LEXICAL LEARNING IN BILINGUAL ADULTS:

THE RELATIVE IMPORTANCE OF SHORT-TERM MEMORY FOR SERIAL ORDER AND PHONOLOGICAL KNOWLEDGE

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ABSTRACT

Studies of monolingual speakers have shown a strong association between lexical learning and short-term memory (STM) capacity, especially STM for serial order information. At the same time, studies of bilingual speakers suggest that phonological knowledge is the main factor that drives lexical learning. This study tested these two hypotheses simultaneously in participants with variable levels of English-French bilingual proficiency. A word-nonword paired associate learning task was administered, with nonwords obeying French phonotactic patterns. French phonological knowledge was estimated by a composite French proficiency score summarizing productive and receptive French vocabulary knowledge as well as quantitative and qualitative measures of French exposure. STM measures maximized retention of order information (serial order reconstruction) or retention of phonological item information (single nonword delayed repetition). The French proficiency score and the serial order STM measure independently predicted performance on the paired associate learning task. These results highlight the conjoined role of phonological knowledge and serial order STM in lexical learning. Importantly, serial order STM remains a strong predictor of lexical learning, even for bilingual individuals who have broad phonological knowledge.

176 words

INTRODUCTION

During the past 20 years, a large body of literature has accumulated showing consistent associations between verbal short-term memory (STM) and word learning abilities. This association has been documented in many different populations such as typically developing children, healthy adults and brain injured patients (e.g., Baddeley, Gathercole & Papagno, 1998; Gathercole, Willis, Baddeley, & Emslie, 1994; Gupta, 2003; Majerus, Poncelet, Greffe & Van der Linden, 2006; Majerus, Poncelet, Elsen & Van der Linden, 2006; Papagno, Valentine, & Baddeley, 1991; Speciale, Ellis, & Bywater, 2004). However, despite extensive research, the precise significance of this relation remains a matter of debate, and evolves concurrently with successive theoretical developments of the STM literature.

A number of studies, mostly inspired by the phonological loop model by Baddeley and Hitch (1974), suggest that phonological STM capacity is a critical component for new word learning and is causally involved in forming new long-term phonological representations. Evidence for this position comes from two sources. A series of longitudinal studies in children have shown that STM capacity at an early age predicts later native or foreign vocabulary knowledge (Gathercole, Willis, Emslie, & Baddeley, 1992; Service, 1992). A second major source of evidence stems from the neuropsychological literature and shows that patients with selective STM deficits have difficulties in learning new word forms but not in learning associations between familiar words (e.g., Baddeley, Papagno, & Vallar, 1988; Hanten & Martin, 2001). Further studies also show that variables supposed to interfere with the functioning of the phonological loop, such as articulatory suppression blocking the articulatory rehearsal process, interfere with learning new word forms (Ellis & Sinclair, 1996; Papagno et al., 1991).

Although this causal, unidirectional link between STM and new word learning capacity became an increasingly accepted interpretation, especially in the light of the growing neuropsychological literature providing many replications of an association between new word learning and STM impairments, an alternative theoretical interpretation has emerged, based on studies highlighting the role phonological long-term knowledge plays during STM performance (see also Snowling, Chiat & Hulme, 1991, for an early expression of concern about these issues). A number of studies show that long-term phonological knowledge influences STM performance, as reflected by better recall for words of high versus low lexical frequency or for nonwords containing high versus low probability phonotactic patterns (e.g., Gathercole, Frankish, Pickering & Peaker, 1999; Majerus, Van der Linden, Mulder, Meulemans, & Peters, 2004; Thorn & Gathercole, 1999; Thorn & Frankish, 2005; see also Goh & Pisoni, 2003, and Roodenrys & Hinton, 2002, for related findings). Furthermore, although phonological STM capacity at Age 4 predicts vocabulary knowledge at Age 5, this relationship later reverses, with vocabulary knowledge at Age 5 predicting phonological STM capacity at Age 6 (Gathercole et al., 1992). These observations support STM models that assume close interactions between phonological STM and long-term phonological representations, either via reconstruction processes of the decaying STM trace at the moment of recall using long-term phonological knowledge, or via direct activation of phonological long-term representations during encoding (e.g., Baddeley et al., 1998; R. Martin et al., 1999; N. Martin & Saffran, 1992; Schweickert, 1986). In sum, these data and models suggest that verbal STM performance is strongly determined by access to and support from phonological long-term memory. It follows that the observed correlations between STM and new word learning capacity might reflect a common reliance on the temporary activation of long-term phonological representations rather than a simple ‘STM-to-word learning’ causal relationship.

There is growing support for this ‘phonological knowledge’ hypothesis as an explanation of STM-word learning associations. In a recent study, Masoura and Gathercole (2005) showed that in native Greek speaking children with considerable English language knowledge, speed of learning new English words was influenced by existing English vocabulary knowledge but not by phonological STM as measured by nonword repetition. This study suggests that, at least in bilingual children who have acquired broad and rich networks of phonological representations, phonological knowledge seems to drive further lexical learning and not STM capacity. Similarly, Cheung (1996) observed that STM capacity predicted second-language vocabulary learning in a group with low knowledge of that language, but not in a group with high knowledge. Furthermore, bilingual phonological knowledge affects STM performance: Thorn and Gathercole (1999, 2001) observed that English-French bilingual children performed equally at a nonword repetition task for nonwords obeying either English or French phonotactics while monolingual English or French speaking children showed poorer performance for nonwords conforming to the phonotactics of the language they had not learned.

More recently, Storkel (2001) showed that sublexical phonological knowledge drives lexical learning also in monolingual children; they observed that new words containing phonological sequences that are frequent relative to the phonology of their language are learned faster than new words containing less frequent sound structures. An effect of sublexical phonological knowledge on new word learning has also been shown in monolingual adults (Storkel, Armbruster, & Hogan, 2006). Similarly, new words having a large number of lexical phonological neighbours (familiar words that differ from the target word by a single phoneme addition, substitution or deletion) appear to be learned faster than new words with a low density lexical neighbourhood (Storkel et al., 2006). These findings support earlier theoretical proposals by Fowler (1991) and Metsala (1999), suggesting that growing vocabulary knowledge leads to the construction of phonological representations that are increasingly segmented and precise. These fine-grained phonological representations will boost further lexical learning, and support processing of novel verbal material such as nonwords in STM tasks. In sum, the different studies reported here suggest that both sublexical and lexical phonological knowledge are important determinants of lexical learning, while determining at the same time performance in STM tasks. However, except for the study by Masoura and Gathercole (2005), these studies do not preclude the possibility that STM capacity is also a determinant of lexical learning, in addition to phonological knowledge.

