



Semantic convergence in the bilingual lexicon

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ABSTRACT

Bilinguals' lexical mappings for their two languages have been found to converge toward a common naming pattern. The present paper investigates in more detail how semantic convergence is manifested in bilingual lexical knowledge. We examined how semantic convergence affects the centers and boundaries of lexical categories for common household objects for Dutch–French bilinguals. We found evidence for converging category centers for bilinguals: (1) correlations were higher between their typicality ratings for roughly corresponding categories in the two languages than between typicality ratings of monolinguals in each language, and (2) in a geometrical representation, category centers derived from their naming data in the two languages were situated closer to each other than were the corresponding monolingual category centers. We also found evidence for less complex category boundaries for bilinguals: (1) bilinguals needed fewer dimensions than monolinguals to separate their categories linearly and (2) fewer violations of similarity-based naming were observed for bilinguals than for monolinguals. Implications for theories of the bilingual lexicon are discussed.

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Introduction

Languages differ in how they map words onto referents, even for concrete, familiar objects for which perception of stimulus properties may be shared (Malt, Sloman, Gennari, Shi, & Wang, 1999). For example, Polish speakers use the same label for a telephone table and a coffee table but a different one for a dining room table, whereas English speakers label all three by the same name (Wierzbicka, 1992). Malt et al. (1999) found that speakers of American English, Mandarin Chinese, and Argentinean Spanish differed in how they divided 60 common household containers by name. For instance, for the 16 objects named *bottle* in English, seven different names were used in Spanish. The Chinese category that contained the 19 objects called *jar* in English also included 13 objects called *bottle* in English

and 8 called *container*. Similar discrepancies in naming patterns exist for speakers of Belgian Dutch and French (Ameel, Storms, Malt, & Sloman, 2005). Malt, Sloman, and Gennari (2003) examined in more detail the relation among the linguistic categories across the three languages and found a complex pattern. Only a few category pairs were based on shared prototypes. Some categories of one language were nested within those of another, while others showed cross-cutting in which objects from a single category in one language were distributed across several categories in another language that each had additional members. These findings show that naming patterns for even concrete objects are language-specific rather than universal. This paper addresses how bilinguals exposed to two languages from birth meet the challenge of learning two languages with overlapping yet distinct sets of lexical categories.

If bilinguals' two languages were acquired and stored in isolation from each other, then the key question would be how they manage the task of mastering the two different language systems in parallel. But there is growing evidence that the two language systems in a bilingual's mind inter-

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act, with the result that the systems may affect one another (Grosjean, 1982; Schmid & Köpke, 2007). Traditionally, the focus of investigations into cross-language influence has been on the influence of L1 (the first language) on L2 (the second language) (Jiang, 2000; Kroll & Curley, 1988; Kroll & Stewart, 1994). Recently, however, second language acquisition scholars have begun documenting effects of the L2 on the L1 in adult L2 users at levels including phonological (e.g., Major, 1992; McKay, Flege, Piske, & Schirru, 2001), syntactic (e.g., Dussias, 2001, 2003; Dussias & Sagarra, 2007; Pavlenko, 2000), and lexical (e.g., Pavlenko, 1999, 2000) (see also Cook, 2003). Thus even a well-established first-language system seems to be susceptible to influence from exposure to another language. Given this evidence of the vulnerability of the two language systems to influence from each other, then a third possibility must also be considered: For the bilingual exposed to two languages from birth, the two systems may exert a mutual influence on each other, yielding language patterns that converge onto each other. The current work focuses on this bi-directional influence and resultant convergence.

The notion of convergence

The notion of convergence has been used to describe several related but distinct phenomena that involve interactions between two languages. It has been applied both in the context of contact between speakers of different languages and in the context of contact in the mind of an individual who knows two languages. Convergence in the case of language contact refers to a process occurring when speakers of different languages interact closely and their languages influence each other over time, altering elements of the syntax, semantics, phonology, etc., of one or both languages such that new patterns are handed on to new generations of speakers (e.g., Thomason & Kaufman, 1988; Winford, 2003). In the context of language contact in a bilingual's mind—the focus of this paper—convergence can be defined as the enhancement of inherent structural similarities in the two linguistic systems (Bullock & Gerfen, 2004; Bullock & Toribio, 2004). Similarly, Pavlenko (1999) defines convergence as a kind of language change whereby a new, intermediate, system is created by a bilingual from elements of both languages. The resulting system is distinct from either as spoken by monolinguals. The term “convergence” as it has been used in the context of language contact in a bilingual's mind, and as it will be used in the current paper, does not refer to the process of evolution but rather to the outcome. That is, it refers to the existence of some element(s) of the languages that are more similar to each other as used by bilinguals compared to monolingual speakers.

Convergence is to be distinguished from language attrition, which implies an influence of L2 on L1 that leads to a negative change, including a decline or loss of ability or competence in one language (Köpke, 2004). In contrast, convergence makes a bilingual's two languages different from both as spoken by monolinguals, but it leaves the bilingual no less expressive or proficient a language user. Convergence is also to be distinguished from cases of language transfer in which a single system is entirely based on the L1 (Pavlenko, 1999).

Different aspects of a bilingual's linguistic systems can undergo convergence. Numerous studies demonstrate phonological or orthographic convergence. Bullock and Gerfen (2004), for example, showed that speakers of French in Frenchville, Pennsylvania, U.S.A., systematically merged the French mid-front rounded vowels [ø] (as in *deux*) and [œ] (as in *soeur*) into a single surface variant, the rhoticized schwa of American English, their dominant language. (For more evidence of phonological/orthographic convergence, see Colantoni & Gerlukian, 2004; Kehoe, Lleó, & Rakow, 2004). The morpho-syntactic system is also vulnerable to convergence. For example, Sánchez (2004) observed mutual convergence in tense in Quechua–Spanish bilingual children. Spanish and Quechua differ in the features associated with past tense forms (aspectual versus evidentiality features). In Spanish, the bilingual children produced past tense forms associated with evidentiality features which are not manifest in monolingual Spanish. In Quechua, aspectual features were linked to the past tense forms (For more evidence of morpho-syntactic convergence, see Montrul, 2004; Sanchez, 2006; Toribio, 2004).

Most relevant to the present studies, early evidence for semantic convergence was reported by Ervin-Tripp (1961) who found that Navajo–English bilinguals differed systematically in their uses of color terms in each language from monolinguals in the two languages. For example, when the two languages differed in category boundaries of roughly equivalent terms, the dominant language determined the boundary for both terms in the bilingual's two languages. Or, when a domain was divided into two categories in one language and three in the other, bilinguals tended to reduce the size of the middle category when using the latter language. Further evidence for semantic convergence is provided by Brown and Gullberg (2008) who studied the bi-directional influence of L1 and L2 on word choice and gesture in speech production in each language. Participants were asked to describe a cartoon event in which a cat swings on a rope across the street. Choice of words and gestures for encoding the manner and path of the cat's movement was compared between monolingual speakers of Japanese and English and Japanese speakers with high-intermediate knowledge of English. The bilinguals speaking English (L2) encoded manner less frequently in speech than the monolingual English speakers did, demonstrating the influence of L1. Bilinguals speaking Japanese (L1) differed from Japanese monolinguals by encoding manner in speech, but often not in accompanying gesture, as monolingual English speakers do. Pavlenko and Jarvis (2002) studied oral narratives of Russian speakers of English, and found an influence of Russian on English multiple semantic elements of their narratives, and vice versa.

In our own previous work (Ameel et al., 2005), we examined naming differences between Belgian Dutch- and French-speaking monolinguals and Dutch–French bilinguals for two subsets of the domain of common household objects (storage containers and dishes for preparing and serving food). The naming data of the Dutch- and French-speaking monolinguals revealed substantial differences in the composition of their lexical categories. For example, the 25 objects named *fles* (roughly, English *bottle*)

by Dutch-speaking monolinguals were subdivided into two equally-sized lexical categories by French-speaking monolinguals: *bouteille* (13/25) and *flacon* (10/25). However, the Dutch and French naming patterns of the bilinguals did not fully parallel the naming patterns of the corresponding monolinguals. Instead, the bilinguals' naming in each language converged on a common pattern; bilinguals agreed better on naming in their two languages than monolinguals of the two languages agreed with each other. For example, the nesting relation found for Dutch- and French-speaking monolinguals between *fles* on the one hand and *bouteille* and *flacon* on the other hand was found in bilinguals as well, but in contrast to the equal distribution of *fles* objects to the French monolingual *bouteille* and *flacon* categories, most *fles* objects were called *bouteille* (21/30) in French and only a minority was called *flacon* (6/30), making the bilingual French *bouteille* category more similar to Dutch *fles*.

This paper further investigates the nature of bilingual convergence in the use of names for household objects (Ameel et al., 2005). We focus specifically on “semantic” or “lexical” change, as opposed to “conceptual” change. We ask how word forms are mapped to referents, and how these mappings, representing knowledge of word meanings (at least in part) and differing across language groups, might converge for bilinguals as compared to monolinguals. We make no claim about the relation of the naming patterns or word meanings to more general purpose conceptual representations serving non-linguistic cognitive processes or to the possibility of changes at this general conceptual level (See Pavlenko, 1999, Jarvis & Pavlenko, 2008, for a somewhat different distinction attached to the terms “semantic” and “conceptual” knowledge in which “conceptual” information is taken to be part of word knowledge).

In this paper, we ask how convergence is manifested in two aspects of lexical category structure in the two languages: the category centers and the category boundaries. We next discuss possible mechanisms underlying convergence, and we then describe the manifestations of convergence that may be evident in the category centers and boundaries.

Possible mechanisms underlying semantic convergence

The evidence for phonological, morpho-syntactic, and semantic convergence described earlier demonstrates that the representations of bilinguals' two languages are not separate and encapsulated but rather are interrelated and subject to interaction. Language processing studies further demonstrate this interaction in online tasks. Several studies using lexical decision to examine cross-language semantic priming have shown that the advantage for a related prime holds regardless of whether it appears in the same language or a different language from the target word (De Groot & Nas, 1991; Kirsner, Smith, Lockhart, King, & Jain, 1984; Schwanenflugel & Rey, 1986). Other studies have shown that semantic processing in one language can automatically interfere with processing in another. For instance, in a Stroop-like between-language picture–word interference task, picture naming in one

language is slowed by having an incongruent word superimposed on or presented simultaneously with the target picture even if the incongruent word is in a different language (Costa, Miozzo, & Caramazza, 1999). These studies suggest that activation spreads from one language to the other through access to a shared meaning representation system.

This activation of each language system by the other may provide the basic mechanism by which convergence occurs. If each use of words in one language causes word knowledge in the other to become activated, the representations activated may influence each other. Some or all of the exemplars that are experienced as instances of a lexical category in one language may become encoded as members of a roughly corresponding category in the other language, resulting in categories that are more like each other than the monolingual versions.

