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The effect of age of L2 acquisition on the organization of the bilingual lexicon: Evidence from masked priming*

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This study investigates the role of age of acquisition (AoA) on the bilingual mental lexicon. Four groups of participants were tested: (i) English native speakers with minimal exposure to French; (ii) late English–French bilinguals; (iii) early English–French bilinguals; and (iv) simultaneous English–French bilinguals. We used a masked priming paradigm to investigate early, automatic lexical processing at the semantic level by testing both a within-language semantic condition and a cross-language translation condition. AoA was investigated both through group effects and a correlation analysis. We found significant translation priming effects for the simultaneous and early bilinguals only, and a significant correlation between AoA and translation priming effects. Due to the matched L2 proficiency of the early and late bilinguals, these results support our hypothesis that an early AoA, regardless of L2 proficiency, is crucial in order to find the L2-to-L1 priming effects that have often been elusive in recent studies.

Keywords: bilingualism, AoA, masked priming, translation priming, mental lexicon

Introduction

Do English–French bilinguals automatically active the word *neige* "snow" upon hearing the word *snow*? If so, are the mental representations of these two words organized together in an integrated neural system or are they each organized in separate, language-specific, lexicons? Further, if the system is indeed integrated, at which level of representation (lexical or semantic) is this so? And to what extent does age of acquisition (AoA) affect the integration or separation of the two lexicons?

Extensive research has investigated the interaction between the two lexicons of bilinguals, resulting in two conflicting views. One approach argues for an integrated lexicon where both languages are activated during bilingual language processing (e.g., Costa, 2005; De Groot, Delmaar & Lupker, 2000; Dijkstra, Timmermans & Schriefers, 2000; Finkbeiner, Forster, Nicol & Nakamura, 2004). The other approach argues for separated lexicons in which the activation of one language does not entail the activation of the other (e.g., Gerard & Scarborough, 1989; Ibrahim, 2009; Li, Mo, Wang, Luo & Chen, 2009; Soares & Grosjean, 1984). For early balanced bilinguals, it is generally assumed that the two lexicons are interconnected (Costa, 2005; Fabbro, 2001; Kroll & Stewart, 1994; Paradis, 2001); however, the precise roles of different factors that affect processing of each of a bilingual's languages (e.g., AoA, proficiency, and language dominance, among other factors) remain largely unexplored, with the exception of a masked translation priming study by Dimitropoulou, Duñabeitia and Carreiras (2011a), who did investigate proficiency effects while controlling for AoA. Their results show that when AoA is controlled for, proficiency does not appear to affect bilingual lexical organization. However, no native-like L2 participants were included in this study. In addition to this, a neural network model by Zhao and Li (2013) incorporated aspects of AoA to simulate neural organization of the bilingual mental lexicon.

The current paper explores the role of AoA on the organization of the bilingual mental lexicon of native speakers of English with AoAs of French at three distinct periods between birth (simultaneous bilinguals) and adulthood. In particular, we investigate AoA effects on the organization of translation equivalents by looking at French-to-English masked translation priming effects. This equates to investigating priming effects from the

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second language (L2) to the first language (L1) for the English–French bilinguals who did not acquire French starting at birth.

Below we will briefly discuss four models of the bilingual mental lexicon: (i) Kroll and Stewart's (1994) Revised Hierarchical Model (RHM); (ii) Dijkstra and Van Heuven's (2002) revised Bilingual Interactive Activation model (BIA^{+}); (iii) Silverberg and Samuel's (2004) interactive model; and (iv) Finkbeiner et al.'s (2004) Sense Model. In the discussion, we focus on how these models link translation equivalents (compared to how semantically related within-language items are linked) and how they may be able to account for AoA effects.

The bilingual mental lexicon

The RHM (Kroll & Stewart, 1994; Kroll & Tokowicz, 2001), as originally proposed, is a hierarchical model in the sense that word forms are represented at a lexical level and their meanings are represented at a semantic (or conceptual) level. At the lexical level, each language has its own memory store, while a joint semantic level contains the shared meaning information. At the lexical level, the L1 and L2 lexicons are thought to interact with generally stronger connections in the L2-to-L1 direction than vice versa. This was postulated to reflect the fact that in late L2 learning, many lexical items are learned by associating them directly to their L1 translation equivalents. In addition, both lexical stores have direct connections to the semantic store (albeit with L1 lexical items having much stronger connections to their meanings). The RHM, due to its separation of the lexical and semantic level, is able to explain much of the conflicting data regarding shared vs. separate bilingual lexicons; if the lexical level is being tested, then separate lexicons should be found, whereas testing at a more semantic level should provide evidence for a shared lexicon. In addition, due to the different strengths of connections between the separate lexical stores and from each lexical store to the shared semantic store, this model is able to account for the directional asymmetries found in studies of bilingual lexical processing. Finally, the RHM is also able to explain some of the developmental effects by postulating that the strengths of the connections can change with varying proficiency. However, while the RHM takes L2 proficiency into consideration, no specific claims are made regarding the impact of AoA on the organization of the lexicon.

Dijkstra and Van Heuven (1998, 2002) challenged the RHM by proposing the BIA and, subsequently, the BIA^{+} models, which postulate a single, integrated, lexical memory system, where lexical items from both languages are stored together and activated in a language non-selective process of word recognition. This computational model was able to account for how a bilingual can rather effortlessly make use of a single language without much interference from the other, even though the lexicon is integrated (known in bilingual research as the HARD PROBLEM; Finkbeiner, Gollan & Caramazza, 2006). Indeed, the BIA model was able to simulate the results of several experimental studies that provided evidence for shared lexical stores (e.g., Van Heuven, Dijkstra & Grainger, 1998). In the BIA^{+} model, two of the primary modifications made are of concern for the current paper: first, semantic and phonological levels of representation were added; and second, a structural distinction was made between the word identification system, where only linguistic input is processed, and the task/decision system, where non-linguistic contextual information (e.g., task expectations and strategies) is processed. As L2 items have lower frequency (assuming that the L2 is the less used language), the resting activation levels of L2 lexical nodes are lower, resulting in a need for greater excitatory energy to become activated. Activation of semantic representations of L2 words is therefore predicted to be delayed (the "temporal delay assumption") compared to the representations of the more frequently-used L1 words. Different experimental results for bilinguals of differing proficiency levels and with differing lengths of exposure to the L2 (which can be related to AoA) are thus attributed to frequency effects according to the BIA^{+} model.