Given the different theoretical accounts of lexical learning exposed here, the present study aims at testing an integrative account of lexical learning, exploring the impact of both phonological knowledge and STM capacity on lexical learning. No study has specifically examined the simultaneous impact of both types of predictors on new word learning, while ensuring at the same time that the STM predictor is not itself contaminated by phonological knowledge. However, before further explaining the rationale of our study, we need to consider a fundamental question: Is it possible to measure STM capacity independently of phonological knowledge? In order to answer this question, we will shortly turn to the distinction between item and order information, assumed in most of recent STM models, and show how this distinction allows separating basic STM capacity from the influence of phonological knowledge.

Current models of STM distinguish processes involved in storing item information (the phonological and lexico-semantic content of the stimuli to be retained) and processes involved in storing order information (the serial order of presentation of the stimuli) (e.g., Brown, Preece & Hulme, 2000; Burgess & Hitch, 1999; Gupta, 2003; Henson, 1998; Page & Norris, 1998). Although these models differ in the precise instantiation of how order information is represented (cf. Burgess & Hitch, 2005, as well as Hitch, Fastame, & Flude, 2005, for recent reviews), they assume that order information is stored via some form of specialized STM system while representation of item information depends directly on activation of the language system. Hence, according to these models, storage of serial order information remains specific to a specialized STM system while storage of item information strongly depends on the richness of the phonological knowledge system. Experimental data support this distinction, by showing that linguistic knowledge has an impact on item but not order recall, as suggested by the reduction of item but not order errors for recall of high versus low frequency word lists or semantically related versus unrelated word lists (e.g., Poirier & Saint-Aubin, 1995, 1996; Nairne, 2004). Recent neuropsychological data also demonstrate that serial order and item STM capacities can be selectively impaired, and that the impairment of item STM capacity is directly related to the integrity of underlying representations in the language network (e.g., Majerus, Norris, & Patterson, 2007; Majerus, Van der Linden, Braissand, & Eliez, 2007).

In the light of these data, we can posit the following hypothesis: If there is actually a relationship between STM capacity and new word learning, we should expect a strong relationship between new word learning and STM tasks that maximize the retention of serial order information but minimize the retention of item information (presumably depending on temporary activation of language knowledge). Gupta (2003) proposed that the order STM system is critical for new word learning because it ensures the ordered reactivation and rehearsal of new phonological sequences in the language network, increasing the probability that a new temporary phonological representation in the language system is transformed into a stable long-term memory representation. A specific link between serial order STM and lexical learning has indeed been recently observed. Majerus, Poncelet, Elsen et al. (2006) showed that measures maximizing serial order retention (e.g., serial order reconstruction for lists containing highly familiar items (digits)) are a better predictor of new word learning capacity in monolingual adults than measures maximizing item STM (e.g., item errors in an immediate serial recall task; phonological item recognition). Similarly, a study with children aged 4 to 6 years showed that STM tasks maximizing serial order or item recall (serial order reconstruction of highly familiar word lists *versus* single nonword delayed recall) are independently associated with vocabulary development (Majerus, Poncelet, Greffe et al., 2006). In sum, these studies demonstrate that it is possible to design STM tasks to measure the capacity to retain serial order information, independent from phonological knowledge. However, although these studies show that serial order STM is specifically related to new word learning capacity, they do not exclude the possibility that phonological knowledge is also important, given that they did not specifically investigate the role of phonological knowledge on new word learning.

The present study examined the relative importance of phonological knowledge and STM capacity on new word learning capacity. Previous studies reveal conflicting results with respect to this question, because the experimental designs were optimized to measure only one of the two predictors, or because the STM task was ‘contaminated’ by phonological knowledge. We assessed STM capacity using an adaptation of a serial order reconstruction task (e.g., Majerus, Poncelet, Elsen et al., 2006). The impact of phonological knowledge on new word learning performance was assessed by two different means: (1) the participants were native English speakers with variable levels of proficiency in a second language, French; the participants had to learn new words obeying French phonotactics; if pre-existing phonological knowledge is critical to new word learning, participants with more developed French knowledge and phonological representations should learn French-like new words faster; (2) the participants performed an item STM task consisting of delayed repetition of single short nonwords and reflecting the intervention of English sublexical phonological knowledge, by contrasting nonwords with frequent or infrequent sound structures relative to

English phonology; if there is a specific relationship between phonological knowledge and new word learning, we should expect an effect of language specificity on the relationship between phonological knowledge and learning, i.e., French but not English phonological knowledge should predict learning of French-like nonwords. Given dependency upon English phonological knowledge, we did not expect the item STM task to correlate with learning of new French-like words. Furthermore, contrasting item and order STM tasks allowed us to assess the specificity of order STM, relative to item STM, as a predictor of new word learning performance.

EXPERIMENT

New word learning capacity was assessed using a word-nonword paired associate learning task adapted from Majerus, Poncelet, Elsen et al. (2006). The participants learned four word-nonword pairs, the nonwords consisting of bisyllabic nonwords obeying French phonotactics. The number of learning trials was relatively small (five trials) as we were interested in the initial stages of new word learning whereby STM contributions are most likely to intervene via refreshment and stabilization of the initial representation of the new phonological form, later learning stages being more likely to depend on consolidation processes in episodic and lexical long-term memory. A word-word learning task was also administered as a control condition.

To measure French phonological knowledge, French receptive and productive vocabulary tasks were administered, as well as a detailed anamnestic questionnaire assessing the quality and the amount of past and current experience with French, based on self-assessment. English phonological sensitivity was determined via a delayed single nonword repetition task, measuring at the same time phonological item STM capacity and access to

English phonological knowledge, as described above (adapted from Majerus, Norris et al., 2007). By using nonwords, we aimed at using a very sensitive item STM task, reflecting to a maximal extent the level of detail and segmentation of the structure of the network of sublexical English phonological representations. As we have mentioned before, a number of studies suggest that the more detailed and finely grained the structure of the phonological network, the higher the efficiency of nonword segmentation and temporary representation (e.g., Metsala, 1999). This reliance on sublexical phonological knowledge in the item STM task was also directly controlled by contrasting nonwords with high or low phonotactic frequency patterns relative to English phonology; these nonwords differ according to sublexical frequency (frequency of phoneme co-occurrences) but also lexical frequency measures, nonwords containing more frequent phoneme associations having typically a higher number of lexical neighbours (e.g., Majerus et al., 2004; Thorn & Frankish, 2005).