Wolff and Ventura (in press) termed such a process *retrieval-induced reconsolidation*, drawing on memory research demonstrating that a memory trace can become temporarily labile and susceptible to change after reactivation by a different memory trace (Alberini, 2005; Walker, Brakefield, Hobson, & Stickgold, 2003). Wolff and Ventura suggested that L2 to L1 influence can be understood in terms of this phenomenon: The L1 may be vulnerable to change or interference when elements in the L2 reactivate their analogs in the first language. Wolff and Ventura studied causal expressions based on verbs for causing and enabling in Russian and English, which have different patterns of use of the roughly corresponding verbs. They found that the causal descriptions of Russian–English and English–Russian bilinguals in their L1 differed from the descriptions of L1 monolingual speakers in the direction of the L2. Retrieval-induced reconsolidation may likewise provide a way of thinking about the case of simultaneous bilinguals. It is particularly noteworthy that for simultaneous bilinguals, language input and use often consists of encounters with one language interleaved with encounters with the other. Encounters in each language may reactivate the other language frequently, resulting in labile memory traces that are susceptible to cross-linguistic interference in both directions.

In fact, simultaneous bilinguals may be particularly vulnerable to this bi-directional convergence because their lexical representations in each language may be more fragile than those who have just one language to master. Building up word meanings that precisely mirror those of adult speakers of a language can take an extended period of time even for monolingual children. As many as 14 years of exposure may be required before full match to adult usage is achieved for some common words (Ameel, Malt, & Storms, 2008; Andersen, 1975; Bowerman, 1974; Clark, 1980; Clark & Garnica, 1974; Gentner, 1978; Gropen, Pinker, Hollander, & Goldberg, 1991; Pye, Loeb, & Pao, 1996). Gollan, Montoya, Fennema-Notestine, and Morris (2005) note that because bilinguals use each language less often than do monolinguals, they have only half the opportunities relative to monolinguals to receive feedback in each language and to acquire mappings between words and objects in each language. Gollan et al. found that bilinguals name pictures in their dominant language more slowly

and with more errors than did monolinguals, and they suggested that given the reduced practice bilinguals accumulate in each language, their mappings between semantic and lexical representations in both languages will be weaker than monolingual mappings in either language. Supporting this account, they found that, after four presentations, bilinguals named pictures as quickly as did monolinguals. Further, bilinguals benefited more from repetition effects than did monolinguals. By analogy with the finding that low-frequency words benefit more from repetition than high-frequency words (Griffin & Bock, 1998), Gollan et al. suggested that bilinguals have more functionally lower-frequency word forms in their lexicon than do monolinguals. The memory traces, thus, may be weaker than a monolingual's would be and particularly susceptible to change as a result of exposure to input in the other language.

The notions of retrieval-induced reconsolidation and fragile lexical representations paint only a broad picture of how convergence may come about, though. How, exactly, might meaning representations be affected by this process? That is, what aspects of the knowledge associated with each word will be changed? Below, we consider several alternative possibilities motivated by these two general notions. It is beyond the scope of the present paper to test whether these specific elements of an explanation for lexical convergence are correct. However, they provide a useful heuristic for considering the different ways in which convergence may be manifested. We pose several alternatives that our data will discriminate among.

Possible manifestations of convergence

Category centers

If bilingual representations are particularly fragile due to reduced input in each language, this fragility may be greater for some aspects of the word knowledge than others. Category centers and category boundaries differ in the type of exemplars that mostly contribute to their formation. Given the strong correlation between typicality and production frequency (Barsalou, 1985; Hampton, 1979; Hampton & Gardiner, 1983; Mervis, Catlin, & Rosch, 1976), category centers are thought to be strongly determined by high-frequency items (i.e., items that are generated frequently as instances of the category), while the boundaries should mainly reflect exposure to low-frequency items. Hence, category centers may be less vulnerable to convergence than the category centers, since memory traces of high-frequency typical exemplars of a lexical category may be stronger than those of low-frequency atypical exemplars as members of the category. The memory traces for category centers may be strong enough to overcome interaction between the representations of the two languages and to allow monolingual-like central tendencies for words in each language to be established. Under this possibility, the convergence found in the naming patterns of bilinguals for common household objects (Ameel et al., 2005) may be restricted to convergence in the boundary regions.

On the other hand, it is possible that category centers in bilinguals converge regardless of the relatively stronger traces for more typical exemplars. According to prototype

models, category centers are calculated as the average or median of all the exemplars in the category (Hampton, 1979, 1993; Smith, Shoben, & Rips, 1974). So, even though category centers are mainly determined by high frequency, typical exemplars of the category, atypical items situated at the boundaries may contribute to the establishment of the centers as well. To the extent that the category boundaries in each language are fragile and susceptible to influence from the other language—which is likely as discussed below—bilinguals may fail to establish monolingual-like corresponding category centers in the two languages. But even without influence of the category boundaries on the establishment of category centers, the centers may still converge as a result of the continuous reactivation of representations in the other language. If enough entities learned as belonging to a category in one language are integrated into membership in the roughly corresponding category in the other language as well, then category centers calculated as the averages of the category exemplars in the two languages may converge towards each other due to the higher overall overlap of corresponding category memberships.

Category boundaries

Category boundaries for many types of entities, including artifacts, are known to be fuzzy (e.g., Rosch & Mervis, 1975). For such categories, there exist borderline cases situated at the boundaries of the category, which are not clearly in or out of the category. These boundary exemplars are subject to inter- and even intra-individual naming variability (Hampton, 1979; McCloskey & Glucksberg, 1978). They share fewer features with other category exemplars and are less typical for the category (Rosch & Mervis, 1975). Furthermore, their naming may be more strongly determined by idiosyncrasies of specific cultural and linguistic histories than naming of other category members (Malt et al., 1999). For instance, market forces may sometimes lead to different naming choices for new products in different countries, and the opportunity for cultural variation will be greatest for objects with ambiguous category affiliation on the basis of features.

In short, category boundaries can be considered to contribute much of the language-specific complexity in naming, and boundary exemplars are more likely to receive different names in two languages. Moreover, the names of boundary exemplars are more difficult to learn, and hence, are learned later, than names for more centrally situated or more typical exemplars, even for monolinguals (Posner & Keele, 1968; Rosch, 1973; Rosch & Mervis, 1975) since the former are less likely determined by similarity and at the same time less frequently experienced as members of the lexical category. Related research further shows that atypical exemplars are verified slower in a category verification task (Hampton, 1979; Larochelle & Pineu, 1994; McCloskey & Glucksberg, 1978; Rips, Shoben, & Smith, 1973; Smith et al., 1974) and categorized slower and less accurately (Fujihara, Nagaishi, Koyama, & Nakajima, 1998). This difficulty in learning is likely to result in particularly fragile knowledge of boundary exemplars in both languages for the bilingual, given the reduced input they receive in each language.

It is possible in principle that bilinguals somehow, nevertheless, manage to learn the language-specific complexity at the category boundaries in both languages. In this case, the observed convergence must arise entirely from some other aspect of the lexical representations. However, given that Ameel et al. (2005) established that convergence does occur in some form, it seems likely that at least some of it is manifested in effects on the category boundaries.

The possibility of boundary convergence for bilinguals can be framed in terms of the complexity level of the category structure as compared to the complexity level of monolinguals. Complexity is defined as the degree to which category assignment is determined by the similarity principle. The more exemplars are assigned to the category to which they are most similar, the simpler the category structure. The more that category assignments reflect language-specific idiosyncrasies rather than similarity relations, the more complex the category structure.

Convergence of category boundaries could be manifested either in more complex or simpler categories. Bilinguals may encode boundary exemplars but not be able to keep them separate in each language due to the effects of retrieval-induced reconsolidation. That is, boundary exemplars of a particular category in one language may come to be incorporated into the corresponding category in the other language as well. Suppose that a (boundary) object has come to be called *fles* in Dutch, even though it does not share many features with other *fles* objects. Then, this object may also be represented as a member of the corresponding French *bouteille* category, even though this assignment is not monolingual-like in French (since the language-specific event that caused the object to be named *fles* in Dutch did not operate on the French naming pattern). Incorporating boundary exemplars of both languages into the lexical categories of each would result in more similar but more complex categories for bilinguals as compared to monolinguals.

Alternatively, it is possible that the boundary exemplars get only poorly encoded as a member of the monolingual's preferred category in either language for a bilingual, as a result of the low frequency of exposure. Thus, some boundary exemplars will be absent relative to monolingual lexical categories in each of the bilingual's languages, resulting in less complex categories for bilinguals as compared to monolinguals. Under this scenario, when faced with naming a particular object that would be an atypical member of a particular lexical category for a monolingual, bilinguals may be more likely to assign the exemplar to the category (and the corresponding category in the other language) to which it is most similar, rather than following the monolingual category assignment reflecting language-specific idiosyncrasies. This sort of strategy would result in more similar and simpler (because similarity-based) categories in the bilingual's two languages.

Overview of the studies

To discriminate among these possibilities and identify how convergence is manifested in bilingual lexical categories, four studies were designed. The first two focused on category centers. Study 1 used raw typicality ratings and

compared the extent to which bilinguals agree on typicality ratings for corresponding categories to the extent to which monolinguals agree on typicality ratings for corresponding categories. If bilinguals agree better on typicality judgments for corresponding categories in their two languages than monolinguals in each of the same two languages agree with each other, we infer that the corresponding bilingual category centers are more similar to each other than corresponding monolingual category centers.

In Study 2, a geometrical representation (Ameel & Storms, 2006) was used to represent the linguistic categories. Both for monolinguals and bilinguals, centers were computed for different categories as the weighted averages of the exemplar locations. The distances between the centers of corresponding categories were compared for bilinguals and monolinguals. Smaller distances between corresponding category centers for bilinguals compared to monolinguals would indicate that bilingual category centers move towards each other. This study further allows us to discriminate between convergence of the centers due to boundary exemplar convergence versus overall membership convergence by varying exactly how the centers are calculated.

Studies 3 and 4 were designed to find out how the category boundaries are affected by convergence. In Study 3, a method was applied that allowed comparison of the complexity of bilingual categories to the complexity of monolingual categories. The method, called LINSEP (Van Assche, 2006), quantifies the complexity of categories in terms of linear separability; that is, it determines how many dimensions it takes to separate the categories. The more complex the categories are, the more dimensions are needed to separate the categories linearly. We apply this method here to ask whether bilingual categories are separated by different numbers of dimensions than the corresponding monolingual categories. If the same number of dimensions is needed to separate bilingual and monolingual category pairs, bilingual and monolingual categories are equally complex. If higher dimensionalities are needed to separate bilingual category pairs, they are more complex than monolingual categories. If lower dimensionalities are needed, then bilingual categories are less complex.

