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Understanding bilingual memory: models and data

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Bilingual memory research in the past decade and, particularly, in the past five years, has developed a range of sophisticated experimental, neuropsychological and computational techniques that have allowed researchers to begin to answer some of the major long-standing questions of the field. We explore bilingual memory along the lines of the conceptual division of language knowledge and organization, on the one hand, and the mechanisms that operate on that knowledge and organization, on the other. Various interactive-activation and connectionist models of bilingual memory that attempt to incorporate both organizational and operational considerations will serve to bridge these two divisions. Much progress has been made in recent years in bilingual memory research, which also serves to illuminate general (language-independent) memory processes.

It is widely assumed that at least half of the world's population is bilingual. It comes, therefore, as somewhat of a surprise to learn that there is not a long tradition in bilingual memory research in psychology. The first attempts to put the study of bilingual memory on a sound scientific footing date only from the beginning of the 1950s and only in the past two decades has the field of really come into its own.

In this article we restrict our focus primarily to experimental and computational studies of bilingual memory, with a particular emphasis on the complementary issues of lexical organization and control. Although the early years of bilingual memory research posed many of the questions that remain central to research in this field, such as whether bilingual speakers have two separate lexicons, one for each language, or one large 'bilingual' lexicon, what the underlying mechanisms are that allow language lexical access and lexical selection, and so on, they produced few conclusive answers. Bilingual memory research in the past decade and, particularly, in the past five years, has been exciting because, for the first time, the experimental, neuropsychological and computational techniques of the field have evolved to the point of allowing researchers to begin to answer some of these major outstanding questions. Also of great interest is what the study of bilingual memory might tell us about memory mechanisms in general.

The present article will be organized along the lines of the conceptual division suggested by Grosjean [1]: language knowledge and organization, on the one hand, and the mechanisms that operate on that knowledge and organization, on the other. Various connectionist models of bilingual memory that attempt to incorporate both organizational and operational considerations will serve to bridge these two divisions.

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Bilingual knowledge and language organization

Uriel Weinreich's [2] and Ervin and Osgood's [3] seminal work laid the foundation for early research in bilingualism. The compound/coordinate distinction that they suggested ultimately evolved into the more general question of language storage – specifically, do bilinguals store their languages as a single large or two small stores (SLOTS) [4]?

Initially, three major experimental paradigms dominated the field – namely, word association and naming, recognition and recall, and (beginning around 1970) language transfer and interference (e.g. [5]). The experiments based on these methods, however, produced highly contradictory results concerning knowledge organization in bilinguals. To reconcile these apparent contradictions, language-tag models were developed, in which each word in the store was 'tagged' with the language to which it belonged [6]. Language-tagging, in a modified form, has remained part of current models of bilingualism and their precise status remains a subject of on-going debate (see [7] for a discussion of language tags). For a comprehensive review of this initial period, see [8] and [9].

The modern era of bilingual memory research was ushered in by (i) the highly influential information processing (IP) approach to experimental psychology, (ii) an understanding of the importance of task-specific analyses of experimental data and, (iii) above all, the realization of the need to separate semantics from the lexical instantiation of this semantics.

The IP approach led to the use of experimental tasks involving automatic processing (i.e. driven by spreading activation) and measured by reaction times. These tasks included interference tasks [10], priming tasks, and so forth. Furthermore, by the late 1970s it became increasingly clear that, to understand the contradictory results of previous research, data from bilingual memory studies had to be interpreted in a task-specific manner [11]. Ultimately, there was more-or-less general agreement on the necessity of separating conceptual and lexical levels, the conceptual level being seen as shared by both languages with lexical representations being specific to