Finally, to measure STM capacity independently of phonological knowledge, we used a serial order reconstruction task that minimizes item processing and retention requirements (adapted from Majerus, Poncelet, Elsen et al., 2006). The task involves presentation of digit sequences of increasing length, the digits being known in advance: for a sequence length of 6 digits, all the digits were sampled from the pool of digits 1-6, for a sequence length of 7 digits, the digits were sampled form the digit pool 1-7, etc. Furthermore, at the moment of recall, the participants were given cards on which the digits were printed, and they used these cards to arrange them on the desk to recall their order of presentation. The items were therefore highly familiar, known in advance and available at the moment of recall, and minimized item STM requirements.

Relative to the item STM task, the serial order reconstruction task maximized retention requirements for serial order information. These were minimized in the item STM task, given that a single and short nonword had to be recalled. Furthermore, in order to reduce order requirements at the phonemic level of representation for this task all items had the same short monosyllabic CVC (consonant-vowel-consonant) pattern. We should note here that this is very different from traditional nonword repetition STM tasks which typically use more complex nonwords of increasing length, probing item retention and phonemic serial order retention processes at the same time.

With respect to recent STM models (e.g., Gupta, 2003), the serial order reconstruction task was designed to maximize the recruitment of serial order representation and storage processes while the item STM task was supposed to tap phonological activation and decay processes within the sublexical network of English phonological representations. It must be noted that besides their differential reliance on serial order and item STM requirements, another major difference between the tasks is the intervention of serial rehearsal processes, which are possible during the serial order reconstruction task, but not during the item STM task, the filled delay blocking serial rehearsal processes. In line with Gupta (2003), serial order storage and serial rehearsal processes are both assumed to be causally involved in learning new verbal sequences, by permitting the ordered rehearsal of the phoneme sequence to be learned.

Participants

Fifty-two students (undergraduates or graduates) of the University of Sussex participated in the study. Their mean age was 21 years (range: 18-42 years); there was a majority of female participants (n=39). To be included in this study, the participants (1) had to speak English as first language, (2) have no history of neurological or developmental impairment, (3) have no history of hearing disorders. The participants received either course credits or a compensatory fee (£7) for participation.

Methods and material

Serial order reconstruction

The serial order reconstruction task consisted of the auditory presentation of digit lists of increasing length. The lists, containing 6 to 9 digits, were sampled from the digits 1-9. For list length 6, only the digits 1, 2, 3, 4, 5 and 6 were used. For list length 7, only the digits 1, 2, 3, 4, 5, 6, and 7 were used, and so on for other list lengths. This procedure ensured that item knowledge was known in advance, and that the participants only had to remember the position in which each item occurred. The lists were recorded in a male voice and stored on computer disk, with a 350-ms inter-stimulus interval between each item in the list (mean item duration: 540 ($\pm$176) ms).

The sequences were presented via high quality loudspeakers connected to a PC that controlled stimulus presentation by running E-Prime software (version 1.0, Psychology Software Tools). They were presented with increasing length, with six trials for each sequence length. At the end of each trial, the participants were given cards (size: 5x5 cm) on which the digits presented during the trial were printed in black font. The number of cards corresponded to the number of digits presented and were presented in numerical order to the participants. The participants were requested to arrange the cards on the desk horizontally following their order of presentation. We determined span size (longest sequence length for which at least 50% of trials were correctly recalled), number of trials correct (by pooling over the different sequence lengths; maximum score: 24), and number of positions correct (by pooling over trials and sequence lengths; maximum score: 180). The task started with three practice trials of a shorter sequence length (5 digits) in order to familiarize participants with the task requirements.

Delayed repetition of high and low phonotactic frequency nonwords

The single nonword delayed repetition task was comprised of 30 high and 30 low phonotactic frequency nonwords. Stimuli were classified as high or low phonotactic frequency according to summed token frequencies of the CV* and *VC diphones taken from the CELEX corpus of English (Baayen, Piepenbrock, & Gulikers, 1995) (see Appendix 1 for more details). Mean summed English diphone frequencies were 64920, for high frequency nonwords, and 2098 for low frequency nonwords, $t(58)=3.75$, $p<.0001$. As expected, the number of phonological neighbours (words differing from the nonword by a single phoneme substitution, addition or deletion, based on the MRC Psycholinguistic Database, Coltheart et al., 1981) was greater for high relative to low phonotactic frequency nonwords (mean number of phonological neighbours: 19.97 and 5.73, respectively, $t(58)=8.06$, p.0001). As our participants were bilingual, we also checked the French phonotactics of the two nonword classes, by assimilating all French and English vowels that could be uttered in a partially overlapping way in both languages (see note of Appendix 1 for more details); the French CV* and *VC diphone frequencies were computed based on the raw diphone frequencies listed in the corpus of spoken French by Tubach and Boë (1991). This analysis showed that the high and low frequency nonwords did not differ with respect to approximate French phonotactics: mean summed French diphone frequencies were 582, for high frequency nonwords, and 501, for low frequency nonwords, $t(58)<1$, n.s.

Each nonword was recorded by a male native English speaker and stored on computer disk. Duration of pronunciation did not differ between the two nonword conditions (474 ± 108 and 481 ± 97, for high and low phonotactic frequency nonwords, respectively; $t(58)<1$, n.s.). The different nonwords were presented in isolation, via the same audio setup as in the previous task. After each nonword, there was an 8-second filled delay during which the participants had to count backwards in steps of 3, starting at 95. At the end of the delay, the experimenter tapped sharply on the desk, indicating that the participant should repeat the target nonword. There were 3 practice trials. High and low phonotactic frequency nonwords were presented in a mixed and random order. The responses were recorded via a digital microphone, and stored on computer disk for later scoring. We determined the number of correct responses, as a function of nonword condition.

French and English vocabulary knowledge

Receptive vocabulary knowledge was assessed using the British Picture Vocabulary Scales (Dunn, Dunn, Whetton, & Pintilie, 1982) as well as its French adaptation, the EVIP (Echelles de vocabulaire en images de Peabody; Dunn, Thériault-Whalen, & Dunn, 1993). These scales contain items ordered as a function of difficulty and age of acquisition. For both scales, the final score represents the rank of the final item reached minus the number of erroneous responses (stop criterion: six erroneous responses on the last eight trials).

Following the recommendations of Jared and Kroll (2001), we assessed productive vocabulary knowledge using a picture naming task (see also Francis 1999; Grosjean, 1998). The pictures were a subset of the Snodgrass and Vanderwart (1980) colorized pictures (Rossion & Pourtois, 2004). Forty-eight pictures were selected, sampling equally through high and low lexical frequency ranges (CELEX log frequency range: 0.00 – 1.91; mean: 1.00). The pictures were presented for naming in English and in French, on different occasions during the testing session (see below for details on order of presentation). The English naming condition was merely a control condition as we expected no errors on this task for native English speaking participants. For both English and French versions, we determined the number of correct naming responses.