To provide more direct evidence for whether bilinguals incorporate or drop boundary exemplars, Study 4 compared the proportion of outliers (i.e., objects that are more similar to the center of another category than to their own category center) for bilinguals and monolinguals in a given dimensionality. Fewer outliers for bilinguals indicates dropping boundary exemplars; more indicates incorporating extras from the other-language category.

Study 1

The first study evaluates how convergence is manifested in the centers of corresponding categories in the two languages of a bilingual by looking at typicality ratings. We compared the degree of correspondence in typicality ratings for roughly corresponding categories for bilinguals to the degree of correspondence for monolinguals. If the bilingual prototype representations in the two

languages are sufficiently strongly established independent of each other, centers of corresponding categories for bilinguals in their two languages will be similar to centers of corresponding categories for monolinguals in either language. This should be manifested in bilinguals agreeing to the same extent on typicality judgments for roughly corresponding categories in their two languages as do monolinguals in each of the languages. If, however, category centers are influenced by converging boundaries or overall converged membership, then bilinguals are not able to establish all the nuances of monolingual-like corresponding prototypes in the two languages and the centers will converge toward each other. This will be manifested in better agreement for bilinguals' typicality judgments for roughly corresponding categories in their two languages compared to monolinguals in the two languages.

Methods

Participants

The typicality ratings we evaluate here were collected (but not reported) in Ameel et al. (2005) naming study in which 28 Belgian Dutch-speaking monolinguals, 24 Belgian French-speaking monolinguals and 21 Belgian Dutch–French balanced bilinguals participated.² All participants were students or research assistants at Belgian universities. Although the monolingual participants had some knowledge of the other language through formal instruction at school, they did not consider themselves proficient in it (see Ameel et al., 2005) and considered themselves to have one native language. The bilinguals had a Dutch-speaking mother and a French-speaking father or vice versa, and from childhood onward, each parent had consistently been speaking their own language to them.

Materials

The categories for which typicality ratings were collected were derived from the naming data of Ameel et al. (2005) study. In that study, two sets of common household objects were used. The 'bottles set' contained 73 objects that were likely to receive the name *bottle*, *jar*, or *container* in American English, or else to have one or more salient properties in common with objects called *bottle*, *jar*, or *container*. The 'dishes set' consisted of 67 objects that were likely to be called *dish*, *plate*, or *bowl* in American English, or else to share one or more salient properties with objects called *dish*, *plate*, or *bowl*. Some examples of the two sets are provided in Figs. 1 and 2.

Participants were asked to name each object giving whatever name they thought was best, and they were told it could be one word or more than one. For each object, linguistic category membership was determined by the name most frequently generated for the object by the relevant language group in Ameel et al. (2005). For example, an object that was labeled *fles* by most Dutch-speaking monolinguals was taken to belong to the category *fles* for this group.

In order to compare the typicality ratings of different language groups, we selected pairs of frequently generated category names that were considered sufficiently good (but not perfect) translation equivalents in Dutch and French. All selected names were most frequently generated for at least 10 percent of the objects of a stimulus set (up to 34%). For the bottles set, the selected pairs of category names were *fles*–*bouteille* and *pot*–*pot* (first name in Dutch; second name in French). For the dishes set, four pairs of category names were selected: *kom*–*bol*, *tas*–*tasse*, *schaal*–*plat*, and *bord*–*assiette*.³

Procedure

To obtain typicality ratings, participants were instructed to rate on a 7-point scale, with 1 labeled 'very atypical' and 7 labeled 'very typical', how good an example each object of a stimulus set was of the linguistic categories selected for the relevant set and language group. Each monolingual participant gave ratings in one language for the categories of both the bottles and dishes set. More specifically, for the bottles set, Dutch-speaking monolinguals rated typicality of the objects for *fles* and *pot*; for the dishes set, they rated typicality for *kom*, *tas*, *schaal*, and *bord*. French-speaking monolinguals gave typicality ratings for the categories *bouteille* and *pot* of the bottles set and for the categories *bol*, *tasse*, *plat*, and *assiette* of the dishes set. The bilinguals provided the complete set of typicality ratings for each stimulus set both in Dutch and in French, with order of languages counterbalanced. For each stimulus set in a given language, pictures of all the objects were presented in random order on a computer screen. The stimulus set was presented and the rating task carried out as many times as there were category names for the set. At the top of the screen appeared the category name for which participants rated typicality. At the bottom of each picture appeared the 7-point scale. The order of presentation of the categories to be rated for one stimulus set, as well as the order of presentation of the stimulus sets (bottles vs. dishes), were counterbalanced across participants.

Results and discussion

The reliability of the typicality ratings for each language group (Dutch-speaking monolinguals, French-speaking

² Only the typicality ratings of the Dutch-speaking monolinguals have been previously reported (see Ameel & Storms, 2006).

³ Translating these category names into English may not give a very good indication of what these words mean due to the inexact correspondence of the word meanings across languages. However, naming data of American English speakers are informative about the extension of the different names. Within the scope of a different study, we gathered naming data of American English speakers both for the bottles and dishes set. A comparison of the dominant names of Dutch-speaking, French-speaking, and English-speaking monolinguals revealed that objects from the bottles set named by *fles* and *bus* in Dutch, and *bouteille* and *flacon* in French, were mostly called *bottle* in English. Objects called *pot* in Dutch and French mainly received the name *container* or *jar* in English. For the dishes set, objects with *kom* as Dutch dominant name and *bol* as French dominant name were mostly called *bowl* in English, objects called *tas* in Dutch and *tasse* in French were mostly labeled *mug* or *cup*, objects called *schaal* in Dutch and *plat* in French were labeled *dish* or *bowl* and objects called *bord* in Dutch and *assiette* in French mostly received the name *plate* or *bowl* in English.



Fig. 1. Some of the exemplars of the bottles set used in the experiment.

monolinguals, bilinguals in Dutch, bilinguals in French) was evaluated. First, the correlation was computed between the typicality ratings of the odd-numbered participants and the typicality ratings of the even-numbered participants (r_{half}). This halves-reliability estimate (r_{half}^*) was then adjusted using the Spearman–Brown prediction formula $r_{half}^* = 2 * r_{half} / (1 + r_{half})$.

For both stimulus sets, estimates of reliability were very high. For the bottles set, the estimated reliabilities were 0.97, 0.96, 0.97, and 0.97 for, respectively, the typicality ratings of Dutch-speaking monolinguals, French-speaking monolinguals, Dutch typicality ratings of bilinguals, and French typicality ratings of bilinguals. For the dishes set, the respective reliabilities were 0.97, 0.98, 0.98, and 0.99.

For each language group, typicality ratings were averaged across participants for each object in each category. For each pair of corresponding categories, we then computed: (1) the correlation between the mean Dutch typicality ratings of bilinguals and the mean French typicality ratings of bilinguals, and (2) the correlation between the mean typicality ratings of Dutch-speaking monolinguals and French-speaking monolinguals. If bilinguals are able to establish monolingual-like knowledge of category pro-

totypes, the correlation between the Dutch and French typicality ratings of bilinguals should not differ significantly from the correlation between the typicality ratings of Dutch-speaking and French-speaking monolinguals. If, on the other hand, bilinguals fail to establish monolingual-like knowledge, the correlation between the Dutch and French typicality ratings of bilinguals will be significantly higher than the correlation between the typicality ratings of monolinguals in the two languages, due to the higher overlap between corresponding category centers for bilinguals than for monolinguals.

Table 1 shows the correlations between the mean typicality ratings of bilinguals and monolinguals for the different pairs of categories.

The correlations (r) in Table 1 were Z' -transformed to normalize the sampling distribution of the correlations, with $Z' = 0.5 * \ln[(1 + r)/(1 - r)]$. A two-sample paired t -test showed that the mean Z' -transformed correlation for bilinguals was significantly higher than the mean Z' -transformed correlation for monolinguals (r : 0.96 versus 0.84; $Z'(r)$: 2.28 versus 1.47, $t(5) = 3.514$, $p < .01$). Using Z -tests for each pair of category names separately, we tested whether the difference between the correlation for biling-



Fig. 2. Some of the exemplars of the dishes set used in the experiment.

Table 1

Correlations between mean typicality ratings of monolinguals and bilinguals for each pair of categories.

Pairs of categories (Dutch–French)	Monolinguals	Bilinguals
<i>fles–bouteille</i>	0.91	0.98
<i>pot–pot</i>	0.94	0.98
<i>kom–bol</i>	0.70	0.88
<i>tas–tasse</i>	0.99	0.99
<i>schaal–plat</i>	0.91	0.95
<i>bord–assiette</i>	0.94	0.99

uals and monolinguals was significantly larger than 0. The separate Z -tests all reached significance (p varying from $<.05$ to $<.0001$). Even for the pair of category names *tas–tasse* (both roughly translated as *mug* or *cup* in English), the difference in correlation between monolinguals (.985) and bilinguals (.994), although very small, was significant.

One might argue that the bilingual correlations exceed the monolingual correlations because the bilingual typicality ratings come from the same participants, while

monolingual typicality ratings originate from different participants. This possibility can be assessed by comparing the correlations between Dutch and French typicality ratings for different participants for both bilinguals and monolinguals. More specifically, for each pair of bilinguals, correlations were computed between Dutch and French typicality ratings, under the condition that the ratings in the two languages did not belong to the same individual (which results in $21 * 21 - 21 = 420$ pairs). For monolinguals, typicality ratings were correlated for each pair of Dutch- and French-speaking monolingual participants ($28 * 24 = 672$ pairs). For both stimulus sets, the mean (Z -transformed) correlation between Dutch and French bilingual typicality ratings was significantly higher than the mean (Z -transformed) correlation between typicality ratings of Dutch- and French-speaking monolinguals (bottles: $r: .69$ versus $.48$; $Z(r): .86$ versus $.54$, $t(1090) = 29.327$, $p < .0001$; dishes: $r: .68$ versus $.58$; $Z(r): .84$ versus $.68$, $t(1090) = 18.643$, $p < .0001$). In other words, two different bilinguals, each judging typicality in a different language, agree better on their judgments than two different monolinguals who judge typicality in a different language.

In sum, the results of Study 1 showed higher correlations between the Dutch and French typicality ratings of bilinguals than between the typicality ratings of Dutch-speaking and French-speaking monolinguals. This finding suggests that the centers of corresponding categories for bilinguals are more similar to each other than the corresponding category centers for monolinguals. Bilinguals seem to incorporate some exemplars of categories of each language into the roughly corresponding categories of the other language as well, resulting in a higher overlap of corresponding categories in their two languages, and hence, in more similar category centers.