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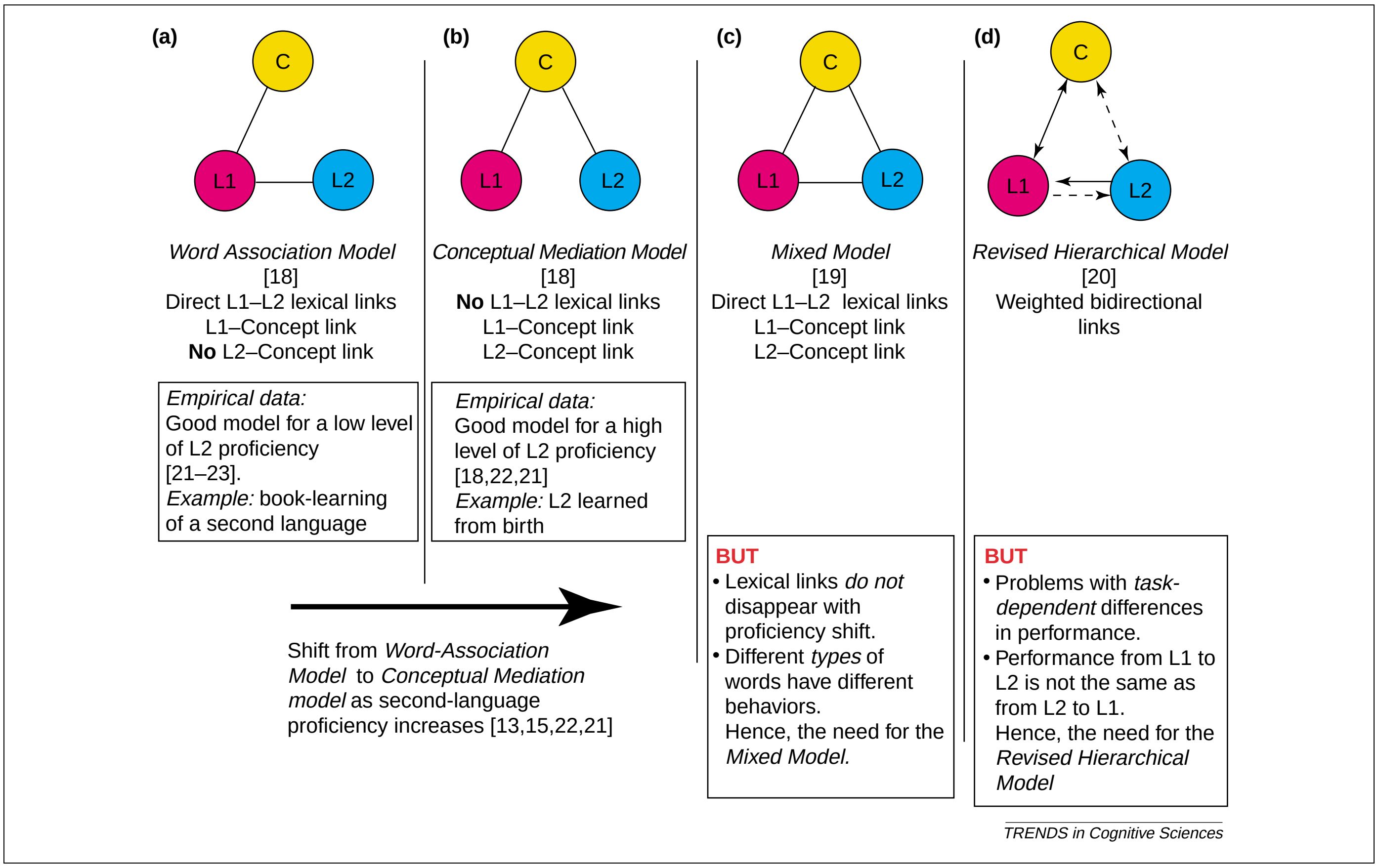

Figure 1. Hierarchical models. There are four types of hierarchical models **(a–d)**, all of which have a single, shared semantic or concept level (C), thereby allowing cross-language semantic priming, and two separate word-form lexicons for the two languages (L1 and L2), justified by the absence of cross-language repetition priming. The models each differ in the number, type and location of the links between these three nodes.

each language. Support for a single conceptual store came from myriad results indicating cross-language semantic priming [12–15]. Support for separate lexical stores came largely from the lack of any convincing evidence of cross-language repetition priming [14,16,17].