Inventory of French language experience

French proficiency was further assessed using a questionnaire addressing foreign language exposure and experience. The following information was collected: (1) age at onset of learning French; (2) number of French lessons per week; (3) duration of French learning in years; (4) French exposure other than in school (duration in years); (5) self-rated level of proficiency for spoken French (on a 7-point rating scale ranging from 'very limited' (some words) to 'highly proficient' (like native language); (6) other languages learned at school.

French proficiency composite score

Based on the French vocabulary scores and the responses to the questions on the anamnestic questionnaire, a normalized composite score was computed, reflecting a summary score of French experience and knowledge. The vocabulary scores and the responses to each sub-question on the questionnaire were transformed into Z-scores for each participant (relative to group mean and standard deviation for the given subquestion), indicating the extent that a given participant's response/performance was above or below the average level of response/performance obtained for the entire group. For each participant, the different Z-score values for the 6 sub-questions and the two vocabulary measures were added to compose a normalized composite score.

Paired associate word-nonword learning task

Four word-nonword pairs were constructed. The cue words were all bisyllabic: "cancel" "hatred", "ragtime", "discuss". They were randomly paired with the following four nonwords which each contained two successive CVC syllables: /kubtal/, /ʒɛzkɔl/, /kɪksɛ̃s/, /mastɑ̃s/. Only diphones that are frequent in French phonology were selected when creating the nonwords. Mean diphone frequency was 1005 occurrences per 152376 diphones (range: 192-2180), according to the database of French phonology by Tubach and Boë (1990).

In order to control for general processes involved in learning bindings between two items, a paired associate word-word learning condition was also administered. The cue words were “medicine”, “gospel”, “mushroom” and “furnish”. They were randomly paired with the target words “basket”, “bathroom”, “cactus” and “kingdom”. The phonological structure of the target words (CVCCVC) was identical to that of the nonwords. Furthermore, for half of the participants, the cue words for the word-word and word-nonword conditions were exchanged, by using the original cue words of the word-nonword condition as cue words for the word-word condition, and by using the original cue words of the word-word condition as cue words for the word-nonword condition.

All stimuli were prerecorded by a highly proficient bilingual English-French speaker and stored on computer disk. The experimenter manually activated the presentation of the stimuli, with the same audio setup as for the other tasks. After a first presentation of the four word-nonword/word pairs, the four cue words were presented in random order. After each cue-word, the participant was requested to recall the corresponding nonword/word. No feedback was given. Then the complete list of word-nonword/word pairs was re-presented in a different order, followed by a new cued recall session. This procedure was repeated five times. There was a delayed cued recall trial twenty minutes after the last immediate cued recall. An entirely correct response was assigned one point. For the nonwords, a response where only one of the two CVC syllables was correctly recalled was credited with half a point. The final score represented the total number of points for the five cued recall trials; a separate score was computed for performance on the delayed cued recall. We also computed a score reflecting learning speed, or rather, lack of it, and controlling for performance on the initial learning trial which reflects recall from STM rather than learning of new phonological information. This score was derived from the following formula: L_L = {[8-(T4+T5)]+T1}/8, where T1, T4 and T5 are the scores for the first, the fourth and the fifth learning trials, respectively. L_L varies between 0 and 1 (by assuming that the scores at T4 and T5 are at least equal or are superior to the score at T1); L_L=1 represents complete lack of learning.

Half the participants received the word-word learning condition first, followed by the word-nonword learning condition, whereas the reverse order of presentation was used for the other participants (see below for details).

Estimate of general reasoning abilities

The Standard Progressive Matrices by Raven (1938) were administered in order to obtain an estimate of reasoning abilities and to control for general intellectual functioning and abilities in the correlation analyses reported in the next section.

General procedure and order of task administration

The tasks were presented in a single session lasting about 90 minutes. The session began with the administration of the French experience questionnaire, followed by the English productive vocabulary task. The remaining tasks were administered in two different orders as follows (the tasks for the second order of presentation are indicated between brackets): the word-word learning task (or the word-nonword learning task), the serial order reconstruction task (or Raven's matrices), a delayed cued recall trial, the English receptive vocabulary test (or the single item delayed repetition task), the word-nonword learning task (or the word-word learning task), Raven's matrices (or the serial order reconstruction task), a delayed cued recall trial, the single item delayed repetition task (or the English receptive vocabulary test), and the French productive and receptive vocabulary tests.

Results

Descriptive statistics are presented in Table 1 for the STM, language and non-verbal intelligence measures, and in Figure 1 for the paired associate word-word and word-nonword learning measures. All tasks yielded balanced levels of performance with no marked floor or ceiling effects, except for the productive English vocabulary task, as expected; this task will not be further considered in the analyses reported here. Although performance levels on the word-word paired associate learning task were relatively high and superior to those observed for the word-nonword paired associate learning task, the size of variance was similar for the two tasks. The lack of learning score (L_L), not presented in the tables, yielded a mean of .38 ($\pm$.18).

< INSERT TABLE 1 AND FIGURE 1 ABOUT HERE >

General correlation analysis

We checked the validity of the predictor measures by determining whether they conformed to the expected correlation patterns. For the two types of STM tasks, we expected minimal correlation, since we have assumed that they measure distinct capacities. All correlations between the three serial order reconstruction and the two nonword delayed recall measures were non-significant; as expected, the correlation between the high frequency and low frequency nonword delayed recall measures was significant (see Table 2). With respect to the language measures, we expected that the French proficiency composite score would not correlate with English vocabulary knowledge. We also expected that the high frequency and low frequency nonword delayed recall measures show differential correlation patterns with English knowledge, given that mainly item STM for high frequency nonwords should be influenced by English phonological knowledge. A significant correlation was indeed observed between the high frequency nonword delayed recall task and English receptive vocabulary knowledge. The lack of significance of the correlation between STM for low frequency nonwords and English receptive vocabulary should however be considered with caution given that this correlation would have been significant with a slightly larger sample size (N=60). Note that there was also a significant correlation between the low frequency nonword delayed recall task and the French proficiency score. Finally, we should mention that the serial order reconstruction task did not correlate with the language knowledge measures, except for a modest correlation between the number of positions correct measure and English receptive vocabulary. This is important for exploring the independent contribution of serial order STM capacity and phonological knowledge on new word learning performance.