This shift of corresponding category centers towards each other for bilinguals can either be due to converging boundaries influencing the category centers or to more general, overall, convergence of category membership. Study 1, however, could not discriminate between these two possible sources of the category center convergence. Therefore, a second study was designed that allowed us to do so, along with providing additional evidence for the convergence.

Study 2

Study 2 investigated whether the shift of bilingual category centers was independent from an influence of the category boundaries or not, using a different measure of central tendency. Before addressing this question, the new central tendency measure was applied to provide further evidence for the shift of bilingual category centers. The linguistic categories were represented in an M -dimensional geometrical space. In such a geometrical representation, each exemplar of a category is represented by a vector of M coordinates, one on each of the M underlying psychological dimensions. According to a prototype view (Hampton, 1979; Rosch & Mervis, 1975), categories can be represented by the point in the M -dimensional space that is located in the middle of the points representing the category exemplars, that is, by the prototype of the category (Smith & Minda, 1998; Smits, Storms, Rosseel, & De Boeck, 2002). Representing each category as a centroid point in the geometrical representation allows us to evaluate how corresponding categories of bilinguals and monolinguals are situated in relation to each other.

Given the outcome of Study 1, we predict that the centers of roughly corresponding categories in Dutch and French for bilinguals (e.g., *fles* in Dutch and *bouteille* in French) will be located closer to each other than the centers of corresponding categories for monolinguals. In other words, the distances between the centers of roughly corresponding categories for bilinguals will be smaller than the distances between the centers of the categories for monolinguals. Further, we expect that the category centers of the bilinguals will be situated more or less between the category centers of the monolinguals, since the higher overlap in corresponding categories for bilinguals drives the two centers towards each other along the lines that connect the monolingual category centers. To obtain multidimensional scaling (MDS) representations and to determine the positions of the different category centers, the sorting and naming data, respectively, from Ameel et al. (2005) were used.

Positions of category centers can be determined both in a boundary-dependent and a boundary-independent way (for

more details see Results section). To address the question about the source of convergence, positions of boundary-independent category centers were compared for bilinguals and for monolinguals. If boundary-independent category centers for bilinguals are situated closer to each other than boundary-independent category centers for monolinguals, bilingual category centers converge regardless of influence of the boundary exemplars. If the bilingual boundary-independent category centers are not situated closer to each other than monolingual ones, convergence of category centers is entirely dependent on convergence at the boundaries.

Methods

Participants

Naming and sorting data were taken from Ameel et al. (2005) study in which 32 Dutch-speaking monolinguals, 29 French-speaking monolinguals, and 25 Dutch–French bilinguals named and sorted the objects of the bottles set and the dishes set. The monolingual participants were different from those who provided typicality ratings, while most of the bilingual participants had also rated typicality. All participants were students or research assistants at Belgian universities. As in Study 1, the monolingual participants did have some knowledge of the other language through formal instruction at school, but they did not consider themselves as proficient in it (see Ameel et al., 2005). The bilinguals had been raised speaking both languages from childhood onward.

Materials

The stimuli were the bottles and dishes picture sets from Ameel et al. (2005), also used in Study 1.

Procedure

In the sorting task, participants sorted the objects of each set into piles according to the overall similarity of their features (without regard to names). Both monolinguals and bilinguals performed the sorting task once. The procedure of the naming task was described in Study 1. (For more details on the sorting and naming task, see Ameel et al., 2005).

Results and discussion

The analyses, performed to provide further evidence for the shift of bilingual category centers, and to investigate the source of category center convergence, consisted of three main steps: First, for each stimulus set and each language group separately, pairwise similarity judgments were derived from the sorting data and used to obtain multidimensional scaling representations for each of the two stimulus sets. Based on the naming data, the positions of the centers for different category names were then determined for each of the language groups in the MDS representations. This was done both in a boundary-dependent and a boundary-independent way. Finally, the distances between centers of corresponding categories were computed for bilinguals and monolinguals and compared to verify whether distances between corresponding category centers were smaller for bilinguals than for monolinguals. The different steps are described in detail below.

Multidimensional scaling solutions

Since we want to compare the positions of category centers of different language groups, it was desirable to start from a common underlying representation reflecting the similarity relations between the objects. The assumption of a common underlying object representation for the different language groups is supported by Ameel et al. (2005) who did not find substantial differences between the sorting data of the different language groups (see also Malt et al., 1999), suggesting that the underlying representation of the object set is shared by the different language groups. Hence, we derived pairwise similarity judgments by counting the number of participants across language groups who placed an object pair in the same pile (instead of tabulating separately for the different language groups). Aggregating over language groups enlarges the number of participants, which improves the reliability of the pairwise similarity measure. Using the split-half technique followed by the Spearman–Brown formula, we estimated for both object sets the reliability of the pairwise similarity measure based on the sorting data of the different language groups separately and the reliability of pairwise similarity judgments based on the sorting data aggregated over the three language groups. For the bottles set, the estimated reliability of the pairwise similarity judgments of Dutch-speaking monolinguals, French-speaking monolinguals, and bilinguals separately, were, respectively, 0.93, 0.91, and 0.87, while the reliability of the pairwise similarity judgments of the three language groups pooled was 0.97. For the dishes set, the reliability estimates for Dutch-speaking monolinguals, French-speaking monolinguals, and bilinguals separately, equaled, respectively, 0.92, 0.93, and 0.88, while the reliability estimate of the three language groups pooled was 0.97.

Because the choice of the number of underlying psychologically relevant dimensions is not always obvious (see Verheyen, Ameel, & Storms, 2007), we computed 2- to 5-dimensional MDS solutions using the SAS MDS procedure (SAS Institute Inc., 1999). For the bottles set, stress values were 0.22, 0.15, 0.11, and 0.08 for MDS solutions in, respectively, 2–5 dimensions. For the dishes set, the stress values were, respectively, 0.17, 0.11, 0.08, and 0.06.

Determining positions of category centers

For each object set and for each language group, centers were computed for the different category names. More specifically, for the bottles set, the category centers of *fles* and *pot* were computed for the Dutch-speaking monolinguals and the bilinguals. For the French-speaking monolinguals and the bilinguals, we calculated the centers of *bouteille* and *pot*. For the dishes set, the category centers of *kom*, *tas*, *schaal*, and *bord* were computed for the Dutch-speaking monolinguals and the bilinguals. For the French-speaking monolinguals and the bilinguals, the category centers of *bol*, *tasse*, *plat*, and *assiette* were determined.

The boundary-dependent center for each category was computed across all the stimuli of an object set. Thus outliers at the boundaries of the categories contribute to location of the calculated centers in this method, as well as all other exemplars. Each stimulus of an object set was

weighed by its name frequency so that objects that were named frequently by a particular category name across participants affect the position of the category center to a large degree, while objects that were labeled with the particular category name by only few (or no) participants affect the position of the corresponding category center to a small degree (or not at all). For example, to compute the coordinates in the MDS solution of the category center of *fles* for the Dutch-speaking monolinguals, the coordinates of each object given by the sorting data were multiplied by the frequency with which the object was called *fles* by the Dutch-speaking monolinguals. Next, the weighted coordinates were summed and the coordinates of the weighted category center were calculated as the weighted sum divided by the sum of all the frequencies. This procedure was repeated for 2- to 5-dimensional MDS representations.

To determine positions of category centers that were independent from boundary exemplars, we computed central tendency points that were defined by the median values on each of the coordinate axes in a 2-dimensional MDS representation for the two stimulus sets.⁴ Since median values are not affected by outliers, this method eliminates the influence of boundary exemplars. Similar to the procedure used to determine the average-based category center positions, the coordinates of all exemplars were used to determine the medians, weighed by name frequency (by including the coordinate of each exemplar as many times as the exemplar was called by the particular category name).

Distances between weighted category centers

Figs. 3 and 4 contain the two-dimensional MDS representations for, respectively, the bottles set and the dishes set, together with the boundary-dependent centers of the different categories for each language group.

From Figs. 3 and 4, it is clear that, for each pair of category centers, the bilingual boundary-dependent centers of roughly corresponding categories are closer to each other than the monolingual boundary-dependent centers of the categories. Furthermore, the bilingual category centers are situated in between the category centers of the monolinguals.⁵

⁴ While average-based prototypes were calculated in 2- to 5-dimensional MDS representations, medians were only computed in 2-dimensional representations, since the medians were calculated to investigate what happens to the prototypes when boundary exemplars are ruled out.

⁵ To verify whether bilingual prototypes were also situated in between monolingual prototypes for higher-dimensional solutions, we computed for each pair of category names the ratio of the indirect distance between the monolingual prototypes (via the bilingual prototypes) to the direct distance between the monolingual prototypes. The indirect distance between the monolingual prototypes is the sum of three distances: the distance between the monolingual Dutch prototype and the bilingual Dutch prototype, the distance between the bilingual prototypes and the distance between the monolingual French prototype and the bilingual French prototype. An indirect–direct distance ratio of 1 indicates that the bilingual prototypes are situated perfectly on the straight line that connects the monolingual prototypes. For the 2-dimensional solutions, in which the bilingual prototypes are situated in between the monolingual prototypes (visible in Figs. 3 and 4), the ratios were close to one. Similar ratios were found for the higher-dimensional solutions, allowing us to conclude that bilingual prototypes were also situated in between monolingual prototypes for higher-dimensional solutions.

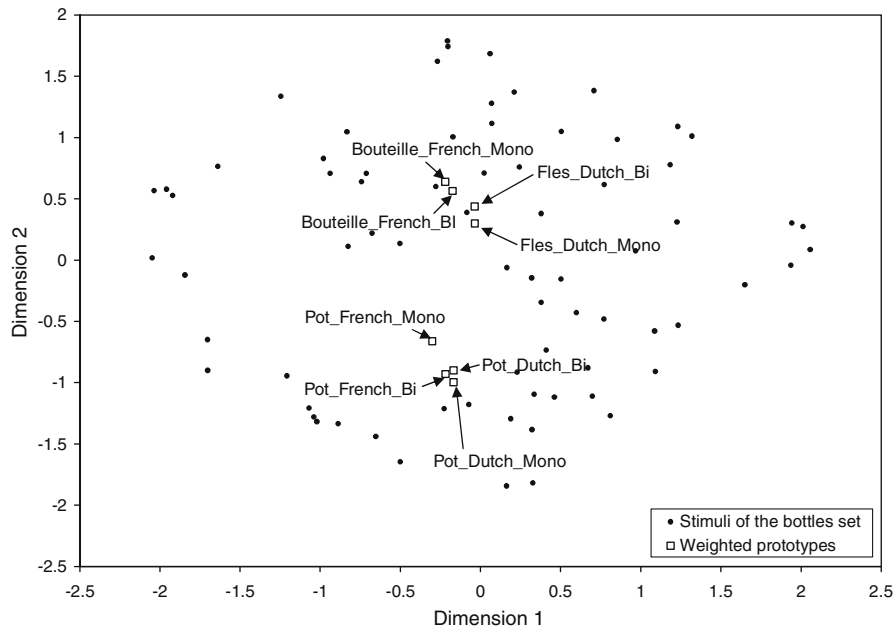


Fig. 3. Two-dimensional MDS representation of the bottles set. The black dots represent the 73 stimuli of the bottles set; the white diamonds represent the prototypes of the four different language groups (suffixes: Dutch_Mono = Dutch-speaking monolinguals, French_Mono = French-speaking monolinguals, Dutch_Bi = bilinguals in Dutch, and French_Bi = bilinguals in French).