Hierarchical models

This conceptual/lexical separation is the basis for the broad class of three-node 'hierarchical models', consisting of the word-association, concept-mediation, mixed and revised-hierarchical models. (See Figure 1 [13,15,18–23]). All these models share a common architecture consisting of two separate lexical stores (one for each language) and one common conceptual store. The type of hierarchical model is determined by the location and weighting of the links between the L1 (first language) and L2 (second language) lexical nodes and the Conceptual node.

In addition, data from bilingual patients with brain lesions have shed considerable light on bilingual memory organization. For example, certain bilingual aphasics also show translation disorders that would seem to support the revised hierarchical model. Various disorders can be described in terms of breakdowns of various links in this model [24,25]).

Hierarchical models have been criticized by several authors because the memory structure for an individual bilingual seemed to vary depending on numerous factors, including the concreteness or abstractness of a given word, its part of speech and, especially, whether its translation was a cognate or not (for a review, see J.G. Van Hell, PhD thesis, University of Amsterdam, 1998). In hierarchical models, although the two lexicons can interact to varying degrees, they are nonetheless separate. This proposed separation was due to the lack of long-term repetition priming: having seen the word 'chien' in a list of French words does not produce faster subsequent word recognition (or related behaviors) of its orthographically dissimilar translation equivalent 'dog' in a list of English words. This argument for a separate-lexicon structure for bilingual memory is, nonetheless, open to a 'level-of-observation' problem. If we consider the phenomenon at the perceptual level, repetition priming involves similar perceptual components [26]. When we fail to observe repetition priming between orthographically dissimilar synonyms (e.g. [27]), we do not conclude that each word is part of a different lexicon, so why should we arrive at that conclusion when we fail to observe equivalent priming effects between orthographically dissimilar translation-equivalents?

Other arguments for separate lexical stores

The two other powerful arguments for the separate lexicon view of bilingual memory organization come from:

(i) Release from proactive interference [5]. A release from proactive interference is observed by changing the language between two lists to be memorized.

(ii) Language recall (see [8] for review). Language-specific recall of previously presented words is performed well by bilinguals.

However, these arguments for a separate-lexicon structure for bilingual memory are, once again, open to a 'level of observation' problem. Consider the release from proactive interference. This is a well-known and widely investigated effect in monolingual studies, achieved by changing the semantic category of the two lists to be learned. Yet no one concludes from this that there are two 'lexicons', one for each category. Why should an identical result in the bilingual case cause us to propose two separate language lexicons?

Furthermore, the role of context in recall performances is also well-established. Marian and Neisser have recently shown that language acts as a context cue in memory retrieval [28]. Good language-recall performance might, therefore, be a product, not of separate language storage, but of the contextual effect of the specific language on recall. We discuss this in more detail below in the discussion of the role of the task.

Support for separate lexical stores and separate language processing has also been weakened by numerous overlapping empirical studies on language at the neuro-anatomical level. These studies, too, have shown that this question cannot be resolved without taking into consideration numerous factors, such as language proficiency ([29]), age of acquisition ([30], but criticized by [29]), level of processing ([31]), and so forth (for reviews, see [32] and [33]). These studies highlight the considerable degree of variability at the level of individual bilinguals [34]. Recent work [35] suggests there might be a common neural substrate for semantic processes. A special issue of *Bilingualism: Language and Cognition* [36] was largely devoted to functional magnetic resonance imaging (fMRI) and evoked response potential (ERP) techniques used to study a wide variety of phenomena specifically related to bilingual memory, such as language switching, inter-lingual homograph recognition, bilingual aphasia, etc.