In order to explain the large amount of mixed data concerning the organization of the bilingual mental lexicon when highly proficient bilinguals are tested, Silverberg and Samuel (2004) investigated the role of AoA in a cross-language lexical decision priming study. They found evidence that a shared semantic level is only present for early bilinguals and not late bilinguals (when proficiency has been controlled for). Based on their results, they proposed a model where early bilinguals have separate lexical stores but one shared semantic store, while late but proficient bilinguals have an integrated lexical store but separate semantic stores.

The Sense Model (Finkbeiner et al., 2004) was developed to account for the differing results found in lexical decision versus semantic categorization tasks, and to explain the robust within L2 priming effects. It proposes that the translation priming asymmetry found in lexical decision tasks is due to the natural representational asymmetry found between pairs of words when one of the items (usually the L1 item) has more senses than the other (usually the L2 item, when L2 usage/proficiency is relatively low). L2 items thus activate a smaller proportion of L1 senses than vice versa. The translation priming asymmetry therefore disappears in the semantic categorization task because the nature of this task requires the participant to focus on a particular sense of the word, thus eliminating the effect of the relative sense asymmetry. They found evidence that such cross-language word pairs produced similar effects to within-language word pairs that also had a sense asymmetry (e.g., the within-language words such as *huge–large* showing similar effects as French-to-English cross-language translation pairs *grand–large*).

These current theories on the organization of the bilingual lexicon are based on data from lexical processing studies that are rife with contradictions (see Francis, 2005, for a review). These conflicting results have been partially dependent on the task used, the type of bilinguals investigated, and the languages involved in the bilingual pairings. Silverberg and Samuel's model (2004) provides a very important addition to the issue of modeling the bilingual lexicon; that the organization may differ due to language background information such as AoA. As AoA is the main effect explored in the current study, we will further discuss AoA effects in the context of bilingualism.

AoA effects

In bilingualism and L2 acquisition research, the age at which L2 learning begins (Hernandéz & Li, 2007), or the age at which an individual is first exposed to the target language (Flege, Yeni-Komshian & Liu, 1999), is referred to as AoA. Many studies have provided evidence supporting the intuition that the earlier a person learns an L2, the more native-like they will be (e.g., Meisel, 2009). The mechanisms responsible for this early advantage, however, have long been debated. Are they related to cognitive development, such that learning an L2 before some developmentally significant age is crucial in order to attain native-like competence? Or are other psychosocial processes responsible, resulting in a more gradual decline in potential L2 attainment as AoA increases?

There have been numerous attempts at investigating L2 age effects on the organization of the bilingual lexicon. For example, similar to the Silverberg and Samuel (2004) study, Isel, Baumgaertner, Thrän, Meisel and Büchel (2009) provide neuroimaging data suggesting that the bilingual mental lexicon may only show shared conceptual representations for early bilinguals, and further, only if there was exposure to the L2 (or second L1) during a pre-grammatical stage between five and 20 months; otherwise, L2 lexical processing may not make use of native-like processing routines. Other research suggests that as long as the L2 or other languages are learned before the age of seven, native-like processing strategies are possible for both languages (Fabbro, 2000, 2001; Hernandéz, Li & MacWhinney, 2005; Osterhout, Kim & Kuperberg, 2012; Paradis, 1998, 2001; Ullman, 2001a, b).

The current study, observing this suggested cut-off period of age seven, will contribute to the debate on age effects in L2 lexical processing by examining lexical organization in a group of bilinguals with differing AoAs. AoA will be used in two different ways: first, to separate participants into discrete groups; and second, to place them along a continuum, thus using a correlational analysis. Correlational analyses are particularly important because there is no real consensus with respect to how participants should be divided into AoA groups, as there is no clear evidence for an exact "cut-off" point at which language acquisition processes change. To our knowledge, this is the first study that has used such an approach to study gradational age effects on the organization of the bilingual lexicon.

Testing the lexicon

An important breakthrough in psycholinguistic research was made in the 1960s and 1970s, when a theory of semantic memory search was developed (e.g., Collins & Quillian, 1969). In this theory, concepts are represented as nodes in a web-like semantic network, such that they are interconnected through links that represent different types of relationships, for example subordinate links (e.g., *vegetable–carrot*), conjunctive links (e.g., *peas–carrots*) and modifier links (e.g., *carrot–orange*). Nodes that have closer relationships are stored more closely together in this semantic network, and some links may be stronger than others. While the nature of the links and the specific organization of the semantic network has been questioned and modified over the years, a crucial aspect of this model remains relevant to the present discussion: the mechanism of spreading activation. It was proposed that when a concept node is activated in memory due to an input stimulus, this activation spreads outwards through the semantic network to other concept nodes (the more closely related nodes first), thus activating them as well. This idea was further developed by Collins and Loftus (1975).

Such a relationship-oriented organization of the mental lexicon can be tested directly by means of priming paradigms. This type of organization suggests that when one item (e.g., *cold*) is accessed, spreading activation causes semantically related items (e.g., *snow*, *ice*) within that language to also become activated. In a lexical priming paradigm, spreading activation is thought to spread from a prime to a target item, where the target is the stimulus requiring an overt response with respect to some task, and the prime is a previously presented stimulus. The typical priming paradigm, however, is thought to reflect processing of a more controlled nature (for example post-lexical integration or a top–down translation strategy) as opposed to automatic processes such as spreading activation; thus, in order to determine whether automatic activation is indeed occurring, a MASKED priming paradigm is utilized. In a masked priming paradigm, the prime is presented to the participant for such a short time (30–60 ms) that they are not usually conscious of the presentation (e.g., Chauncey, Grainger & Holcomb, 2008) and are thus unable to employ processing strategies (Rastle, Davis, Marslen-Wilson & Tyler, 2000). Masked priming has indeed provided

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evidence for early, automatic semantic priming effects in monolingual populations (Grossi, 2006).

Most importantly, the masked paradigm is also widely used to investigate BILINGUAL lexical processing, where the presence or absence of CROSS-LANGUAGE priming effects are studied (e.g., Neely, 1991). The presence of such priming effects supports a single-lexicon model, as it implies that activation of a prime in one language spreads to a target in the other language, while their absence supports a two-lexicon model for bilinguals (e.g., Dong, Gui & MacWhinney, 2005). Indeed, while some studies using this technique have found evidence for one shared lexicon for items in both of a bilingual's languages (e.g., Costa, 2005; De Groot et al., 2000; Dijkstra et al., 2000; Finkbeiner et al., 2004), others have found evidence suggesting that separate lexicons exist for each language (e.g., Gerard & Scarborough, 1989; Ibrahim, 2009; Li et al., 2009; Soares & Grosjean, 1984).