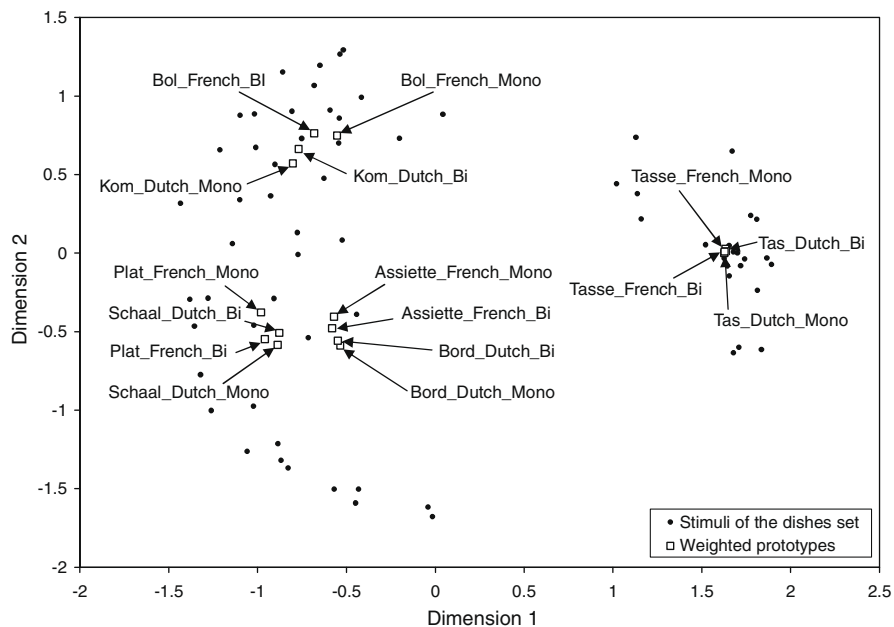


Fig. 4. Two-dimensional MDS representation of the dishes set. The black dots represent the 67 stimuli of the dishes set; the white diamonds represent the prototypes of the four different language groups (suffixes: Dutch_Mono = Dutch-speaking monolinguals, French_Mono = French-speaking monolinguals, Dutch_Bi = bilinguals in Dutch, and French_Bi = bilinguals in French).

In order to determine quantitatively whether category centers for bilinguals were situated closer to each other than those of monolinguals, Euclidean distances were calculated between bilingual centers for corresponding categories and monolingual centers for corresponding

categories in 2- to 5-dimensional MDS representations (e.g., the distance between *fles* and *bouteille*). Then we tested the difference in average Euclidean distance between corresponding centers for bilinguals versus monolinguals across category pairs of both the bottles and

dishes set (*fles–bouteille*, *pot–pot*, *bord–assiette*, *kom–bol*, *schaal–plat*, and *tas–tasse*) and across dimensions (2–5). A two-sample paired *t*-test for means revealed that the average distance between corresponding bilingual category centers was significantly smaller than the average distance between corresponding monolingual category centers ($t(23) = 5.97$, $p < .0001$). For the *tas–tasse* pair, the centers can hardly be distinguished from each other (see Fig. 4). This suggests that the words *tas* and *tasse* are used in the same way by Dutch-speaking and French-speaking monolinguals, and, logically, therefore, also by the bilinguals in their two languages.

Similar to the positions of the boundary-dependent (average-based) category centers, the boundary-independent median values of corresponding categories for bilinguals were situated closer to each other than the median values of corresponding monolingual categories, and the bilingual points were situated in between the monolingual medians.⁶ This finding indicates that the smaller distances between bilingual category centers than between monolinguals' category centers are not due just to convergence of the category boundaries, but to overall membership convergence.

In sum, when representing the semantic categories and their centers in a *M*-dimensional space (on the basis of naming data), smaller distances were found between bilingual centers of roughly corresponding categories than between monolingual centers of the same categories (and the bilingual points are situated between the monolinguals'). Similar to Study 1, these results suggest that bilinguals are unable to keep exemplars of each language separate, resulting in more similar category centers in the two languages of a bilingual. Further, this convergence of bilingual category centers cannot be due to the boundary exemplars alone, since the same pattern of results was observed with boundary-independent median-based central tendencies of categories. Instead, bilingual category centers converge independently from converging boundaries and category membership must converge beyond just the boundary cases.

Study 3

While Study 1 and 2 addressed the issue of how convergence was manifested in the category centers of corresponding categories in a bilingual's two languages, Study 3 focused on evaluating convergence in the category boundaries. As described earlier, there are three possible outcomes: First, bilinguals might learn the language-specific complexity at the category boundaries in both languages, in which case bilingual and monolingual categories will be equally complex. If so, the observed convergence must arise entirely from other aspects of the lexical representations.

It is more plausible, however, that bilinguals are unable to learn the language-specific complexity at the category

boundaries in both languages, since category boundaries are mainly determined by low-frequency, atypical exemplars which are more likely to be poorly encoded than high-frequency, typical exemplars situated in the category center. This would result in convergence at the category boundaries. Convergence at the category boundaries could be manifested either in more complex or simpler categories for bilinguals as compared to monolinguals. On the one hand, it is possible that bilingual categories are more complex than monolingual categories because bilinguals incorporate the boundary exemplars of a particular category in one language in the corresponding category in the other language as well, and vice versa. In other words, under this hypothesis, boundary exemplars of each language do get encoded by bilinguals but are not kept separate in the two languages. As a result, the categories of each language acquire language-specific complexities of both languages and will be more complex than the categories of monolinguals.

On the other hand, it is possible that the boundary exemplars of each language get only poorly encoded into the lexical categories to which monolinguals assign them. As a consequence, bilinguals may drop (some of) the boundary exemplars in each language. In other words, mechanisms responsible for language-specific idiosyncrasies will not operate (or at least to a smaller degree) on each language for the bilingual, resulting in less complex categories compared to monolinguals. Under this scenario, bilinguals may be more likely to assign the boundary exemplars to the category to which they are most similar, rather than to the category to which they are assigned by monolinguals reflecting language-specific idiosyncrasies.

Study 3 was aimed at evaluating whether bilinguals have an equally, a more, or a less complex category structure than monolinguals. We compared the complexity of bilingual categories to that of monolingual categories. Complexity of categories was quantified by the number of dimensions needed to separate pairs of categories linearly. The more complex the categories, the more dimensions are needed to separate the categories linearly. An equal number of dimensions needed to separate bilingual category pairs and monolingual category pairs would indicate an equally complex category structure for bilinguals and monolinguals. Higher dimensionalities to separate bilingual category pairs linearly compared to monolingual category pairs would indicate more complex categories for bilinguals as compared to monolinguals. Lower dimensionalities to separate bilingual category pairs linearly compared to monolingual category pairs would be evidence for less complex categories for bilinguals as compared to monolinguals.

Methods

The same naming data of Dutch- and French-speaking monolinguals and Dutch-French bilinguals were used as in Study 1 and Study 2. Also, the same MDS representations, based on aggregated sorting data over the three participant groups, were used.

LINSEP (Van Assche, 2006) is a method that allows us to determine whether two categories are linearly separable in

⁶ Since the results for the boundary-independent (median-based) category centers are similar to the results for the boundary-dependent (average-based) category centers, we do not show the MDS representations with the positions of the median-based category centers.

a given number of dimensions by looking for a linear function that perfectly divides the extensions of the two categories when projected onto the specified number of dimensions. LINSEP (Van Assche, 2006) assumes an underlying M -dimensional geometrical representation in which the exemplars belonging to different categories of a semantic domain are embedded. Each exemplar is represented by a vector of M coordinates, one on each of the M underlying psychological dimensions. The input data for LINSEP were the coordinates of the objects derived from MDS representations in 2–5 dimensions. Two categories P and Q are linearly separable in a particular dimensionality M if there exists a linear function $f: R^n \rightarrow R$ and a discrimination value c , such that for all $x \in X$ holds (1):

$$f(x_1, x_2, \dots, x_n) \leq c \Rightarrow x \in P$$

$$f(x_1, x_2, \dots, x_n) > c \Rightarrow x \in Q.$$

The real function f is linear if it can be written as

$$f(x_1, x_2, \dots, x_n) = a_1x_1 + a_2x_2 + \dots + a_nx_n,$$

in which $x_i \in R$ is a variable and $a_i \in R$ a constant.

To test whether P and Q are linearly separable categories, a function f has to be found such that the restrictions under (1) are met. LINSEP returns a dichotomous value (1 or 0) that indicates whether or not such a function can be found for a particular pair of categories in a particular dimensionality (For more technical details, see Van Assche, 2006.). The more dimensions that are needed to separate the categories linearly, the more complex the categories are. In principle, two arbitrary categories are always linearly separable, as long as one is willing to add enough dimensions to the geometrical representation.

For the present study, we investigated whether pairs of category names within a language were linearly separable in 2–5 dimensions. Note that these category pairs are different from the ones used in Study 1 and 2 in which the category pairs consisted of a category name in L1 and its corresponding category name in L2. For the category pairs in this study, we selected the most frequently generated names for at least 10% of the objects of a stimulus set (the percentage of objects varied between 12% and 34%). For the bottles set, the pairs *fles-bus*, *fles-pot*, and *bus-pot* were selected for the Dutch-speaking language groups. The pairs *bouteille-flacon*, *bouteille-pot*, and *flacon-pot* were selected for the French-speaking language groups. For the dishes set, the pairs *kom-tas*, *kom-schaal*, *kom-bord*, and *schaal-bord* were selected for the Dutch-speaking language groups. The pairs *bol-tasse*, *bol-plat*, *bol-assiette*, and *plat-assiette* were selected for the French-speaking language groups. As can be seen, for the dishes set, not all possible pairs of category names were selected. The Dutch pairs *tas-bord* and *tas-schaal* and their French equivalents *tasse-assiette* and *tasse-plat* were not used, since the category of *tas* (*tasse*) objects is rather isolated from the categories of *bord* (*assiette*) objects and *schaal* (*plat*) objects. The category of *kom* (*bol*) objects is more interrelated to the category of *tas* (*tasse*) objects, at least in the studied dimensionalities.