We also checked for the expected recall advantage for high frequency relative to low frequency nonwords by performing a repeated measures ANOVA with high frequency and low frequency nonwords as within subject variables. This analysis showed a highly significant effect of phonotactic frequency, $F(1,51)=25.68$, $p<.0001$.

< INSERT TABLE 2 ABOUT HERE >

Correlations between STM measures and paired-associate learning

All correlations reported in this and the following sections are partial correlations where the influence of general intellectual abilities (Raven’s matrices) on performance levels has been controlled. We expected a significant relationship between serial order reconstruction measures and learning of word-nonword pairs. The correlations shown in Table 3 highlight a consistent association between the serial order reconstruction measures and word-nonword but not word-word paired associate learning. The correlations between the nonword delayed recall measures and word-nonword learning were not significant. Next we determined whether serial order reconstruction was also associated with delayed recall and the lack of learning score. We limited this analysis to the number of trials correct measure of the serial order reconstruction task. We observed that the serial order reconstruction measure correlated significantly with both the delayed recall measure (R=**.40**, p<.01) and the lack of learning score (R=**-.47**, p<.001); this negative correlation is due to the computation method for the lack of learning score and means that better serial order reconstruction performance is associated with faster learning performance.

< INSERT TABLE 3 ABOUT HERE >

Correlations between language measures and paired-associate learning

As shown in Table 4, a significant correlation was obtained between the composite score of French proficiency and word-nonword learning, but not between the English receptive vocabulary measure and word-nonword learning. No task correlated significantly with the word-word learning task.

As for the serial order reconstruction task, we determined the association strength between the French proficiency composite score and word-nonword learning for the delayed learning and lack of learning measures. The French composite score was significantly associated with both delayed recall (R=**.35**, p<.05) and lack of learning (R=**-.38**, p<.01), as had been the case for the serial order reconstruction measure.

< INSERT TABLE 4 ABOUT HERE >

Multiple hierarchical regression analysis

We conducted a multiple hierarchical regression analysis to determine the relative predictive power of the different STM measures and French language knowledge for word-nonword paired associate learning. We first introduced the high frequency and low frequency nonword delayed repetition measures, both of which made no significant contribution to word-nonword learning performance (see Table 5 for results). Next we introduced the French proficiency composite score as an estimate of French phonological knowledge and observed a significant increase of the explained portion of variance in the nonword learning task (.11); finally, we introduced performance on the serial order reconstruction measure (number of trials correct) and observed a large increase in explained portion of nonword learning related variance (.29). We also conducted the same analyses, but reversed the order of introduction of the serial order reconstruction and the French proficiency measures; in that case, the serial order reconstruction measure explained 35% of variance of nonword learning performance, and French proficiency explained a further 5%. In sum, both the serial order reconstruction measure and the French proficiency score are significant but independent predictors of paired associate word-nonword learning performance.

< INSERT TABLE 5 ABOUT HERE >

Item analysis

Given the reduced set of items used in the paired associated learning task, an item analysis was conducted in order to test the generality of findings and to rule out the possibility that only one or two specific items could have driven the significant correlations we obtained (see Gathercole et al., 1997, for a similar analysis). We computed separate correlations for recall accuracy of each of the four word or nonword items over the five learning trials. As shown in Table 6, recall accuracy for all four nonword items correlated significantly with the serial order reconstruction task while only one nonword item [kubtal] showed a modest correlation with the nonword delayed repetition task. These findings confirm the robustness of the correlation between the serial order reconstruction task and new word learning performance.

With respect to the French proficiency score, at first glance, the results seem slightly less consistent, given that recall accuracy for only two items out of four showed a significant correlation with the French proficiency score. However, if we push this analysis further, a clearer picture emerges. Appendix 2 presents a direct comparison of French and English diphone frequencies for the four nonword stimuli, by taking a very liberal criterion and by deciding that the French vowels /u a ɔ i/ can be assimilated to (and uttered as) the English vowels / ʌ ʊ ɒ ɪ/. Recall accuracy for the two nonwords most distant from the existing English phonological patterns ([kiksɛ̃s] and [mastɑ̃s] contained each at least two diphones that have no equivalent in English) was most reliably associated with the French proficiency score, while the two nonwords with a greater number of correspondences between English and French phonological patterns showed a diminished association with the French proficiency score. Interestingly, the nonword with the greatest overlap between French and English phonology ([kubtal]; all diphones exist in partially overlapping pronunciation patterns in both languages) showed the weakest correlation with the French proficiency score but a modest correlation with the English high-frequency nonword delayed repetition condition, tapping English phonological knowledge. This distinctive pattern of correlation between nonword learning performance and the French proficiency score, depending on the level of French phonological typicality of the nonword to be learned, further strengthens the role of phonological knowledge in new word learning performance.

Finally, the same item analysis was conducted for the word-word paired associate learning condition, confirming an absence of significant correlation between recall accuracy for the different word-word pairings and the different STM and phonological knowledge predictor measures (only one item showed a modest correlation with two of the predictor measures).

< INSERT TABLE 6 ABOUT HERE >

DISCUSSION

This study tested an integrative account of new word learning ability in adults, by simultaneously exploring the respective importance of phonological knowledge, serial order STM, and item STM as predictors of new word learning performance in adult participants with variable levels of English-French bilingual proficiency. The participants' first language was English and they had to learn new word forms that conformed to French phonotactic rules. We observed that performance on a serial order reconstruction task was the most important predictor of new word learning performance, followed by a composite measure of French proficiency, estimating French phonological knowledge. Delayed single nonword recall, reflecting item STM capacity as well as access to English phonological knowledge, did not predict new word learning performance.

Implications for the relationships between new word learning, phonological knowledge and STM

Figure 2 illustrates competing theoretical accounts of the relationships between new word learning, phonological knowledge and STM that have been proposed. A first position considers a simple bidirectional relationship between phonological STM capacity and phonological knowledge, with STM determining the acquisition of new phonological information (i.e., new word learning), and existing phonological information determining phonological STM performance; this position does not consider the role of phonological knowledge during new word learning, nor does it distinguish between item and order STM processes (Baddeley et al., 1998). A second position makes a more careful distinction between item and order STM processes, enabling the measurement of STM capacity (conceptualized as serial order STM capacity) independently of phonological knowledge; this position allows circular interpretations of correlations between traditional STM tasks, such as nonword repetition, and new word learning to be avoided. Given that nonword repetition tasks and new word learning tasks both require the temporary maintenance of new phonological sequences as well as access to the phonological knowledge base, it is possible that these tasks correlate because they require similar phonological processes. By using serial order STM tasks that minimize the recruitment of phonological processes, we can measure STM independently of access to phonological knowledge. Using this rationale, Majerus et al. (2006) were able to show a selective relationship between serial order STM measures and vocabulary knowledge in children as well as new word learning capacity in adults. However, by controlling for the influence of phonological knowledge on STM tasks, these studies are not informative about the impact of phonological knowledge on new word learning. The third position illustrated in Figure 3 is much more explicit with respect to this issue: Metsala (1999; see also Fowler, 1991) argued that new word learning, as well as nonword repetition, depend on the level of complexity and segmentation of the phonological knowledge base: the richer and more segmented the knowledge base is, the more easily new word forms can be integrated (provided there is any correspondence between the structure of existing phonological representations and that of the new phonological form to be integrated).