Recent research addressing this issue evinces a large amount of disagreement as to whether or not semantic masked priming is found across a bilingual's two languages (e.g., Finkbeiner et al., 2004; Gollan, Forster & Frost, 1997), with at least one study suggesting that priming across languages is only possible if controlled processes are employed (Grainger & Beauvillain, 1988). In addition, some research has found that masked translation priming is only present for cognates (Davis, Sánchez-Casa, García-Albea, Guasch, Molero & Ferré, 2010); while other studies have found that, at least for early balanced bilinguals, non-cognate translation priming is also present (Duñabeitia, Perea & Carreiras, 2010). Still other research has shown that translation priming only occurs when the prime is in the L1 (or dominant language) and the target is in the L2 (or subordinate language) (Gollan et al., 1997; Jiang, 1999; Jiang & Forster, 2001; Keatley, Spinks & de Gelder, 1994; Larsen, Fritsch & Grava, 1994; Williams, 1994), while other research suggests that automatic priming does occur across languages in both directions (Altarriba, 1992; Altarriba & Basnight-Brown, 2007; Dimitropoulou et al., 2011a; Duñabeitia et al., 2010; Tzelgov & Eben-Ezra, 1992). The divergent results reported in the literature, particularly with respect to translation priming asymmetry, may be due to multiple factors including the AoA and proficiency of participants tested, and whether the participants were living in a society where they maintained equal usage of both languages. For example, most studies employing an L1-to-L2 translation priming paradigm have found robust effects when testing early (e.g., Altarriba & Basnight-Brown, 2007; Duñabeitia et al., 2010) and late bilinguals (e.g., Gollan et al., 1997; Kim & Davis, 2003), and even those of relatively low L2 proficiency (e.g., Dimitropoulou et al., 2011a). The results of studies employing an L2-to-L1 translation priming paradigm, however, seem to only find significant priming effects for early and highly proficient bilinguals (e.g., Altarriba & Basnight-Brown, 2007; Duñabeitia et al., 2010; Perea, Duñabeitia & Carreriras, 2008; and for a more in-depth review, see Dimitropoulou et al., 2011a). The present study aims to further clarify this issue by examining the L2-to-L1 translation priming effect in groups of bilinguals varying in both AoA and L2 proficiency. In order to make progress in this field, a careful consideration of these parameters must be taken, as well as of those related to methodology, such as masking, word frequency, and stimulus onset asynchrony (Altarriba & Basnight-Brown, 2007).

It is also important to point out that this translation priming asymmetry is most often observed when the experiment in question involves a lexical decision task. Studies employing the masked priming with a semantic categorization task have not reported this pattern, resulting in the proposal of the Sense Model (Finkbeiner et al., 2004). Further, studies using an episodic recognition task with masked priming have reported an asymmetry in the opposite direction (i.e. robust translation priming in the L2-to-L1 direction and none in the L1-to-L2 direction), leading to the proposal of the Episodic L2 Hypothesis (Jiang & Forster, 2001). To date, however, no single model has been able to account for all of these patterns.

The present study

The main goal of the study presented here is to investigate the role of AoA in the organization of the bilingual mental lexicon. In addition, we will also show the importance of investigating AoA as a continuous, and not simply as a discrete, variable. We investigate these issues through the implementation of a masked priming lexical decision paradigm using only L1 (English) target words, and where the primes are either a repetition of the target word; a semantically associated L1 word; the L2 (French) translation equivalent of the target; or an unrelated L1 item (the control).

The translation condition is of primary interest, as its presence offers insight into how the bilingual lexicon is organized at the semantic level of representation. It should be noted, however, that some researchers (e.g., Perea et al., 2008) have argued that cross-language SEMANTIC/ASSOCIATIVE priming effects are stronger evidence for a shared semantic/conceptual system than translation priming effects, as it is possible that priming effects between translation equivalents are due to lexical level associations (based on co-occurrences between the two translations). By including the within-language semantic priming condition in the current study, however, we can determine whether or not any significant translation priming effects are of similar magnitude to within-language semantic priming effects, as would be expected if they make use of the same neural pathways in semantic memory. Such a result would be suggestive of

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cross-language links at the semantic level and not simply at the lexical level.

Including within-language repetition as well as association conditions also allows us to confirm that participants show the basic and robustly attested repetition and association priming effects expected for such an experimental task, irrespective of AoA.

The native speakers of English who participated in this study all had at least some knowledge of French, primarily because basic ("core") French classes are a mandatory but minimal part of the curriculum at the primary and secondary levels of education in Canada (where all but one participants were educated). A significant number of participants were also enrolled in French Immersion programs. In these programs, the language of instruction of at least 50% of the curriculum, including subjects such as Science and Geography, is French.

Given that many studies suggest an AoA "cut-off" point at approximately seven years old (see discussion above in the "AoA effects" section), we analyze our results initially by using AoA as a discrete variable and by classifying our participants into four groups: A group of Simultaneous Bilinguals, a group of Early Bilinguals who were initially immersed in the French language between the ages of three and five years, a group of Late Bilinguals who were initially immersed in French between the ages of nine and 19 years, and finally a group of participants who have not been immersed in the French language at all (L2 Learners). Note that we are necessarily defining AoA as the age at which the individual began receiving SIGNIFICANT exposure to their L2, or the age at which they were IMMERSED in their L2, either in an instructional setting (i.e. a "French Immersion Program") or in a naturalistic environment. While this definition may differ slightly from those cited above (Flege et al., 1999; Hernandéz & Li, 2007), we believe that ours is more realistic given the type of bilingualism present in Canada, where the study took place.

The impact of our decision to define four groups of participants allows us to further investigate any differences between Late Bilinguals who have received extensive exposure to French and the L2 Learners who are defined as those participants who were never significantly exposed to their L2. Further, in order to test the hypothesis that the bilingual mental lexicon may have a different organization for simultaneous and sequential bilinguals, we will also compare the group of Simultaneous Bilinguals to the group of Early Bilinguals. Additionally, we are able to separate AoA and proficiency by comparing the Early and Late Bilingual groups; because the members of these groups do not differ in their self-reported L2 proficiency, any differences found can be attributed to AoA effects.