Results and discussion

Testing linear separability

Analyses were based on naming data from every participant separately to avoid biases due to averaging. Analyses on aggregated data (i.e., the most frequently generated names) could lead to wrong conclusions (under-estimation or over-estimation of the number of dimensions), since aggregated data contain information about a (non-existent) 'average person'. For each participant of a language group, LINSEP determined for each pair of category names of each stimulus set the lowest dimensionality at which the pair was linearly separable. This yielded for each participant seven different values, one for each pair of category names. Next, for each language group (Dutch- and French-speaking monolinguals, bilinguals in Dutch and French) and for each pair of category names, the minimum dimensionalities at which the pair was linearly separable were averaged across participants. Fig. 5A and B display the averaged minimum dimensionality for the selected pairs of category names for the different language groups for, respectively, the bottles and the dishes set.

To test whether bilingual categories are linearly separable in an equal, a higher, or a lower dimensionality than monolingual categories, a two-sample paired t -test for the means of bilinguals and monolinguals was calculated. Overall, the minimum dimensionality at which perfect linear separability was found was significantly lower for bilinguals than for monolinguals ($3.6 < 3.9$, $t(13) = -2.587$, $p < .05$). The same result was found for the two stimulus sets separately, although significance was only reached for the bottles set ($3.9 < 4.3$, $t(7) = -2.431$, $p < .05$). As can be seen in Fig. 5, there were three exceptions to this general pattern: the categories *fles-pot*, *schaal-bord*, and *bol-assiette* were linearly separable in a higher dimensionality for bilinguals than for monolinguals (respectively, $4.4 > 4.19$, $3.8 > 3.7$, and $3.9 > 3.3$). However, the difference was not significant for any of these category pairs (as indicated by separate t -tests).

In sum, the finding that bilingual categories are linearly separable in lower dimensionalities than monolingual categories implies that the categories of bilinguals are less complex than the corresponding monolingual categories, since bilinguals need fewer features to separate their categories linearly than monolinguals. This finding suggests that language specificities of both languages are poorly encoded in memory, resulting in less complex categories for bilinguals as compared to monolinguals.

This outcome indirectly suggests that boundary exemplars, which are more likely determined by language-specific idiosyncrasies than centrally situated exemplars, are dropped from the monolingual categories in both the bilingual's languages, and instead, are assigned to categories according to their similarity. However, the linear separability analyses do not provide direct evidence for the latter conclusion. A more direct way to evaluate whether bilinguals drop boundary exemplars from categories as compared to monolinguals lies in comparing the proportions of outliers for bilinguals and monolinguals. This was done in Study 4.

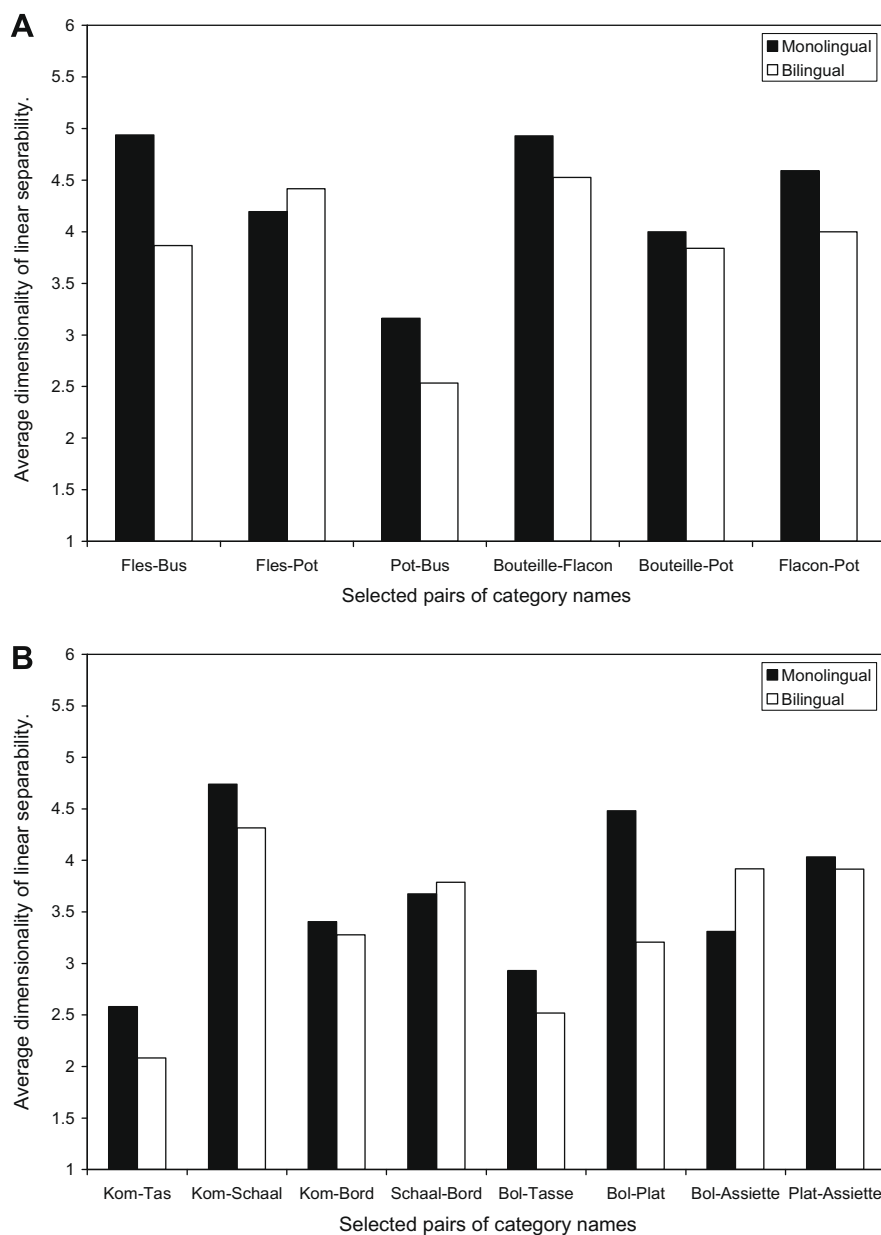


Fig. 5. Average dimensionality of linear separability for different pairs of category names for bilinguals and monolinguals for the bottles set (A) and the dishes set (B).

Study 4

While Study 3 showed that bilinguals need fewer dimensions to separate their categories linearly than monolinguals, Study 4 investigated more directly whether boundary exemplars are dropped from categories relative to their composition for monolinguals in both languages. This was done by comparing the proportion of outliers for bilinguals and monolinguals, with an outlier defined as an object that is more similar to the center of another category than to the center of its own category. Since the findings of Study 3 suggested that bilinguals drop out lan-

guage specificities of both languages, we predict that bilinguals have fewer outliers than monolinguals.

Methods

The same naming data of Dutch- and French-speaking monolinguals and Dutch-French bilinguals were used as in the three previous studies. Also, the same MDS representations, based on aggregated sorting data over the three participant groups, were used.

In geometrical representations, an outlier can be defined as an object that is located closer to the center of

another category than to the center of its own category. We computed outliers for the two sets of stimuli in a 2-dimensional MDS representation. We used only a 2-dimensional space because, if there are differences in the number of outliers between bilinguals and monolinguals, these differences can be less pronounced in higher-dimensional spaces, since increasing the dimensionality of a solution may cause an outlier to become a non-outlier.

Proportions of outliers were determined for the category names that were most frequently generated for at least 10% of the objects of a stimulus set (the same category names used in the pairs of Study 3). For the bottles set, these were Dutch *fles*, *bus*, and *pot* and French *bouteille*, *flacon*, and *pot*. For the dishes set, they were Dutch *kom*, *tas*, *schaal*, and *bord*, and French *bol*, *tasse*, *plat*, and *assiette*.

Results and discussion

To avoid biases due to averaging, outliers were computed for each participant separately. For each participant of a particular language group and for each stimulus set, we first selected the objects that were called by the category names selected for the particular stimulus set and the language of the participant. For example, for each Dutch-speaking monolingual participant, the objects that were called *fles*, *bus*, or *pot* by the participant were selected from the bottles set; the objects that were called *kom*, *tas*, *schaal*, and *bord* were retained from the dishes set. On average across all language groups, 60% of the objects from the bottles set were selected (varying between 42% and 78%) and 69% of the objects from the dishes set (varying between 37% and 94%). Next, for each participant, the distances were computed between the selected stimuli for a particular stimulus set and the centers of the selected category names for the stimulus set and the language of the participant. An object was considered to be an outlier if the distance to the center of its own category name was larger than the distance to the center of another category name. For each participant, the proportion of outliers was calculated for each category name. Finally, for each category name of both stimulus sets, the proportion of outliers was averaged across the participants in each language group. This resulted in 14 averaged proportions for bilinguals and 14 averaged proportions of outliers for monolinguals; one for each selected category name. Even though the differences in proportion of outliers between bilinguals and monolinguals were small, in 11 out of the 14 category names (79%), the bilingual proportion of outliers was smaller than the monolingual proportion, which is a significantly larger percentage than would be observed by chance (binomial test, $p < .05$). The smaller proportion of outliers for bilinguals indicates that bilinguals drop at least part of the boundary exemplars compared to the monolingual categories of both languages. Bilinguals make fewer violations of similarity-based naming than monolinguals, confirming the finding of Study 3 that language-specific factors operate to a smaller degree on bilingual naming than on monolingual naming.

General discussion

Summary of the results

Bilingual representations may be highly vulnerable to convergence (Ameel et al., 2005; Bullock & Gerfen, 2004; Bullock & Toribio, 2004; Colantoni & Gerlukian, 2004; Kehoe et al., 2004; Montrul, 2004; Sánchez, 2004, 2006; Toribio, 2004; Wolff & Ventura, in press) as a result of the permeability of their language representations (De Groot & Nas, 1991; Kirsner et al., 1984; Schwanenflugel & Rey, 1986), in combination with frequent reactivation of elements of one language by related elements of the other (Wolff & Ventura, in press) and meaning representations (i.e., mappings from meanings to word forms) that may be less well-established than for monolinguals (Gollan et al., 2005). This paper investigated in which aspects of the bilingual lexical category structure this vulnerability is manifested. Convergence in the category centers was demonstrated by two findings: (1) correlations between Dutch and French typicality ratings for roughly corresponding categories of bilinguals were higher than between ratings for the same categories by Dutch-speaking and French-speaking monolinguals and (2) in a M -dimensional geometrical space, the centers of corresponding categories in the two languages of bilinguals were situated closer to each other than the centers of corresponding monolingual categories. These findings indicate that the centers of corresponding categories for bilinguals are more similar to each other than the corresponding category centers for monolinguals. Moreover, the convergence of bilingual category centers entails overall membership convergence, and not just convergence of the boundary exemplars, since the same pattern of results was observed with boundary-dependent average-based and boundary-independent median-based central tendencies of categories.

