of the revised hierarchical model, one would expect that the semantic priming effect is significantly stronger for forward translation than for the other two conditions. However, the study of Duyck and Brysbaert (2002) reported above suggests that the priming effects in both translation conditions may be the same.

### *Method*

*Participants.* Twenty-two first-year Dutch-French bilingual university students participated for course requirements. All of them were native Dutch speakers, and mainly used this language in everyday life. They had started to learn French at school around the age of 10.

*Apparatus.* All stimuli were presented in yellow on black on a standard 15" VGA colour monitor. Stimulus presentation was computer driven by a PC equipped with a voice key that was connected to the gameport.

*Design.* The experiment had a 2 (Naming Language: L1 versus L2) x 7 (Prime-target distance) x 3 (Target Format: Arabic numeral versus L1 number word versus L2 number word) x 4 (Target Magnitude: 5, 6, 11 or 12) full factorial design. The seven possible prime-target distances were T-3, T-2, T-1, T, T+1, T+2 and T+3, with T referring to the magnitude of the Target (i.e., for target 6, the primes were 3, 4, 5, 6, 7, 8, and 9). Primes were always Arabic numerals; targets were at random Arabic numerals, L1 verbal numerals, or L2 verbal numerals. All variables except Naming Language were repeated measures. Naming language was a between-groups variable.

*Procedure.* All participants were randomly assigned to one of the Naming Language conditions (L1 or L2). Each of them completed eight blocks of 112 trials. Within these blocks, all 84 combinations of Prime-target distance (7), Target Format (3) and Target Magnitude (4) were presented once in a random order, together with 28 filler trials. Because of this presentation method, translation trials (e.g., L2 naming of an L1 number word) and naming trials (e.g., L2 naming of an L2 number word, and L2 naming of an Arabic numeral) were mixed. The filler trials always had the Arabic number 20 as a prime, combined with a randomly chosen target between 1 and 16 (but not 5, 6, 11 or 12). The format of these targets could be Arabic, verbal L1, or verbal L2. The filler trials were included to extend the number of responses that a participant had to give during the experimental session. Within each series of four trials, one of the trials was a filler trial.

Each trial started with the presentation of a pre-mask (two hash-marks: ##) for 71 ms (synchronised with the refresh cycle of the screen). This was followed by the presentation of the prime (42 ms) and a backward mask (##, 71 ms). Then, the target stimulus was presented, and remained on the screen until the response triggered the voice key. The Inter Trial Interval was 1 s. The experiment lasted for about 55 minutes, including a little break.

## Results

The proportion of invalid trials due to naming errors or faulty time registration was 7.3%. These trials were excluded from all analyses. Figure 3 shows the number naming times as a function of naming language, target format, and prime-target distance. A 2 (Naming Language) x 3 (Target Format) x 7 (Prime-target distance) x 4 (Target Magnitude) was run with

mean RTs as dependent variables. Naming Language was the only between-subject variable.

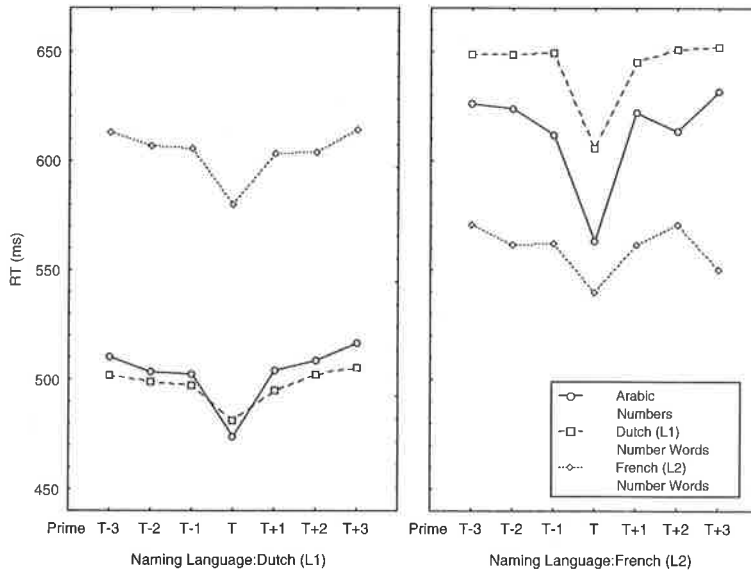


Figure 3. Mean naming RTs by naming language, target format and prime-target distance.