This work will be able to complement and build on two recent studies that have examined L2–L1 priming effects with groups of participants whose L2 proficiency and AoAs were carefully controlled. The first study, conducted by Perea et al. (2008), found significant L2–L1 translation priming effects for simultaneous bilinguals and for highly proficient L2 learners who had an AoA of six years old. The results of the present study will confirm these findings and to further them by adding a group of participants who acquired their L2 at a later stage of development, crucially, after the potential maturational cut-off age of seven years old. Secondly, a study conducted by Dimitropoulou et al. (2011a) investigated the L2/L1 priming asymmetry in a group of sequential L2 learners (average AoA = 7.1–7.7 years old) whose levels of L2 proficiency varied (high, medium, low). By manipulating L2 proficiency while controlling for AoA, they were able to eliminate the confound between these two variables that is pervasive in most other studies of the bilingual lexicon. They found significant translation priming in the L2–L1 direction at all proficiency levels and, importantly, that the magnitudes of the effects were similar across all groups. They concluded that L2 proficiency does not modulate masked translation priming effects for sequential bilinguals and suggested that examining AoA effects might offer more insight. The present study furthers this line of research by testing two groups of sequential bilinguals who are matched for L2 proficiency level but who differ in terms of AoA.

Finally, we will also investigate the continuous nature of AoA by performing correlational analyses and linear regression for the translation priming effect only. These analyses are likely to provide a more informative view of AoA as a variable in L2 research, as they may provide evidence that, unlike L2 morphosyntactic processing, the organization of the bilingual mental lexico is NOT sensitive to a particular time period, as suggested by Wartenburger, Heekeren, Abutalebi, Cappa, Villringer and Perani (2003) and Weber-Fox and Neville (1996). This type of analysis has not yet been done in the context of bilingual lexical organization.

The current experiment and its analyses will examine if the ways in which bilinguals represent lexical items of both languages at the semantic level is dependent on a sensitive period of language acquisition. Further, the AoA correlation analysis that is performed on the translation priming condition should allow us to further determine whether AoA is better considered as a grouping variable (with a definite cut-off point for shared semantic representations) or whether investigating AoA as a continuous variable will be able to provide the field of second language research with more insight.

Method

Participants

One hundred and forty-five native speakers of English with varying levels of French proficiency were recruited

Table 1. *Participant information.*

AoA group	N	Age of immersion in French environment	Age of initial French exposure	Mean self-rated French proficiency (with Std. Dev.) Oral (/5)	Written (/5)
Simultaneous Bilinguals	24	From birth	From birth	5.0 (0.2)	.9 (0.4)
Early Bilinguals	27	3–5 years	3–5 years	3.3 (0.7)	3.2 (0.9)
Late Bilinguals	18	9–19 years	3–10 years	2.9 (0.7)	3.1 (0.7)
L2 Learners	33	N/A	2–29 years	2.0 (0.8)	2.1 (0.8)

to participate in a series of on-going bilingual language processing analyses using one masked priming paradigm. Of these, 119 (95 female; mean age: 22.9 years, standard deviation: 4.5) were eligible for inclusion in the analysis for this particular study. Participants were excluded due to having unbalanced exposure to both English and French during infancy (12), having significant exposure to a language other than French or English during infancy (7), and technical malfunctions (7).

Before performing the experiment, all participants were required to complete a language background questionnaire to report information regarding their proficiency as well as current and past language use to ensure their eligibility in this study. After having tested 43 participants, all new participants were also asked to complete a French cloze task (Tremblay, 2011) in order to further assess their L2 proficiency, the results of which are significantly correlated with those participants' self-reported proficiency scores ($r = .830$, $p < .001$). The cloze task scores are not reported in the current study, as they are not available for all participants. Participants were either offered a small financial compensation for their participation or were awarded a percentage towards their course grade if recruited through the Psychology participant pool.

Detailed language history

All participants were highly proficient native speakers of English who had at least some knowledge of French. Twenty-six participants had also acquired French simultaneously with English, reporting current native or near-native competence in both languages.

Based on their language history, the participants were classified into the four participant groups discussed above: Simultaneous Bilinguals, Early Bilinguals, Late Bilinguals, and L2 Learners. A summary of each group's linguistic characteristics (after all exclusions had been made, as detailed below) is presented in Table 1. All but eight participants provided self-rated oral and written proficiency scores (scored out of 5). Note that only the *Simultaneous Bilinguals* rated their French proficiency level as "native", whereas the self-reported French proficiency ratings of all other participants ranged from very low to near-native (Mean = 5.44/10, SD = 1.74). In a one-way ANOVA looking at the effect of group on self-reported proficiency, a significant main effect of group was found ($F(3,107) = 92.69$, $MSE = 153.80$, $p < .001$). Using pairwise comparisons it was found that the Simultaneous Bilinguals were more proficient than all other groups (all *p*s $< .001$), that the L2 learner group is the least proficient (all *p*s $< .001$), but crucially, that no significant difference exists between the early and late bilinguals (using their combined scores out of 10; mean difference = 0.50, $p = 1.000$).

Materials

The stimuli created for this experiment were high-frequency English–French translation pairs. Critical target words consisted of 62 high-frequency English nouns with an average $\log_{10}$ frequency of 3.59 and ranging from 0.49 to 6.63 (Collins COBUILD English Language Database, 1995). The translation equivalents in French of these target words were non-cognates with an average raw frequency of 104.01 and ranging from 1.71 to 696.42 (Lexique 2; New, Pallier, Ferrand & Matros, 2001). An additional 11 English nouns and 65 pseudowords were used as fillers. Pseudowords were created by changing one or two letters of existing English words such that no meaning would be associated with that form, but such that English phonotactics were still respected.

Four primes were created for each real-word target, resulting in four experimental conditions: a repetition prime, a semantically related association prime, a translation prime, and an unrelated (control) prime. For example, for the target word *APPLE*, the repetition prime was *apple*, the association prime was *pie*, the translation prime was *pomme* (the French translation equivalent of "apple"), and the unrelated prime was *web*. A complete list of the experimental stimuli with varying primes can be found in the appendix. Real-word primes were also chosen and presented before pseudowords in order to maintain

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consistency in the task. All primes for pseudowords were in English.