Convergence in the category boundaries was also demonstrated by two findings: (1) fewer dimensions were needed to linearly separate bilingual categories than monolingual categories, and (2) fewer violations of similarity-based naming were observed for bilinguals than for monolinguals. Together these results indicate that bilingual lexical categories are simplified compared to monolingual lexical categories and the naming of boundary exemplars in bilinguals is less determined by language-specific idiosyncrasies than the naming of boundary exemplars in monolinguals.

Possible accounts for the semantic convergence

Gollan et al. (2005) suggested that the meaning representations in a bilingual's two languages are less well-established relative to monolingual meaning representations because bilinguals use each language less than monolinguals. Although the current studies did not directly test the relevance of this observation for explaining convergence, it suggested some possibilities for how semantic convergence could be manifested in the centers and boundaries of linguistic categories. Especially regarding boundary exemplars which are encountered less fre-

quently, the reduced language use idea is useful. Names of atypical boundary exemplars are less similarity-based, and so, more difficult to learn, because they can't be learned through generalization (e.g., apply the name *fles* to all objects with a neck). Rather, they have to be learned through experience with specific name–object pairings. As discussed earlier, even for monolinguals, atypical members of lexical categories are learned later than typical ones (Posner & Keele, 1968; Rosch, 1973; Rosch & Mervis, 1975), verified slower in a category verification task (Hampton, 1979; Larochelle & Pineu, 1994; McCloskey & Glucksberg, 1978; Rips et al., 1973; Smith et al., 1974), categorized slower and less accurately (Fujihara et al., 1998), etc. For bilinguals as opposed to monolinguals, atypical exemplars are encountered even less frequently. As a consequence, the encodings of these exemplars may be more fragile and susceptible to being lost from lexical categories. Our findings for the category boundaries are in line with this account.

With regard to exemplars situated at the center of a category, the reduced language use notion seems less useful, since category centers are mainly determined by high-frequency typical exemplars, which are more likely to be well-encoded. In light of this explanation, the finding of convergence in the category centers seems rather surprising. However, the position of category centers could be influenced by category boundaries, and converging boundaries could account for converging category centers. But, even without an influence of the category boundaries, bilingual category centers could still converge if the overall membership of the categories converges to some degree. The shifts towards each other of median-based central tendencies for bilingual corresponding categories as compared to monolingual categories demonstrated that bilingual category centers do indeed converge independent of convergence at the category boundaries. It's at this point that the retrieval-induced reconsolidation notion (Wolff & Ventura, *in press*) provides a key element of the explanation: According to this idea, the two languages reactivate each other continuously in simultaneous bilinguals, resulting in representations in both that are vulnerable to mutual influence. This influence need not be restricted to boundary areas, and our data suggest it is not.

An alternative reason why convergence might take place, which we have not addressed so far, is cognitive economy (cf. Muysken, 2000). One might argue that storing the language specificities of two languages is very demanding on the resources of memory. In order to satisfy individual cognitive constraints (that is, reduce the demand on memory), bilinguals might drop out language-specific subtleties, making the lexical categories of the two languages simpler and more similar to one another than the roughly corresponding monolingual categories. However, we believe this explanation is less likely to be correct, since the capacity of long term memory is potentially unlimited. Given the ability of healthy adults to continue to learn sizeable new amounts of information in many different domains across the lifespan, there is no clear reason to think that the memory demands of learning two distinct sets of word-to-referent mappings or abstracted word meanings would exceed the limits of mem-

ory. Rather, it seems more likely that it is the variables that drive the formation of memories—such as frequency of exposure, practice, and the retrieval and integration of related information already stored in memory—that result in the particular form that any particular piece of bilingual lexical knowledge takes.

Finally, the methods used in this paper measure bilingual lexical representations at one particular moment in time. We do not know whether bilinguals initially develop fully monolingual-like lexical representations in each of their languages before convergence takes place, or whether they never acquire monolingual-like representations in either language and instead develop merged lexical representations as they acquire the two languages in childhood. The reduced language use idea suggests that convergence might be greatest early in language acquisition, since children have received less input in both languages than adults. As representations become more established over time with additional language input, convergence might diminish. The retrieval-induced reconsolidation idea, on the other hand, implies that convergence might be greatest later in life. The more the two languages reactivate each other over time, the more similar the language representations might become. Below, in considering generalization to other types of bilinguals, we note evidence that late L2 learning can influence language use in a well-established L1; such evidence suggests that convergence does not require early exposure to both languages. More fully examining this interesting issue will require a developmental approach, and ideally a longitudinal approach.

Illustrations of simplifications

The finding of a less complex nature of bilingual categories can be illustrated through two concrete examples for the bottles set, derived from the naming data of Ameel et al., 2005 study. Fig. 6 shows the two examples.

As described in Ameel et al. (2005), it appears that French-speaking monolinguals subdivide the group of objects named *fles* by Dutch-speaking monolinguals into two major linguistic categories: *bouteille* (13/25) and *flacon* (10/25). This pattern, illustrated in Fig. 6A, suggests a more complex naming pattern for French-speaking monolinguals than for Dutch-speaking monolinguals, at least for this particular region of the stimulus space. A similar nesting relation was found for the bilinguals, but in contrast to the equal distribution of *fles* objects among the French monolingual categories, the majority of *fles* objects for bilinguals are called *bouteille* in French (21/30) and only a minority are called *flacon* (6/30). Thus, the bilinguals' French naming pattern for this particular region of the stimulus space is less complex than the corresponding monolingual naming pattern, because, instead of using two separate names for *fles* objects, bilinguals mainly use only one name, *bouteille*.

In light of the finding that bilinguals need fewer dimensions than monolinguals to separate their categories linearly, this simplification can be explained by the elimination of language-specific features. Dutch-speaking monolinguals have only one general name for bottles, that is: *fles*. In contrast, French-speaking monolinguals use a

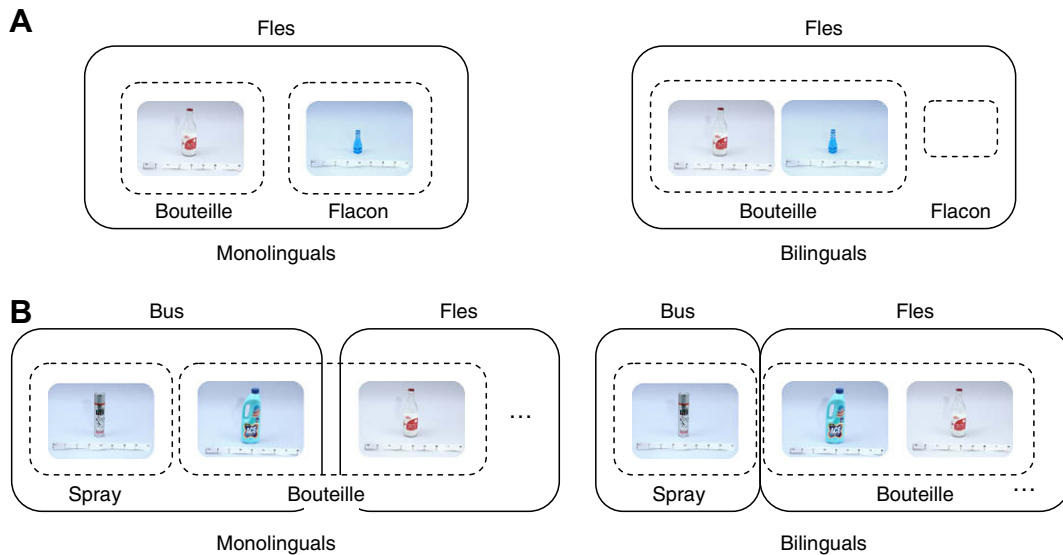


Fig. 6. Two illustrations of the less complex category structure of bilinguals versus monolinguals. The upper panel (A) shows the composition of the *fles*, *bouteille* and *flacon* categories for monolinguals and bilinguals. The lower panel (B) shows the composition of the *bus*, *fles*, *spray* and *bouteille* categories for monolinguals and bilinguals.

distinct name *flacon* to refer more specifically to small, narrow bottles containing perfume or tablets, to differentiate these small bottles from the more ordinary *bouteille* objects. This French differentiation is probably represented by the addition of extra features to the meanings of *bouteille* and *flacon* to distinguish between objects of the two categories. The finding of a much smaller *flacon* category for bilinguals as compared to French-speaking monolinguals suggests that bilinguals drop the French-specific features that determine the distinction between *bouteille* and *flacon* and apply the word *bouteille* predominantly in the same way as the word *fles* in Dutch.

Another simplification, derived from the naming data of Ameel et al. (2005), can be found in Fig. 6B. The left-hand part of Fig. 6B shows a nesting and cross-cutting relation between Dutch- and French-speaking monolingual categories: the Dutch category of *bus* objects is separated into a French *spray* category and a French *bouteille* category. The latter, however, contained not only *bus* objects, but also *fles* objects. To be fully monolingual-like in both languages, bilinguals would have to incorporate additional French-specific features to make the *spray-bouteille* distinction (within the Dutch category of *bus* objects), and additional Dutch-specific features to make the *bus-fles* distinction (within the French category of *bouteille* objects). However, the data showed that bilinguals did not distinguish *bus* from *fles* objects within the French category of *bouteille* objects (right-hand part of Fig. 6B). This finding suggests that bilinguals drop the Dutch-specific features that determine the *bus-fles* distinction within the French category of *bouteille* objects, and instead, apply the French boundary in both languages. The portion of representational space associated with *bus* in Dutch is similar to the portion of representational space associated with *spray* in French. Analogously, the portion of representational space associated with *fles* in Dutch is similar to the portion of

representational space associated with *bouteille* in French. In other words, bilinguals use the name *bus* in Dutch exclusively for objects called *spray* in French, while Dutch-speaking monolinguals use the name *bus* for a more diverse set of objects, not only including typical *spray* objects, but also larger types of bottles containing cleaning products. The larger bottles containing cleaning products are called *fles* instead of *bus* by bilinguals, just as they receive a different name in French (*bouteille* instead of *spray*). In other words, dropping the Dutch-specific features results in more strongly shared category centers for *bus* and *spray*, and *fles* and *bouteille* for bilinguals than for monolinguals.⁷

The latter example shows that bilinguals do not necessarily drop language-specificities of both languages for a given set of interrelated words. It is even possible that in most cases bilinguals drop the language specificities of only one language; namely, the language that imposes the most complex category structure on the relevant portion of the stimulus space. Indeed, the average minimum dimensionality to separate *bus* objects from *fles* objects for Dutch-speaking monolinguals is 4.94, while French-speaking monolinguals on average only need 2.35 dimensions to separate *spray* objects from *bouteille* objects. Furthermore, the *bus* objects and the *fles* objects within the French category *bouteille* are more similar to each other than the *spray* objects and the *bouteille* objects within the Dutch *bus* category (average similarity of 19 versus 11, N.S.). Thus, from the perspective of the bilingual, it is easier (less complex) to use a common word for the (more simi-

⁷ Note that *spray* was not included in the analyses of the presented studies, because there were only 5 objects (7% of the bottles set) with *spray* as the dominant name. However, similar to the other category pairs, the prototypes of *bus* and *spray* moved towards each other for the bilinguals in the 2- to 5-dimensional scaling solutions.

lar) *bus* and *fles* objects in both languages, than to use a common word for the (less similar) *spray* and *bouteille* objects.