Responses were faster in L1 (535 ms) than in L2 (605 ms;  $F(1, 18) = 6.70$ ,  $MSE = 313800.3$ ,  $p < .02$ ). They also differed as a function of stimulus format ( $F(2, 36) = 12.19$ ,  $MSE = 6441.9$ ,  $p < .001$ ). When participants could respond in their native language, L1 word naming and Arabic numeral naming were nearly the same, and both were about 100 ms faster than backward translation (see the left panel of Figure 3). In contrast, when participants had to name the targets in their second language, they were faster when the stimulus was presented as a word of this language than when it was presented as an Arabic numeral, which in turn elicited faster naming than forward translation (see the right panel of Figure 3). This pattern of results closely resembles the one of Figure 2.

Two effects are important for the issue of semantic mediation in number naming and number translation: The number magnitude effect, and the distance-related priming effect. As for the former, the main effect of target magnitude was not significant ( $F(3, 54) = 1.41$ ,  $MSE = 12707.7$ ,  $p > .24$ ), which could be expected given that in Figure 2, none of the naming conditions



resulted in a strong number magnitude effect (only the translation conditions did; see below). The main effect of prime-target distance was significant,  $F(6, 108) = 41.15$ ,  $MSE = 1022.8$ ,  $p < .001$ . The mean RTs for prime-target distances T-3, T-2, T-1, T, T+1, T+2 en T+3 were 579, 574, 571, 541, 572, 575 en 580 ms respectively. Trials in which prime and target were the same (i.e., distance 0), yielded the fastest response times and were significantly faster than trials with a distance of 1 ( $F(1, 18) = 87.98$ ,  $MSE = 1752.7$ ,  $p < .001$ ). There was a nearly linear increase from distance 1 to distance 3, which was also significant (distance 1 vs. distance 2:  $t(1, 18) = 1.75$ ,  $p < .05$ , one-tailed; distance 2 vs. distance 3:  $t(1, 18) = 2.13$ ,  $p < .05$ ). The distance-related priming effect differed, however, between the conditions as evidenced by significant two-way interactions with the other variables of the design and a significant three-way interaction between naming language, prime-target distance, and target format ( $F(12, 216) = 2.56$ ,  $MSE = 660.5$ ,  $p < .01$ ).

To get a clearer idea of the semantics-related effects in the different conditions, we ran a multiple regression analysis for each of the 6 Naming Language x Target Format condition. The regression analysis included the following predictor variables: Target Magnitude, Distance between prime and target (absolute value), and whether or not prime and target referred to the same magnitude (repetition priming). We made a distinction between distance-related priming and repetition priming because the repetition priming effect (prime "5", target "5/vijf/cinq") may involve lexical word-word associations as well as spreading of activation along the semantic number line (Ratinckx & Brysbaert, 2002; Reynvoet et al., 2002). Following Lorch and Myers's (1990) recommendations for linear regression analysis in repeated measures designs, a separate analysis was calculated for each participant and overall significance of the regression weights was determined with t-tests. The results of the analysis are displayed in Table 1.

Table 1. *The Regression Equations for the Six Naming Language X Target Format Conditions According to the Procedure Described by Lorch and Myers (1990, Method 3)*

		Intercept	Absolute Value of Prime-Target Distance	Repetition Priming	Target Magnitude
L1 Naming (Dutch)	Arabic	$Y = 479$	+ 5.12 D**	- 23.50 I**	+ 2.14 M*
	L1 (Dutch) Number Words	$Y = 498$	+ 3.99 D*	- 11.10 I*	- 0.67 M
	L2 (French) Number Words	$Y = 554$	+ 4.60 D*	- 18.77 I*	+ 5.25 M*
	Arabic	$Y = 604$	+ 5.88 D*	- 46.46 I*	+ 0.62 M
L2 Naming (French)	L1 (Dutch) Number Words	$Y = 643$	+ 1.69 D	- 40.05 I**	+ 3.84 M
	L2 (French) Number Words	$Y = 626$	- 0.74 D	- 24.30 I**	- 7.31 M**

\*  $p < .05$ ; \*\*  $p < .01$ .