Participants were randomly assigned to one of four test lists such that approximately the same number of participants saw each list and no participant saw more than one list. Each list presented all 62 critical targets only once, in each of the four experimental conditions. Due to an unbalanced distribution of targets into the four conditions, in each list two experimental conditions had 16 items and the other two conditions had 15 items. This slight inequality was counterbalanced across the four lists. Each target was presented in a different experimental condition in each list. The same 62 pseudowords were presented in each of the four lists. A single practice list was created using three pseudowords along with seven of the real-word fillers. All pseudo- and real-word targets of the practice list followed primes, and of the primes for the real-word targets, three were repetition, two were association, and two were unrelated.

The 124 targets in each of the four test lists were presented semi-randomly[1] in four blocks. One of the four remaining real-word fillers were presented at the beginning of each block as opening items, two with an unrelated prime and two with an association prime.

Procedure

Of the 119 eligible participants, 31 performed the experiment while event-related brain potentials (ERPs) as well as behavioural responses were being measured. The 88 participants who only performed the behavioural version were seated in front of a computer monitor in a sound attenuated room and given headphones to further attenuate any noise in the laboratory environment. The 31 ERP participants performed the experiment in a sound proof room and thus did not require headphones. Instructions were given both verbally by the experimenter and visually on the computer screen in front of the seated participant. Each participant completed one practice trial with feedback from the experimenter before beginning the experiment. All participants were instructed to focus on the target word appearing in upper case characters.

The design of this experimental task used a forward-masking paradigm with the prime presented between the forward mask and the target item (this is following Forster & Davis, 1984; and Wang & Forster, 2010). Stimuli presentation and the recording of responses and response times were controlled using the *Presentation* stimulus delivery and experimental control program (Neurobehavioral Systems). Stimuli were presented visually on the computer screen one at a time, and participants were asked to decide, as quickly and as accurately as possible, whether each string of letters was a real word of English or not. “Real word of English” was defined as being a word that would be found in an English dictionary with the given spelling. Participants either responded using a button box (the 31 ERP participants) or by using the “Z” and “/” keys on a keyboard. No mention was made of the primes. For each item, a forward mask consisting of ten hash marks (##########) was first presented in the centre of the screen for 500 ms, followed by the prime in lower case letters for 50 ms, and finally the target in upper case letters for 500 ms. The inter-trial interval consisted of 1720 ms duration for each button press response following presentation of target item, plus 100 ms delay preceding the start of each trial. Total duration of each trial was 3000 ms. Participants were given self-regulated breaks between each block and encouraged to rest their eyes and fingers during that time, but were prohibited from interaction of any kind.

Results

Of the 119 participants, seven participants (three L2 Learners, two Early Bilinguals, one Late Bilingual and one Simultaneous Bilingual) were excluded due to a high error rate of greater than 20%, and one participant (a Late Bilingual) was excluded because more than 20% of responses were greater than 1200 ms. None of the critical items exceeded the 20% error rate threshold, therefore no items were excluded. From the data of the remaining 111 participants, all incorrect and missed responses were removed (2.6% of the data), as well as correct responses whose response times were greater than 1200 ms or less than 300 ms (0.70% of the data). Finally, responses that were greater than 3 standard deviations above or below the mean for each participant were also removed (1.4% of the data). Mean response times (RTs) were then calculated for each participant and for each item. Box plots conducted on average participant RTs revealed three participants as being outliers. Data from these participants were also excluded from the analyses (one Early Bilingual, one Late Bilingual and one Simultaneous Bilingual), leaving 108 participants. None of the participants whose RT data was collected during ERP measurements were identified as being outliers. Boxplots conducted on average item RTs revealed no outlying items.

In the following analyses, Data Analysis 1 represents the group analyses using the four AoA groups, as described above. In order to ensure that the Early Bilingual and Late Bilingual groups were sufficiently distinct to detect behavioural differences, participants whose AoA fell within one year of the hypothesized cut-off age of 7 years old were excluded from this analysis (6 participants). While reducing the group sizes in this way also reduced statistical power, we considered this to be justified given that current research supports the idea of a

[1] Across all lists, each block contained between 38% and 59% pseudowords (mean = 50.0%, SD = 4.9%) and between one and nine critical targets in each condition (mean = 3.9, SD = 1.3).

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sensitive period rather than a critical period, and also given our hypothesis that AoA effects are more gradational in nature. Data Analysis 2 addresses this issue by examining the correlation between AoA and the translation priming effect.

Data analysis 1[2]

The trimmed RT data collected for each participant were analyzed together with a linear mixed-effects model that included both *Participant* and *Item* as separate random effects (essentially combining F_1 and F_2), and *Participant* with *Condition* included as a crossed random effect (following the model of Baayen, Davidson & Bates, 2008). Accuracy data (untrimmed) were also analyzed with a generalized linear mixed-effects model that included both *Participant* and *Item* as separate random effects, but the crossed random effect was removed because that model failed to converge (indicating that the variance for the crossed effect was probably zero). The Satterthwaite adjustment was used on the results from the mixed-effects model as well as the planned comparisons. For the planned comparisons, the differences of least square means were computed from the mixed-effects model for the interaction term. Independent variables were *Condition* (Repetition, Association, Translation, and Unrelated) and *AoA Group* (L2 Learners, Late Bilinguals, Early Bilinguals, and Simultaneous Bilinguals), with *Condition* as a repeated measure.

Analyses of the RT data revealed a significant main effect of Condition ($F(3,289) = 78.40$, $MSE = 6566.11$, $p < .001$). Planned pair-wise comparisons showed that this reflected an overall significant repetition priming effect (mean difference = 44.8 ms; $p < .001$), a significant association priming effect (mean difference = 19.7 ms; $p < .001$) and a significant translation priming effect (mean difference = 9.5 ms; $p = .002$), when all participants were grouped together. A trend towards a significant main effect of AoA Group was seen ($F(3,98.1) = 2.33$, $MSE = 6566.11$, $p_1 = .079$). Post-hoc comparisons show that this was because the Simultaneous Bilinguals had slower overall response times than all other AoA groups (all *p*s < .051), with no other groups differing significantly (all *p*s > .977). This result is consistent with the idea that simultaneous bilinguals have a larger lexicon from which to activate lexical items, due to having a shared store for items from both languages.