Implications for models of the bilingual lexicon

Ameel and colleagues (2005) considered Van Hell & De Groot (1998) distributed conceptual feature model to be a useful framework to account for the bilingual naming pattern. We believe that the model could also more specifically account for the simplification that takes place in bilinguals as compared to monolinguals (see Fig. 7).

In the distributed feature model (Van Hell & De Groot, 1998), a word (on the lexical level) is represented as a pattern of activation across a network of interconnected units or features. In line with most models of bilingual memory, the distributed feature model assumes that the feature space representing knowledge of the world itself is shared across a bilingual's two languages and features on this level are available to either language. However, how these features combine is language-specific. While this model was developed to account for differences in the extent to which a bilingual's lexical representations overlap for the two languages depending on word-type and grammatical class (e.g., abstract vs. concrete words; nouns vs. verbs), we believe that the model is also a useful framework to understand differences in the extent to which they overlap for two languages depending on the speaker (monolingual versus bilingual⁸). Since similarity perception is shared across languages (Ameel et al., 2005; Malt et al., 1999), we assume that featural knowledge is shared, not only across a bilingual's two languages, but also across speakers of different languages.

Fig. 7A shows the monolingual situation. The circles on the lexical level represent words in Language 1 and Language 2 that are rough translation equivalents of one another for monolinguals in each. The black circles in the feature space represent features that are relevant to the words of interest in both Language 1 and Language 2. The white circles are language-specific features that are not shared across the words in Language 1 and Language 2. These language specificities for the two languages account for the cross-linguistic differences in naming (Ameel et al., 2005; Malt et al., 1999).

Fig. 7B shows the bilingual situation. The less complex category structure found for bilinguals can be explained in terms of dropped language specificities. This is represented by the white circles that are not taken into account to represent meaning in any language, and thus these features are not connected to the lexical level. As can be seen, we allowed some language specificity for bilinguals, since there remain subtle differences between the two naming patterns for bilinguals (see the white circles connected to the lexical level).

As the examples described above suggest, bilinguals do not necessarily drop language-specific features of both languages. What will be dropped may depend on the level of

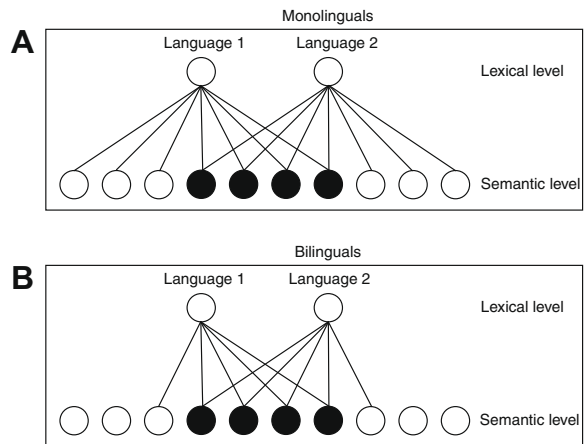


Fig. 7. Schematic representation of the monolingual lexicon (A) and the bilingual lexicon (B). The lower panel represents the less complex category structure for bilinguals as compared to monolinguals.

complexity imposed by the language specificity of the two languages on the category structure. Less complex category structures are more likely to be retained than more complex category structures. Hence, the schematic representation of the bilingual situation (Fig. 7B) is too strong, since it assumes that language specificities of both languages are dropped. More moderate versions need to be considered that allow language specificities of L1 to be retained, while the specificities of L2 are dropped (Fig. 8A), or vice versa (Fig. 8B). Further empirical evidence is also needed about whether it is common for idiosyncratic membership of one language, if it does get encoded, to be imposed on the other language as was true in the second case discussed above.

Generalization to other types of bilinguals

The notion of bilingualism refers to a very heterogeneous group of people who speak, to a larger or smaller degree, two different languages. Organization of the bilingual lexicon strongly depends on the context in which the languages are acquired. The bilinguals who participated in the presented studies were compound bilinguals, simultaneously raised with two languages. Their parents have consistently spoken their own language to them from childhood onward. The conclusions about the convergence in compound bilinguals drawn from the different studies in this paper cannot automatically be generalized to other types of bilinguals having a different language acquisition history. However, some predictions can be made based on the results for compound bilinguals.

Another type of bilinguals are subordinate bilinguals, also called second language learners, who learn the second language at a later age in a L2 language environment well after the first (native) language has been acquired. When these bilinguals start learning their second language, the language specificities of L1 are well-established and very compelling in L1, and they are likely to be imposed in L2, regardless of the complexity level of these L1 specificities

⁸ Note that monolinguals have only one representation, depending on the language they speak, while bilinguals have two representations, one for each language.

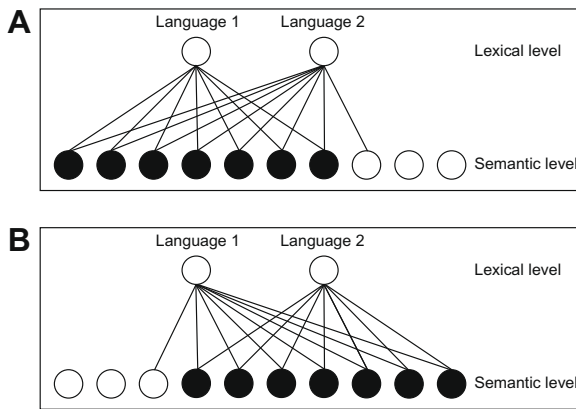


Fig. 8. Two moderate versions of the less complex bilingual category structure that allow the language specificities of one language to be retained, while the specificities of the other language are dropped: Specificities of L1 are retained (A). Specificities of L2 are retained (B).

(like the situation in Fig. 8A). Second language acquisition may initially be determined by a unidirectional influence: from L1 to L2 (Jiang, 2000; Kroll & Curley, 1988; Kroll & Stewart, 1994; Malt & Sloman, 2003). As second language learners receive more L2-specific input, L1-specific mappings will be overruled by L2-specific mappings in their L2. This is likely to be manifested in a replacement of L1-specific features by L2-specific features in L2. However, the L1-specific interference may have a lasting effect, because the pattern of this language has initially been imposed on L2, and because most second language learners continue to use their L1 in many contexts. At the same time, acquiring a second language may also have a backward effect from the second language on the first language, implying that L1-specific features are replaced by L2-specific features in L1. As we noted in the Introduction, such shifts have recently been documented. Pavlenko (1999) found that Russian second language learners of English experienced a shift in the extensions of the Russian equivalents *chastnoye* (*private*) and *lichnoye* (*personal*), resulting in incorrect use of the words in Russian. Pavlenko and Malt (2008) found that even Russian–English bilinguals with high proficiency in Russian as L1 show some effect of the L2 after immersion. Wolff and Ventura (in press) and Brown and Gullberg (2008) similarly found evidence for a backward effect of a second language on the first in the domain of semantics, and Dussias (2001, 2003) has shown such backward influences on parsing preferences for Spanish–English bilinguals. These effects have occurred even when L1 is well-established before exposure to L2.

Whether L1- or L2-specific features will be dropped or retained in the two languages of second language learners may initially be more determined by the dominant language, rather than by the relative complexity level of the language specificities. We suggest, however, that for advanced second language learners, the complexity level of language specificities may be more predictive in explaining which category structure will be applied in the two languages, though less predictive than for compound bilinguals because of the lasting effect of L1 in subordinate bilinguals. However, more

empirical work is needed to determine to what extent the manifestations of semantic convergence are similar in compound and subordinate bilinguals.

Finally, for coordinate bilinguals who acquire and use their two languages in distinct environments or separate contexts (Pavlenko, 1999), we expect some interaction between the two languages, but less than for compound bilinguals (Toribio, 2004), since coordinate bilinguals do not use their two languages simultaneously and hence, their two languages do not reactivate each other continuously. However, it is hard to predict whether this interaction would result in less complex categories in the two languages. More research is required to investigate this issue.

Generalization to other classes of words

The conclusions about convergence in bilinguals drawn from the studies described in this paper are based on concrete nouns referring to common objects. Can these conclusions be generalized to other classes of words, such as abstract words or verbs? According to Van Hell & De Groot (1998) distributed feature model, the degree of overlap in semantic features between translation equivalents is much smaller for abstract words than for concrete words (e.g., De Groot, 1989; Kieras, 1978; Plaut & Shallice, 1993). This means that the meaning of abstract words is more strongly determined by language-specific features (Van Hell & De Groot, 2003). In a study with Dutch–English bilinguals who judged how similar two words of translation pairs were, Tokowicz, Kroll, De Groot, and Van Hell (2002) indeed found that abstract translation equivalents were less likely to share meaning than concrete translation equivalents. We suggest that abstract words might be less vulnerable to convergence through simplification than concrete words, because it would imply that a large part of the meaning (i.e., the language-specific part) is dropped, resulting in a too impoverished meaning in both languages. Similarly, verbs, as compared to (concrete) nouns, may have a broader meaning (Gentner, 1978; Miller & Fellbaum, 1991), their meaning may be more dependent on their linguistic context than the meaning of nouns (e.g., Gentner, 1978), and the meanings of verbs may vary more across languages than the meanings of nouns (Gentner, 1981). Therefore, we expect that convergence (in the form of dropping of language-specific features), is less likely to occur in verbs than in nouns (though, perhaps, the process of grasping the meanings/uses of such lexical items may be delayed relative to monolingual children, due to the added difficulty of acquiring the necessary information from the reduced input in each language).

Conclusions

This paper investigated how semantic convergence affected the category centers and the category boundaries in the two languages of a bilingual. For two subsets of the domain of concrete objects (bottles and dishes), we found more similar centers of corresponding categories for bilinguals than for monolinguals and less complex category boundaries. From a practical perspective, the convergence found in a bilingual's two languages may not often

have crucial repercussions in everyday conversations, because context and the physical presence of referents can clarify the intended meaning of a word. From a theoretical perspective, however, these findings help constrain notions of how the bilingual lexicon is established and represented. A deeper understanding of how the observed convergence comes about will require developing and testing specific notions about the learning process that yields converged representations and how this learning results in the observed forms of convergence.

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