< INSERT FIGURE 2 ABOUT HERE >

The present study tested an integrated account of the three positions described here, illustrated in Figure 2 as position 4. This position assumes that serial order STM capacity and phonological knowledge simultaneously and independently predict new word learning capacity, while item STM capacity depends on the temporary activation of a subset of the representations contained in the phonological knowledge base. The results obtained in the present study lend considerable support to this position. In the hierarchical multiple regression analysis, the serial order reconstruction task and the French knowledge composite score independently predicted new word learning scores for new words obeying French phonotactics. The single nonword delayed recall task, probing item STM, did not predict new word learning capacity. However, this task was influenced by English phonological knowledge, as confirmed by the superior performance for recalling nonwords with frequent English phonotactics relative to nonwords with less frequent English phonotactics. Had we used French-like nonwords instead of English-like nonwords, then we would have expected a correlation between the item STM task and new word learning, given that in that case the item STM task would have recruited the same type of phonological representations as the new word learning task, i.e. French phonological knowledge. However, in that case, it would have been difficult to investigate whether basic item STM mechanisms (phonological activation, decay and inter-trial interference processes) are also involved, given that they would have been confounded with the type of phonological knowledge that is required for performing the new word learning task. The present results show that basic item STM mechanisms are not related to new word learning performance, at least when operating on a different subset of phonological knowledge than that required for learning the new words. The next sections discuss more precisely the relevance and the possible underlying processes of the different predictors of new word learning identified in this study.

Serial order STM and new word learning

The present results are consistent with the hypothesis that serial order STM is a major determinant of new word learning, and are in line with an earlier experiment where we had shown a strong relationship between serial order reconstruction and new word learning (Majerus, Poncelet, Elsen et al., 2006). The present study additionally shows that this relationship holds for all stages of lexical learning, serial order STM performance being associated with performance on both immediate and delayed recall trials. Our results also support recent developmental data that highlight a specific relationship between serial order STM performance and vocabulary development in very young children (four-year-olds) (Majerus, Poncelet, Greffe et al., 2006). The present data show that these serial order STM processes are also related to new word learning performance in bilingual speakers, independently of the learner's phonological knowledge base, which in the present study was broader and richer than that of the monolingual participants in previous experiments. More generally, the contrasting patterns of correlation identified between item STM and order STM measures and lexical measures further supports the existence of distinct mechanisms and capacities involved in item and order STM (e.g., Henson, Hartley, Burgess, Hitch, & Flude, 2003; Majerus, Poncelet, Van der Linden, Albouy, Salmon, Sterpenich, Vandewalle, Collette, & Maquet, 2006; Majerus, Van der Linden et al., 2007; Majerus, Norris et al., 2007).

What are the cognitive mechanisms responsible for the specific link between serial order STM and new word learning capacity? Gupta (2003) has addressed this question most directly (see also Gupta & MacWhinney, 1997). Gupta proposed that during learning of new phonological sequences, the succession of the different phonemes is stored in a specific STM system (called 'sequence memory') while existing sublexical and new lexical representations in the language system are temporarily activated. The information stored in the sequence memory permits the ordered replay of the new phonological sequence in the language system and increases the probability that a stable and accurate long-term phonological representation is formed. Hence, both the storage capacity for serial order information and the reactivation of these temporary sequential representations via serial rehearsal processes determine new word learning according to this theoretical framework. A different account has been advanced by Burgess and Hitch (1999, 2005), who suggest that learning of new phonological sequences is ensured via more durable, Hebbian adjustments of connection weights between lexical and sublexical units in the language network and a serial order system encoding phoneme position specific information. These two theoretical positions are complementary given that they focus on different stages of the learning process: the position by Gupta considers more specifically what is happening during the early learning stages and how STM processes could be involved in these stages while the position of Burgess and Hitch (1999, 2005) considers more specifically the structural changes that occur in the language network as a result of the learning process. The crucial point here is that both models highlight the importance of links between mechanisms representing serial information and the language network during phonological learning.

Phonological knowledge and new word learning

The other predictor of new word learning was phonological knowledge. Importantly, only the phonological knowledge measure corresponding to the phonotactic knowledge base underlying the new words to be learned predicted new word learning, i.e. the composite French proficiency score, whereas the delayed nonword recall task, probing subtle sublexical English phonotactic knowledge, did not. The French composite score reflected the general level of French exposure and knowledge, and estimated the level of development of French phonological knowledge, at both sublexical and lexical levels. These findings support the results of Masoura and Gathercole (2005) with Greek speaking children learning English, showing a strong association between existing English vocabulary knowledge and English word learning. As an extension to the results of Masoura and Gathercole, our data show that serial order STM capacity remains an important predictor of foreign new word learning capacity, in addition to the influence of phonological knowledge for the given foreign language. These results also support the more general theoretical position offered by Metsala (1999) and Fowler (1990) (see also Storkel et al, 2006). This position considers that the increase of vocabulary knowledge in a given language favors segmentation and detailed representation of phonological knowledge, favoring in turn the acquisition of new phonological representations similar to that phonological knowledge. Note however that this framework was developed essentially in order to account for native language development. The present data suggest that this theoretical account applies to any situation of vocabulary acquisition, be it for monolingual child language development, or for the development of a foreign phonological lexicon in adults. We should note that the present arguments are neutral with respect to the issue of ‘single lexicon’ or ‘multiple lexicon’ accounts of bilingual language processing (Kroll & Dijkstra, 2002). Any of the theoretical positions in Figure 2 (including our integrative account) could be amended by duplicating the phonological knowledge base to represent L1 and L2 phonological knowledge with the additional constraint of different sizes for each language network. In any case, the same basic principle should apply: phonological representations within a given knowledge base will determine further acquisition of new phonological representations, especially if there is some overlap between existing phonological representations and the new phonological form to be learned. Furthermore, the impact of serial order STM will be identical, as, in the case of multiple lexicons, serial order STM would be connected to both L1 and L2 lexicons, and support the learning of new lexical representations, in either L1 or L2. One prediction that we can however derive from this account (as well as from the item analyses reported in the results section) is that the larger the discrepancies between the phonological representations of L1 and L2, e.g. Italian-Spanish versus Chinese-English, the more reliant the learner may be on serial order STM capacity to learn the second language.