[2] The RT data was initially analysed with “Experimental Version” (behavioural vs. ERP) as a factor. While Version did show a significant main effect ($p < .001$), it did not interact with AoA Group ($p = .751$) or with Condition ($p = .510$). As such, we feel that, while collapsing data from the two versions in the statistics has added noise, this is countered by the fact that the additional participants sufficiently increased power.

Most important to the goals of the current study, there was a strong trend towards a significant interaction between Condition and AoA Group ($F(9,290) = 1.85$, $MSE = 6566.11$, $p = .059$). Tests of Within-Subjects contrasts revealed that the significant interaction reflected significant translation priming effects for both the Simultaneous Bilinguals (mean difference = 24.4 ms; $t(295) = –4.13$, $p < .001$) and the Early Bilinguals (mean difference = 14.2 ms; $t(298) = –2.05$, $p = .042$) in contrast to no significant translation priming effect for the Late Bilinguals (mean difference = 0.8 ms; $t(287) = –0.35$, $p = .728$) and the L2 Learners (mean difference = –0.4 ms; $t(297) = 1.25$, $p = .799$). Also, repetition priming effects were significant for all four groups (all *p*s < .001), as were Association priming effects (all *p*s < .047). This indicates that the priming paradigm used here effectively produced the well-attested effects of repetition and association priming for all AoA groups. Consequently, any lack of translation priming effects in a given group is not likely attributable to methodological issues. Further, for both the Early Bilinguals and the Simultaneous Bilinguals, the Association and Translation conditions were of a similar magnitude and the difference between them was not significant (mean difference = 3.1 ms; $p = .450$, and mean difference = 2.1 ms; $p = .876$, respectively). As discussed earlier, this suggests that the translation priming effects found here are similar in nature to within-language association priming. In contrast, the Association and Translation conditions were significantly different for the L2 Learners (mean difference = 19.8 ms; $p < .001$) and marginally different for the Late Learners (mean difference = 14.2 ms; $p = .098$). These results are presented in Figure 1.

The Type III tests from the generalized linear mixed model of the probability of accuracy revealed no significant main effect of Condition ($F(3,6305) = 2.01$, $p = .110$), no significant main effect of AoA Group ($F(3,124.8) = 0.69$, $p = .559$), and no significant interaction between Condition and AoA Group ($F(9,6305) = 1.38$, $p = .191$). As such, no pairwise comparisons were conducted.

Data analysis 2

Figure 2 shows the relationship between the translation priming effect, as measured by RT, and AoA, as determined by the age at which the participants were immersed in an L2 environment. Note that the L2 Learners were not included in this analysis, as they were, by definition, never immersed in an L2 environment. The six participants with AoA of between six and eight years that were excluded from Analysis 1, however, were included in Analysis 2. Statistical analysis determined that these two variables are significantly correlated ($r = –.286$, $p = .006$), suggesting that the earlier the L2 is learned, the greater the translation priming effect. The regression model was also

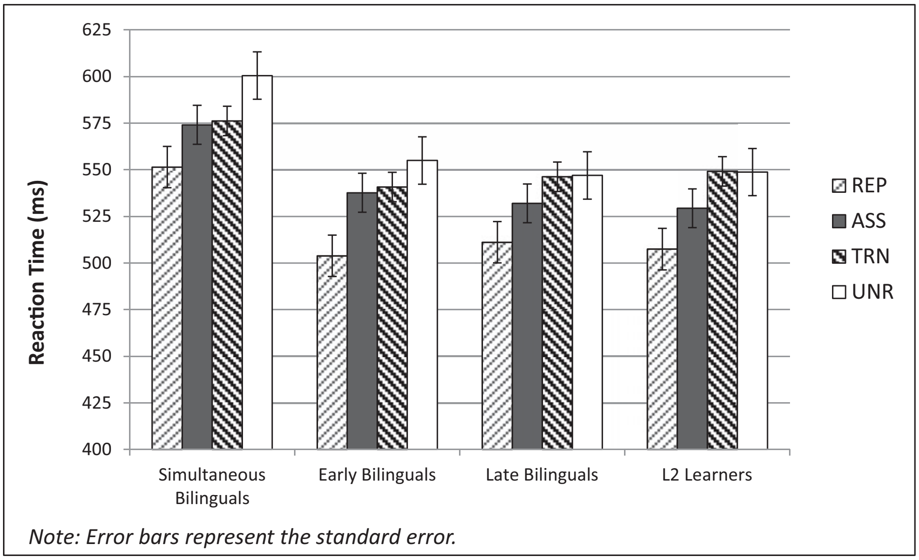

Figure 1. RT results for Data Analysis 1.

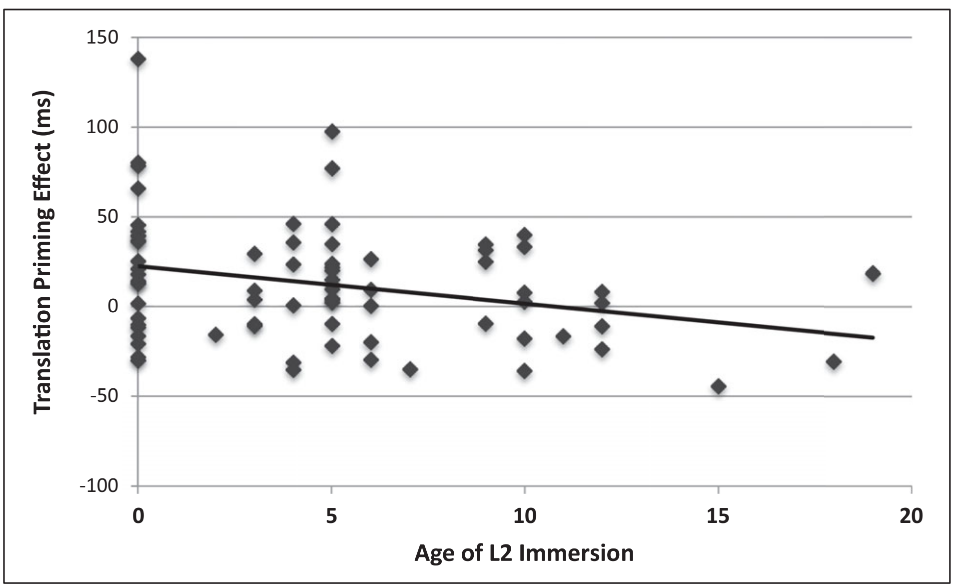

Figure 2. Data Analysis 2: Effect of AoA on translation priming.

determined to be significant, accounting for an estimated 8.2% of the variation ($r^2 = .082$, $p = .013$).