From our previous research (Duyck & Brysbaert, 2002, see Figure 2 for a summary), we expected the largest effects of target magnitude in the translation conditions. As can be verified in Table 1, this was indeed the case. Reaction times increased with 5.3 ms per magnitude unit in the backward translation condition (French number words, Dutch naming) and with 3.8 ms per magnitude unit in the forward translation condition (Dutch number words, French naming). As for the priming, effects tended to be strongest in the conditions with Arabic targets, which is in line with previous research (Reynvoet, 2002, Chapter 5) and with the fact that the primes also were Arabic numerals (which would be particularly important for the magnitude of the repetition priming effect; see above). As for the verbal targets, the effects of distance-related priming and repetition priming clearly were stronger in the translation conditions than in the naming conditions. It is more difficult, though, to compare forward and backward translation, as the former (target L1, response L2) tended to result in a bigger repetition priming effect, whereas as the latter (target L2, response L1) tended to result in a bigger distance-related priming effect. Future research will have to indicate whether these differences are genuine or simply due to noise in the data<sup>3</sup>. On the whole, however, there are no obvious indications that semantic mediation was much stronger in forward translation than in backward translation, in line with the data of Duyck and Brysbaert (2002). The effect of target magnitude for example, was significant for backward translation, but not for forward translation, although this effect also tended towards significance in the latter condition,  $t(9) = 1.93$ ,  $p < .09$ .

### General Discussion

A first important set of findings in this study is that we repeated all number priming effects previously reported with the masked priming paradigm (Reynvoet & Brysbaert, 1999; Reynvoet et al., 2002; Reynvoet, 2002, Chapter 5): (a) Number priming consists of a distance-related priming effect and a repetition priming effect, (b) it is not limited to situations in which prime and target are presented in the same format, and (c) it tends to be smaller with Arabic target numerals than with verbal target numerals. In addition, we have obtained evidence that the priming is stronger in translation conditions than in simple naming conditions.

Specifically related to the question whether semantic mediation is less

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<sup>3</sup> In this respect, it may be good to keep in mind that the distance-related priming effect and the repetition priming effect are not orthogonal variables, so that a shift in the weight of one is likely to induce an opposite shift in the other.

important in backward translation than in forward translation, we have collected corroborative evidence for our claim that as far as number words are concerned, lexico-semantic connections are not stronger for L2 than for L1. Hence, both types of translation are not necessarily asymmetric processes. The only difference we observed (but see footnote 3), was that the priming seems to be more focussed to the target in forward translation (L1 target, L2 response; Figure 3, right panel), whereas there may be more spreading of activation in backward translation (L2 target, L1 response; Figure 3, left panel). If this finding can be replicated in future experiments, it may provide a useful constraint on how to implement the L1 and L2 lexico-semantic connections in a computational model of number translation.

An important question at this point is to what extent the finding of strong semantic mediation in backward translation is limited to numerical stimuli or generalises to other types of stimuli, for instance all concrete stimuli with obvious, unique translations. There are a few other studies in the literature which failed to confirm the predictions of the revised hierarchical model. La Heij, Hooglander, Kerling, and Vandervelden (1996, Experiment 1), for example, used a bilingual version of the Stroop task and asked participants to translate colour words presented in different colours. They found that congruent colour words (for which the ink colour corresponded to the word) were translated faster than incongruent colour words. In a series of further Stroop-like experiments with pictures and words presented on the same display, La Heij et al. (1996) found that participants could translate a target word faster if the distractor picture referred to an object (e.g., a table) of the same semantic category as the target word (e.g., chair). Importantly, these semantic effects were present for forward as well as backward translation. Similar bilingual Stroop effects have been reported by Altarriba and Mathis (1997) with a group of English monolinguals who were trained on a set of English-Spanish word pairs (but see Talamas et al., 1999). Finally, de Groot and colleagues examined whether the impact of semantic word variables (such as concreteness) on word translation times was confined to forward translation or could be observed in backward translation as well. A whole series of experiments consistently showed evidence for the latter alternative (de Groot, 1992b; de Groot et al., 1994; de Groot & Comijs, 1995; de Groot & Poot, 1997; van Hell & de Groot, 1998a; van Hell & de Groot, 1998b). On the basis of these findings, we would like to conclude that the revised hierarchical model has underestimated the importance of semantic mediation in backward translation and not only for number words.

It is important to keep in mind, though, that although clear semantic effects for both forward and backward translation have been obtained, the existence of a semantic translation route does not imply that backward translation is always and automatically semantically mediated. We are not ques-

tioning the direct word-word associations in the revised hierarchical model, we only argue that, at least for some types of stimuli, the contribution of the semantically mediated route is stronger than assumed by Kroll and colleagues. Kroll and de Groot (Kroll & de Groot, 1997) also pointed to the possibility that the weight of the semantic contribution may depend on the context in which the word translation happens. When the translation occurs in a highly constraining semantic context, the semantic route may have more impact than when the translation takes place out of context. An interesting question in this respect is to what extent the semantic context is subject to top-down influences or relies on bottom-up activation (see the discussion between Grosjean and Dijkstra, mentioned above).