Conclusions

The present study highlights the importance of both previous exposure to foreign language phonology and serial order storage and rehearsal capacities for fast learning of new word forms, and favors an integrative model of new word learning, which reconciles ‘STM’ based and ‘phonological knowledge’ based models of lexical learning. Interestingly, our data highlight a prevailing association between serial order STM and new word learning capacity, in participants with already rich phonological networks as a result of exposure to two languages.

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TABLE 1

Descriptive statistics for predictor variables.

	Mean	SD	Range
Serial order reconstruction			
Span (max= 9)	8.02	1.02	6 - 9
Trials correct (max= 24)	14.62	4.81	4 - 23
Positions correct (max= 180)	148.98	18.31	111 - 178
Nonword delayed repetition			
High frequency (max= 30)	22.25	3.27	13 - 28
Low frequency (max= 30)	19.38	3.73	9 - 26
French proficiency (normalised composite score)	0.00	4.74	-12.17 - 10.89
English receptive vocabulary knowledge (max=150)	139.90	6.28	118 - 150
English productive vocabulary knowledge (max= 48)	47.46	0.87	44 - 48
Raven’s matrices (max= 60)	49.29	4.73	37 - 58

TABLE 2

Correlations between the different short-term memory and language measures

	HF Nonword delayed repetition	LF Nonword delayed repetition	French composite proficiency score	English receptive vocabulary
Serial order reconstruction				
Span	.20	.07	.17	.22
Trials correct	.09	.11	.22	.25
Positions correct	.10	.12	.19	.27*
HF nonword delayed repetition		.33*	.07	.34*
LF nonword delayed repetition			.29*	.26
French composite proficiency score				.18

* p< .05; **p<.001

TABLE 3

Partial correlations between the different short-term memory measures and word-word and word-nonword paired associate learning (controlling for general intellectual abilities).

	Word-word (Trials 1-5)	Word-nonword (Trials 1-5)
Serial order reconstruction		
Span	.21	**.62****
Trials correct	.15	**.61****
Positions correct	.11	**.59****
Nonword delayed repetition		
High-frequency	.01	.22
Low-frequency	.08	.08

* p< .05; **p<.001; bold : significant after correction for multiple comparisons

TABLE 4

Partial correlations between the different language measures and word-word and word-nonword paired associate learning (controlling for general intellectual abilities).

	Word-word (Trials 1-5)	Word-nonword (Trials 1-5)
French proficiency composite score	.09	**.33***
English receptive vocabulary	.11	.11

* p< .05; **p<.001; bold : significant after correction for multiple comparisons

Table 5

Multiple regression analyses predicting word-nonword learning by nonword delayed repetition, serial order reconstruction and French proficiency composite scores.

Variables introduced	ΔR^2	*p*	*F*	*p*	*dl*
1. LF nonword delayed repetition	.013	n.s.	0.65	n.s.	1, 50
2. HF nonword delayed repetition	.045	n.s.	1.53	n.s.	2, 49
3. French proficiency composite score	.110	<.05	3.25	<.05	3, 48
4. Serial order reconstruction (trials)	.288	<.001	9.87	<.001	4, 47
3. Serial order reconstruction (trials)	.350	<.001	11.03	<.001	3, 48
4. French proficiency composite score	.047	<.05	9.87	<.001	4, 47

TABLE 6

Correlation coefficients between the serial order STM, item STM, French proficiency composite score and the different item pairings of the word-word and word-nonword learning tasks (controlling for general intellectual abilities).

	Serial order reconstruction	HF nonword delayed repetition	LF nonword delayed repetition	French proficiency composite score
Word-nonword learning				
[kubtal]	.36*	.28*	.26	.17
[mastɑ̃s]	.51**	.08	-.02	.31*
[ʒɛzkɔl]	.38*	.18	-.05	.24
[kiksɛ̃s]	.58**	.12	.08	.26(*)
Word-word learning				
W1	.30*	-.06	-.06	.28*
W2	-.06	-.01	.20	.13
W3	.08	.08	.13	.10
W4	.22	.00	.05	.10