Discussion

To summarize, the main finding of the study presented here is straightforward: that an early L2 AoA is required in order to see L2-to-L1 cross-language translation priming in the English–French participants tested here. This finding emphasizes that AoA is an important factor in the ultimate organization of the bilingual mental lexicon. In Analysis 1, only the Simultaneous and Early Bilinguals showed evidence of masked translation priming, suggesting that being significantly exposed to the L2 at an early age is important for bilingual lexical organization. Crucially, Analysis 2, showed a significant correlation between AoA and the translation priming effect suggesting that the strength of cross-language lexical links is attenuated by later AoA. These results support those of Perea et al. (2008), who also found significant L2–L1 translation priming effects for simultaneous bilinguals and early L2 learners. What is particularly interesting in the present study is that, while the Early and Late Bilinguals had similar self-rated proficiency, only the Early Bilinguals showed masked translation priming effects, suggesting that AoA, rather

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than proficiency, may be an explanatory variable in L2-to-L1 priming effects. This conclusion is consistent with the results reported by Dimitropoulou et al. (2011a), who found that for sequential bilinguals, increased L2 proficiency does not lead to increased L2-to-L1 translation priming.

Our suggestion that AoA plays a more important role than proficiency (as seen in the significant L2–L1 translation priming differences between Early and Late Bilinguals who have equivalent proficiency) in the organization of the bilingual mental lexicon is not fully accounted for by current models. Basically, there are three findings in the literature related to this issue that still remain to be accounted for: (i) why, in lexical decision tasks, is L1-to-L2 translation priming robustly attested across AoAs and proficiency levels, while L2-to-L1 translation priming seems to be sensitive to AoA (more so than L2 proficiency); (ii) why this asymmetry has not been found in semantic categorization tasks; and (iii) why the opposite asymmetry is found in episodic recognition tasks.

To address (i), the RHM (Kroll & Stewart, 1994; Kroll, Van Hell, Tokowicz & Green, 2010) would claim that the links from L2 lexical items to concepts are initially weaker than those from L1 items to concepts, leading to strong L1-to-L2 priming and weak or no L2-to-L1 priming. Then, as L2 proficiency increases, links from L2 lexical items to concepts become stronger, leading to L2-to-L1 priming effects. This account, however, would predict that two groups of bilinguals, matched for proficiency, would perform equally on the L2–L1 translation priming condition. This was not the case in our study. The BIA^+ model (Dijkstra & Van Heuven, 2002), on the other hand, would claim that, as L2 lexical items have lower resting activation levels (assuming that the L2 is the less used language), they would need greater excitatory energy to become activated. The activation of semantic representations of L2 words is therefore predicted to be delayed or less strong compared to the representations of the more frequently-used L1 words. As such, the different experimental results for bilinguals of differing proficiency levels and with differing lengths of exposure to the L2 are essentially attributed to frequency effects. This account would only explain the results of the current study if what we identified as "age of acquisition effects" are actually "length of exposure effects". In other words, the earlier the age of acquisition, the longer the exposure to L2 words, the higher the frequency of these L2 words, and thus the higher level of resting activation they have. Future research would have to tease these two confounded variables apart. Silverberg and Samuel's (2004) model, because it postulates that late bilinguals would have separate semantic/conceptual stores, can account for the lack of L2-to-L1 priming effects in the Late Bilinguals tested here, but cannot account for the presence of L1-to-L2 translation priming effects robustly found in other studies with late L2 learners (e.g., Altarriba & Basnight-Brown, 2007; Dimitropoulou, Duñabeitia & Carreriras, 2011b; Duñabeitia et al., 2010; Gollan et al., 1994; Kim & Davis, 2003).

To address (i) and (ii), the Sense Model (Finkbeiner et al., 2004) proposes that L2 lexical items have fewer senses associated with them than their L1 counterparts, such that L2 items activate proportionally fewer senses associated with their L1 translation equivalent than vice versa, resulting in smaller (or no) L2-to-L1 priming effects. Further, while this L2:L1 sense asymmetry is relevant to the lexical decision task, it is not found in a semantic categorization task, as the latter restricts the set of senses for a given lexical item to only that which is relevant to the category in question, thus eliminating the "sense asymmetry" that leads to the translation priming asymmetry. As the L2 learner becomes more proficient, they acquire more senses for L2 lexical items, thus reducing the L2:L1 sense asymmetry and increasing the size of the L2-to-L1 translation priming effects in lexical decision tasks. As such, this model also has difficulty accounting for the fact that the Early Bilinguals in the current study displayed significant L2-to-L1 translation priming effects while the Late Bilinguals, who were matched for L2 proficiency, did not.

Finally, to address (i) and (iii), the Episodic L2 Hypothesis (Jiang & Forster, 2001) proposes that late bilinguals represent their L2 lexicon separately in episodic memory, and while this does account for why AoA plays such an important role in masked translation priming, it does not account for how L1-to-L2 priming occur so robustly in lexical decision tasks for late bilinguals.

Essentially, most current models of the bilingual mental lexicon have difficulty accounting for the evidence found in the current study that AoA plays a crucial role in bilingual lexical organization. Evidence in the literature of robust L1-to-L2 priming across all AoA (and L2 proficiency) groups strongly suggests that L1 and L2 lexical items do in fact access the same semantic/conceptual network. However, our evidence of L2-to-L1 priming effects attenuating with increasing AoA suggests that the way in which L2 words interact with this network changes depending on how early in the language acquisition process the L2 is learned. The following suggestions may account for these observations.

When learning a native language (or two), concepts are acquired simultaneously with their labels. The longer you spend learning the L1 before an L2 is introduced, the more the semantic/conceptual system is organized based on L1 word meanings. Conversely, the later you learn an L2, the more L2 words are parasitic to this L1-based semantic network. It is now well known that neuroplasticity also decreases with age, therefore the brain's ability to reorganize the lexicon to incorporate L2 lexical items and their meanings could also decrease with age. If the asymmetry in translation priming effects found in lexical decision tasks is, as the Sense Model claims, due to an L1:L2 sense asymmetry, then it is possible that, as L2 AoA increases, it is more difficult to incorporate new L2 senses of translation equivalents into the L1-based semantic network. This could account for the modulation of L2-to-L1 translation priming effects by AoA. If this is the case, then it could be hypothesized that high frequency L2 lexical items, such as the ones used in the present study, would be the first to become well integrated into the semantic network. It would therefore be interesting to determine whether early sequential bilinguals would display attenuated L2-to-L1 priming effects for lower frequency items, which would conceivably be less well integrated into the semantic network. These lower frequency items, on the other hand, may have stronger representations in episodic memory, and so may show more robust L2-to-L1 translation priming in an Episodic Recognition Task, as the high frequency items did for the late bilinguals tested by Jiang and Forster (2001).