To conclude this section on the organizational aspects of bilingual memory, it is safe to say that there is a strong consensus on the need for a conceptual/lexical separation and that the SLOTS debate has shifted heavily, although not entirely, in favor of the single, large store model. However, it is one thing to posit a particular memory organization; it is another to attempt to explain how that particular organization arose. This is where connectionist models have made, and are continuing to make, a contribution to the field.

Connectionist modeling and the emergence of organization

Whereas accurately describing the organization of bilingual memory has traditionally been one of the most important concerns of the field, far less attention has been paid to *how* that organization might have come about. One of the contributions, therefore, of the current neural-network models of bilingual memory is that they suggest how proposed types of organization might have come about as an emergent result of the language acquisition (i.e. learning) mechanisms built into the model, in particular, unsupervised learning mechanisms.

Three distributed connectionist models that learn have been developed. French designed a bilingual simple recurrent network (BSRN) that showed that, after sufficient exposure to both languages, that the internal representations of the words of both languages cluster according to language, even though the activation patterns of these representations remain highly overlapping [37] (see Box 1). SOMBIP (Self organization of bilingual memory) is another recent connectionist architecture that relies on unsupervised learning to produce language separation [38]. A third model was developed by Thomas (M.S.C. Thomas, PhD thesis, Oxford University, 1997). This was a supervised, feedforward connectionist architecture that included explicit language tags for each lexical item.

The first two models, BSRN and SOMBIP, produce their organizational structure as a emergent product of their respective inputs, whereas the third model relies on 'static' tags to engender language organization. However, in this last case, the origin of explicit high-level language tags poses certain problems. The question is not whether tags can be used to produce effective language separation – clearly, they can – but, rather, whether they are actually necessary to produce that separation. In both the SOMBIP model [38], which relies on a variety of phonological cues, and the BSRN model [37], which relies on the statistics of word associations, language separation emerges based solely on the input to the models. In other words, regularities, be they phonological or covariational, of the bilingual language input are sufficient to cluster the two languages, which is distinctly different from including an explicit language tag for each lexical item.

Having considered some of the mechanisms that might give rise to overall language organization, we will now look at some of the mechanisms that allow bilinguals to use each of their languages largely without interference from the other language, to access the words of a particular language, etc.

Language and memory mechanisms in bilinguals

As we have said earlier, most researchers currently accept the notion of at least a partially overlapping organization of bilingual memory. We will now consider the language and memory *mechanisms* that act on this knowledge organization. We will pay particular attention to the issues of lexical access, lexicon selection, and the effect of the task on access and selection.

Lexical access

Lexical access simply refers to the process by which we are able to activate the 'right' word in a given context. It is not a concept limited to bilinguals, although the ability to access the right word *in the right language* is a particularly salient manifestation of lexical access. Certain authors have argued for the existence of lexicon-specific access (i.e. access to one language at a time) (e.g. [17,39,40]) but numerous studies have repeatedly demonstrated evidence of non-selective access (i.e. access to words in both language simultaneously) (see [41–44]; J.G. Van Hell, PhD thesis, University of Amsterdam, 1998; [45] for a demonstration using ERPs). The general view at present largely favors non-selective access. De Groot [46] reviews this issue and, importantly, reinterprets the selective-access results of Gerard and Scarborough [17]

Box 1. The bilingual simple recurrent network (BSRN) model of bilingual learning

A simple recurrent network (Figure Ia) is sensitive to statistical regularities in sequences [73]. No semantics is required. In building this bilingual simple recurrent network (BSRN) two micro-languages, Alpha and Beta, of 12 words each were used [37]. There were no markers between sentences or between languages. After training of the BSRN on 20,000 three-word sentences, clusters have formed not only for the parts of speech in each language, but also *for each language* (Figure Ib). The network has separated the two languages into distinct clusters of hidden-unit representations. The question we would like to answer is how much of this statistically-driven language learning can be done in the absence of semantics.