In our view, many of the findings of word translation can be better understood if the different components of the revised hierarchical model (L1 word forms, L2 word forms, concepts or bundles of concept features) are conceived as different layers of nodes in a connectionist type of model (like in the BIA-model). If such a model is characterised by connections of different weights and by cascaded processing (i.e., activation in one part of the system is automatically propagated to the other parts of the architecture), then the research question no longer is whether one link contributes to the translation "yes or no", but how much each link contributes. A forward word translation could then be considered as a node in L1 that is activated and another node in L2 (preferentially the correct one) that must get enough activation to exceed a certain threshold (to be selected). In a series of cycles, activation from the L1 node will propagate to the L2 nodes and to the semantic nodes (from which it will further propagate to the L2 nodes). The net input from a connection to the target L2 node will depend on the weight of the connection and, for the semantically mediated route, on the activation level of the semantic node(s) involved. The activation coming from L1 and the semantic system will be summed (probably together with inhibitory activation from other, competing L2) and updated each cycle, until the threshold is exceeded. In the process, all connections will have contributed to the selection of the L2 word, but some more than others. On a general level, the connection weights may very well be in line with the proposals of the revised hierarchical model (on average, larger weights between L1 and concepts than between L2 and concepts, etc.), but in addition may differ as a function of the type of words. Similarly, not all forward or backward word-word associations need to have the same weight.

By adjusting the weights in the model and the activation level of the semantic nodes, we are convinced that the above type of model can easily simulate different degrees of semantic mediation in translation. Such a model could also explain the developmental change by assuming that the weights between L2 words and semantic nodes increase as the second lan-

guage learner becomes more proficient. Of course, while the model at present seems plausible in the context of the current paper, it still is a hypothetical description, which needs to be implemented before all the intricacies become clear.

In our hypothetical model we could also take into account all the evidence reported in the introduction showing evidence against two separate lexicons for L1 and L2, and adapt the revised hierarchical model accordingly by considering only one single word layer. Our model, then, would become quite closer to the BIA model, and certainly to the recently presented update, the BIA+ model (Dijkstra, Van Heuven, *in press*). In the BIA+ model, a distinction is made between a word identification system and a task schema. The latter determines which response is to be made (e.g., translation vs. naming) and when a response is to be made on the basis of the input from the identification system and preset decision criteria. The task schema also incorporates all non-linguistic context effects. The word identification system is an extension of the BIA model and, in addition to orthography, includes lexical phonology and semantics. Unfortunately, at present the BIA+ model (just like the model we depicted above) still is a verbal description of a general lay-out without actual implementation.

Finally, we would like to stress that in any viable model of bilingual word representation, the connections between the lexical nodes and the semantic system are likely to be more important than assumed thus far, both for L1 and L2. In one of our experiments (Duyck & Brysbaert, 2002) we found a clear effect of number magnitude for backward translation of number words, even when the targets were scattered among a great deal of filler trials which were not semantically related. Hence, it seems that, at least for number words, the semantically mediated route always has a significant contribution to the translation. As indicated above, we consider it likely that not all connections between word forms and semantic nodes are equally strong. For instance, translation experiments suggest that semantic mediation may be more important for the translation of concrete words than for the translation of abstract words (e.g., de Groot & Comijs, 1995; de Groot & Poot, 1997; but see Tokowicz & Kroll, 2002). A similar conclusion was reached by Jin (1990) who reported larger cross-language priming for concrete than for abstract words. One of the reasons why the translation of concrete words may be more likely to be semantically mediated is that many of these words easily access a visual representation. Indeed, the semantic information need not be verbal information; it can be any information related to the meaning of the word. The possible importance of visual codes for associative word learning was investigated by Duyck, Szmalec, Kemps and Vandierendonck (*in press*) who showed that new word forms are mapped onto existing visual representations quite early in the word acquisition process, provided that

such a representation is available.

In conclusion, several recent experiments on number word translation produced reliable semantic effects of number magnitude in both forward and backward translation. This is strong evidence for the existence of a semantically mediated translation route which can overrule the contribution of the direct, lexical translation route for certain types of words (and under certain circumstances). Any future model of bilingual brain organisation should give this route the importance it deserves.

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