Conclusions

The presence of AoA effects on the organization of the bilingual mental lexicon has clear implications both for the current models in the field as well as for future research directions. We can therefore conclude that AoA is indeed a very important factor to consider in studies examining the lexical organization of bilinguals, and crucially, one that must be taken into account in models of the bilingual lexicon.

Finally, as the regression analysis shows, AoA accounts for only 8.2% of the variation in translation priming effects. This is likely because AoA is not the only factor of importance here. Other factors that remain to be investigated include length of L2 exposure/immersion, manner of acquisition and language aptitude, among others. A more in-depth look at L2 proficiency is also warranted, particularly within the "early" bilingual group. Future studies using multiple regression analyses will allow us to not only determine which of these factors are the most important, but also which are significant predictors of the degree to which a bilingual's two lexicons are integrated, and at which level: lexical or semantic. As many of these factors are often confounded (for example, early learners have generally had more years of experience with their L2, tend to learn their L2 in more naturalistic settings, and often become more proficient), such studies will hopefully be able to tease these factors apart. While the current study only required self-reported proficiency ratings to be collected from participants, using more objective measures of L2 proficiency (such as Tremblay's (2011) cloze test) will enable researchers to include this variable in their analyses. Indeed, exploratory work using this proficiency measure has been conducted in our lab, and preliminary results indicate that L2 proficiency is also a significant predictor of translation priming effects (Burkholder, Brien & Sabourin, 2011).

Appendix. Stimuli

Repetition prime	Association prime	Translation prime	Translation prime frequency (Lexique 2)	Unrelated prime	TARGET	Target log frequency (Collins COBUILD Database)
apple	pie	pomme	26.45	web	APPLE	3.11
barn	farm	grange	20.97	nurse	BARN	2.16
beach	sand	plage	42.23	chain	BEACH	3.96
belt	buckle	ceinture	20.87	refund	BELT	2.94
book	read	livre	144.29	race	BOOK	5.52
bridge	road	pont	61.16	event	BRIDGE	3.54
butterfly	cocoon	papillon	13.03	robot	BUTTERFLY	1.78
carpet	rug	tapis	39.94	beast	CARPET	2.74
cheese	dairy	fromage	12.52	fever	CHEESE	3.26
chicken	soup	poulet	14.53	signal	CHICKEN	3.32
child	kid	enfant	298.06	vote	CHILD	5.46
city	downtown	ville	227.16	belief	CITY	5.69
clock	time	horloge	12.19	room	CLOCK	3.84
cloud	heaven	nuage	19.29	rating	CLOUD	2.82
coat	jacket	manteau	36.29	juice	COAT	3.02
computer	keyboard	ordinateur	2.97	height	COMPUTER	4.81

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Appendix. *Continued*

cow	milk	vache	18.45	plate	COW	2.66
curtain	window	rideau	30.23	valley	CURTAIN	2.58
day	night	jour	568.13	dollar	DAY	6.63
dog	canine	chien	69.68	twist	DOG	4.18
door	knob	porte	426.48	trail	DOOR	5.07
eye	glasses	oeil	179.90	squad	EYE	4.57
finger	ring	doigt	46.87	north	FINGER	3.29
fire	hot	feu	156.29	round	FIRE	4.92
flag	country	drapeau	15.16	arrival	FLAG	3.10
frame	picture	cadre	73.48	wing	FRAME	3.30
girl	boy	fille	244.19	voice	GIRL	4.90
heart	love	coeur	274.94	trade	HEART	5.16
ice	skating	glace	49.58	lemon	ICE	4.07
jewel	diamond	bijou	6.77	breeze	JEWEL	1.82
king	crown	roi	106.61	knee	KING	3.62
kitten	cat	chaton	1.71	handle	KITTEN	0.95
man	father	homme	696.42	number	MAN	6.47
meal	eat	repas	46.84	tape	MEAL	3.43
meat	beef	viande	33.84	wealth	MEAT	3.81
mouth	teeth	bouche	150.68	desk	MOUTH	4.01
noise	loud	bruit	139.52	cable	NOISE	3.61
nose	smell	nez	95.94	gear	NOSE	3.57
pepper	salt	poivre	6.65	tower	PEPPER	2.75
pig	horse	cochon	9.06	breath	PIG	2.60
queen	royalty	reine	37.90	steam	QUEEN	3.88
rain	wet	pluie	69.74	index	RAIN	3.95
sailor	ship	marin	22.03	cult	SAILOR	1.72
scarf	hat	foulard	8.23	nerve	SCARF	1.43
shoe	lace	soulier	2.87	beam	SHOE	2.48
shovel	bucket	pelle	6.55	denim	SHOVEL	0.49
sidewalk	street	trottoir	37.03	fabric	SIDEWALK	1.09
sky	blue	ciel	212.65	profit	SKY	3.87
snow	cold	neige	48.23	target	SNOW	3.52
soap	clean	savon	9.94	dealer	SOAP	2.92
song	lyric	chanson	23.52	straw	SONG	4.12
sun	bright	soleil	227.13	answer	SUN	4.83
ticket	speeding	billet	19.74	temple	TICKET	3.63
toy	play	jouet	183.71	middle	TOY	2.02
tree	leaf	arbre	64.61	joy	TREE	4.03
truck	van	camion	18.19	shirt	TRUCK	3.21
tuna	fish	thon	2.39	crop	TUNA	1.35
umbrella	rain	parapluie	6.65	paint	UMBRELLA	2.07
wall	brick	mur	100.87	theme	WALL	4.59
war	death	guerre	320.87	course	WAR	6.02
water	drink	eau	339.10	stock	WATER	5.70
wine	beer	vin	64.97	wind	WINE	4.36
winter	summer	hiver	70.39	income	WINTER	4.32
woman	mother	femme	400.52	team	WOMAN	5.66

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