The model was also then run with two larger micro-languages, each of whose grammatical structure was identical to the Alpha and Beta languages above, but where each language contained 768 words (i.e. a total of 1536 words), encoded with distributed representations. After exposure to a total of 30,000 sentences, the languages separated out, just as they did in the much simpler 12-word languages above.

What the SRN sees is: BOY LIFTS TOY MAN SEES PEN WOMAN TOUCHES BOOK GIRL PUSHES BALL FEMME SOULEVE STYLO FILLE PREND LIVRE GARCON VOIT BALLON WOMAN SEES BOOK BOY PUSHES PEN...

Its task is to predict the following word (e.g. given BOY on input, produce LIFTS on output; given LIFTS on input, produce TOY on output; etc.)

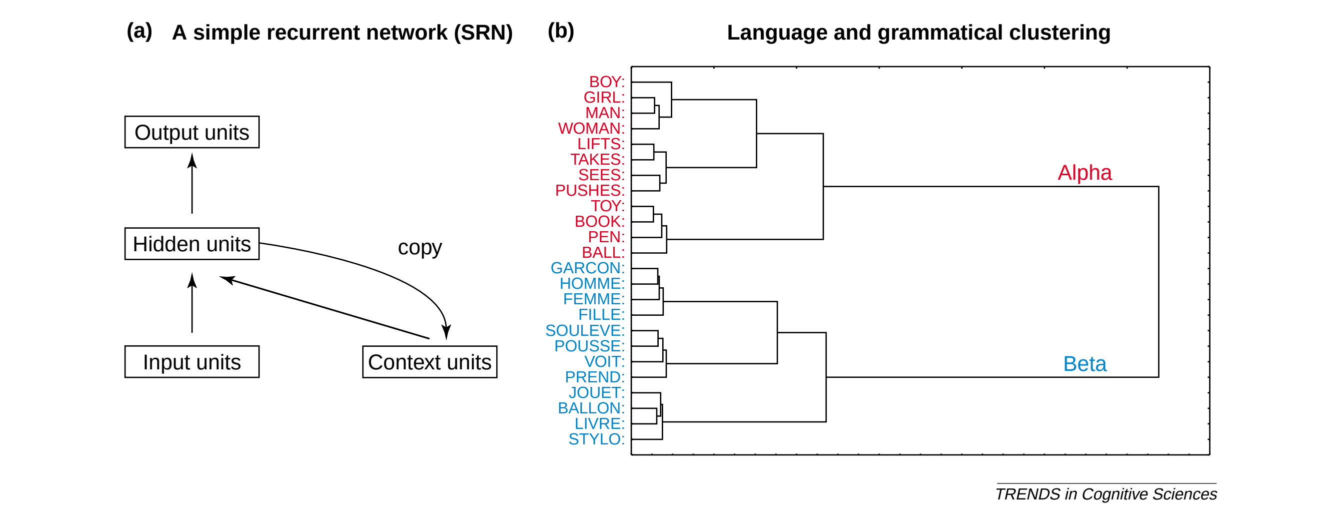

Figure I. **(a)** A simple recurrent network, and **(b)** the language and grammatical clustering of two languages (notionally denoted by Alpha and Beta) that is achieved by a bilingual SRN, after training on 20,000 sentences based only on its input of three-word sentences.

in a non-selective access framework. However, if there is non-selective access within a single integrated bilingual lexicon, how can bilinguals have so little trouble remaining within a single language? This is the problem of lexical selection.

Lexical selection

A particularly successful attempt to explain and model lexical selection has been the Bilingual Interactive Activation (BIA) model. The BIA is a word-recognition model based on McClelland and Rumelhart's well-known proto-connectionist Interactive Activation model [47]. As an integrated lexicon is the basic assumption of this model, one of the authors' primary concerns was to show how a given word was recognized as belonging to one language or the other.

This model has been very successful in extending single-language effects to bilinguals. Its most impressive achievements include its accurate simulation of interlingual orthographic neighborhood effects, cross-language masked orthographic priming effects (for a review, see [48]) and interlingual homograph recognition experiments [46,49–54]. (Interlingual homographs are lexical items with two distinct meanings in each language, words like PAIN = 'bread' in French and 'hurt' in English.)

However, once again, we encounter the problem of explicit language tags. The same level-of-observation issues mentioned earlier apply to the BIA with its underlying assumption of a single, integrated bilingual lexicon and non-selective access. So, although the BIA might be 'integrated' at the level of lexical items, its use of language nodes (essentially equivalent to language tags) to selectively inhibit all words in one or the other language (hence producing lexical selection), means that, above the lexical level, its integrated nature disappears [55]. In short, the lack of a clear definition of language tags, their status and how they might have originally come into being, gives them somewhat of an ad hoc status in the BIA [7].

Although certain problems remain at the level of lexical organization, such as the need for a double representation of interlingual homographs, an extended version of the BIA, the BIA+ [56] and its computer implementation, SOPHIA (W.J.B. Van Heuven, PhD thesis, Nijmegen Institute of Cognition and Information, 2000), has largely overcome the problems with explicit tagging. The BIA+ incorporates phonetic information and makes a clear distinction between an identification system and a new component designed to handle task demands, as suggested in the Green's Inhibitory Control (IC) model [57], another well-known non-selective access model. The BIA+ is in complete agreement with Green's proposed separation between a single bilingual lexico-semantic system and the procedures acting on that system. Although Green's IC model is not alone in using inhibitory mechanisms to produce lexicon selection, it does have the important particularity of insisting on two distinct mechanisms, one that operate on inputs to the bilingual lexico-semantic system, and the other, on outputs from it. These two control mechanisms allowing lexical selection, largely determined by the task schema, limit the influence of the not-in-use language [57] and involve:

(i) an automatic ('bottom-up') process within the bilingual lexico-semantic system, essentially driven by stimulus input (e.g. the make-up of the test list) involving modification of the level of activation in the bilingual lexico-semantic system;
(ii) an intentional ('top-down') process that alters how the individual responds to signals coming from the bilingual lexico-semantic system, but does not modify activation levels within the system itself [58].

This regulation of the bilingual lexico-semantic system provides an explanation of the language modes proposed by Grosjean [1,59,60] that permits bilinguals to remain, without difficulty, in one or the other of their languages. The inhibitory mechanisms of the IC model are not language-specific mechanisms. On the other hand, some authors maintain that lexical selection can be language-specific and achieved by considering only the activation level of the lexical nodes that belong to the target language [43,61,62].

Although the BIA, the BIA+ and the IC models all have certain shortcomings in terms of lexical organization, their reliance on an interactive combination of bottom-up and top-down processing is a very interesting mechanism of lexical selection. In addition, they also take into account participants' problem-solving strategies and goals via an 'experimental task' module. It will no doubt be necessary in the future to go even farther in this direction, incorporating in these models, for example, the means of determining if perceptual processing alone is sufficient for the task demands or whether semantics must also play a role. Moreover, and interestingly, studying the role of task demands in a bilingual setting – for example, studying the role of phonology in word recognition in a bilingual context – not only provides a window on the mechanisms of bilingual memory, but can, at the same time, elucidate various basic mechanisms of memory in general.

The role of task demands

In the context of bilingual memory, the impact of the mechanisms involved in task demands has been clearly demonstrated [49,63]. (For a review of bilingual studies classified by experimental task, see [9].)

In addition to variables that can modify performances among individual bilinguals (e.g. proficiency, age of acquisition…), various authors (e.g. [64,65]) have shown dissociations between different tasks and, consequently insist, once again, on the necessity of taking the task into account to avoid misinterpretation. Certain authors have gone so far as to suggest different underlying processing mechanisms when the task is performed in a within-language or cross-language context (e.g. [66]). Zeelenberg and Pecher, however, argue for identical processes in both monolingual and bilingual contexts [26].

An interesting example of the role of the task is an experiment by Marian and Neisser [28]. They show that autobiographical memory is language-dependent, a result that was interpreted as a proof of separate stores. But, as they remark in their discussion, these results could also be accounted for by the encoding and retrieval context of the test. They showed that linguistic context powerfully influences autobiographical recall. These two last papers ([26,28]), although experimentally very different (i.e. different experimental tasks and procedures), are based on similar underlying logic in extending classical memory theory to bilingual memory. Their message is clear: bilingual memory is, above all, memory and, as such, is amenable to being studied in light of the basic principles of memory, in general. But what about the other direction? To what extent can studying bilingual memory shed light on memory, in general? We will briefly consider this point.

Bilingualism as a means of understanding general *language and memory mechanisms*

To what extent are the processes generally associated with bilinguals, in fact, more basic, language-independent processes? In other words, can studying bilingual memory processes serve to better understand general memory processes? In our view, this is currently one of the most important questions in the field.

For example, in approaching the problem of phonological encoding (phoneme selection in speech production and word recognition) several authors have studied these processes in bilinguals and then extended their results to theories of language processing in general [43,44,62,67]. Other basic questions, such as the nature of lexical input [68], the language-independent nature of memory recall mechanisms in the brain [69], and so forth, can be studied via the use of the particular context provided by bilingualism.

Conclusions

Although many difficulties remain, even at such fundamental levels as exactly what is meant by a language lexicon or even bilingualism itself [9,70], great progress has been made in recent years in bilingual memory research. There has been an emphasis placed on the importance of studying bilingual memory, not only as a means of merely understanding bilingual memory organization and processes *per se*, but rather as a means of shedding light on *general* (language-independent) memory processes. It is interesting to note a parallel evolution in traditional single-language research and bilingual research. Both initially focused on questions of memory organization, gradually converging on a relatively distributed, monolithic view of this organization, and then moved progressively towards the processes acting on this underlying organization: memory processes, such as recall and recognition processes, language-production processes, such as lexical selection, or even task-specific processes.

Box 2. Open questions

- How can computational models of bilingual memory that learn be integrated into the current models, such as the BIA + and the IC models, which model adult bilingual processing?
- How could bilingual processing be modeled at the sentence level as opposed to the word level? At the sentence level we can capture language regularities that are completely absent when only individual words are processed.
- What is the neurobiological correlation between what appears to be physical language separation in the brain and the effective functional separation of language stores?
- Can bilingual language processing be considered to be fundamentally the same as monolingual language processing? How can we use the study of bilingual memory organization and processing as a way of better understanding language organization and processing in general?
- Is there a way to model the *emergent* semantics of bilingual language so that perceptual input can give rise to and, subsequently, interact with this semantics?
- How can the models and techniques of infant and child categorization be applied to the acquisition of two (or more) different languages?
- To what extent can we adopt a 'fractal' point of view of the processes operating on languages? Can we consider a language 'simply' to be a particular type of category, albeit a very large one, and assume that the same underlying mechanisms that apply to all categories apply to languages? In short, are the same, or similar, underlying processes at work when we ask (i) whether a word belongs to a particular language or not, (ii) whether a particular word belongs to a particular category or not, (iii) whether a letter belongs to a particular word, and (iv) whether a vertical bar belongs to a particular letter?

Perhaps one of the most glaring shortcomings of many current models, in particular, the BIA, BIA+ and IC, is that they do not learn and cannot handle sequences of words [55,71]. They cannot, therefore, model the gradual emergence of bilingual memory organization (see also Box 2). On the other hand, those models that that can learn sequences of words, and that do not require explicit language nodes to produce language separation [37,38], cannot yet model many of the high-level effects, such as orthographic neighborhood effects, so elegantly modeled by the BIA. (See [72] for a recent review and comparison of these models.) We agree with Thomas and Van Heuven [72] that combining the two types of models will mark a significant advance in the evolution of bilingual memory research.

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