* $p< .05$; ** $p<.001$

FIGURE LEGENDS

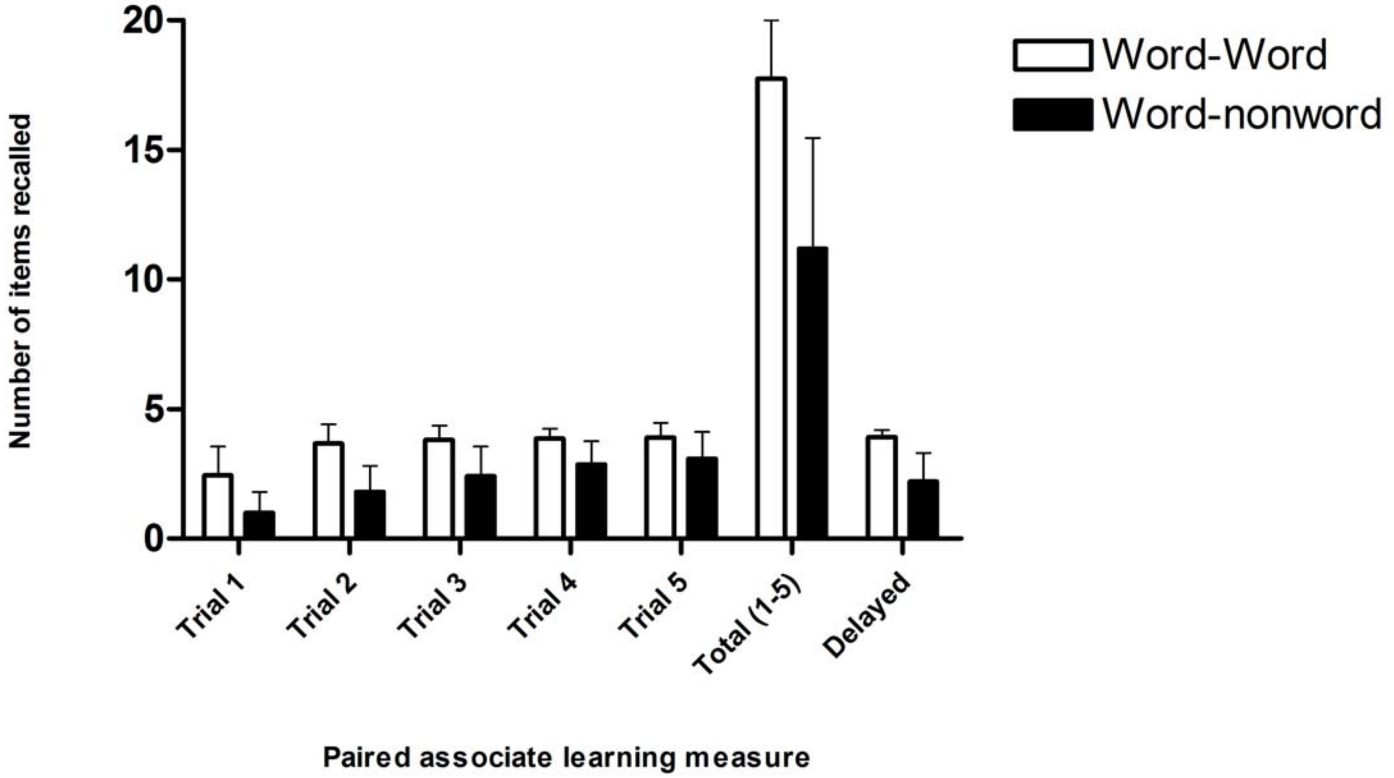
Figure 1

Performance levels for the word-word and word-nonword paired associate learning tasks, as a function of learning trial.

Figure 2

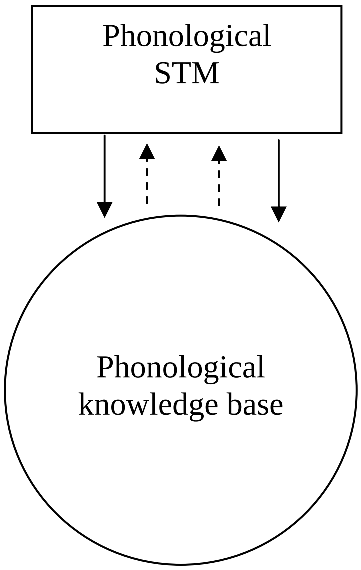
Schematic description of the different theoretical positions regarding the relationship between new word learning, phonological knowledge and STM

Figure 1

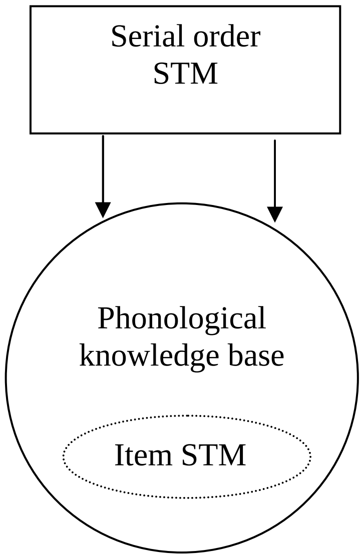


20
15
10
5
0
Number of items recalled
Word-Word
Word-nonword
Trial 1
Trial 2
Trial 3
Trial 4
Trial 5
Total (1-5)
Delayed
Paired associate learning measure

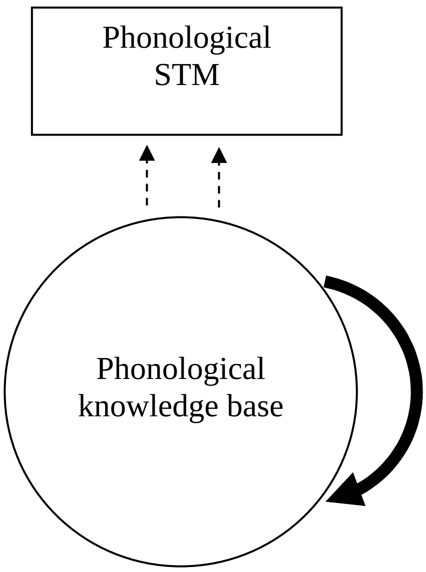
Figure 2



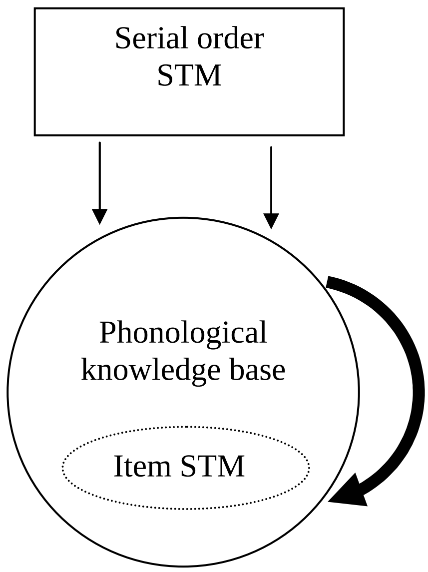
Position 1: Phonological STM determines learning of phonological information and is determined by phonological knowledge; no distinction between item and order STM (Baddeley et al., 1998)



Position 2: Serial order STM determines learning of phonological information; item STM is determined by temporary activation of a subset of phonological knowledge (Gupta, 2003; Majerus, Poncelet, Greffe et al, 2006; Majerus, Poncelet, Elsen et al., 2006)



Position 3: Learning of new phonological information and phonological STM depend on the level of complexity and segmentation of the phonological knowledge base; no distinction between item and order STM (e.g., Metsala, 1999)



Position 4: Serial order STM and level of complexity and segmentation of the phonological knowledge base determine learning of new phonological information; item STM depends on temporary activation of a subset of phonological knowledge

APPENDIX 1

Nonword stimuli used for the single nonword delayed repetition task

HF nonword	Summed Diphone frequency		N count English	LF nonword	Summed Diphone frequency		N count English
	English[1]	French[2]			English[1]	French[2]	
hɒv	520431	69	13	vɛb	4978	891	5
deɪb	42720	0	15	dɜːg	636	0	11
leɪb	38772	0	17	dʒɑːp	1505	512	8
kæz	122001	0	16	lɛð	1847	0	5
waɪm	34029	0	26	tʃɔːv	275	361	4
meɪdʒ	24544	0	25	duːg	586	79	8
pɒn	36700	1362	27	tʃɔːp	1491	437	11
ðæz	103093	0	7	θaʊm	1074	0	3
hɜːv	15834	0	15	zeɪr	144	0	0
lɑːs	23478	5498	24	wæθ	1509	0	5
fɜːs	36307	0	21	sɑːʃ	2678	1910	5
gɛl	35306	1556	22	mʊb	330	119	2
lʊd	28723	500	20	zeʊf	1431	0	3
mɪn	106029	1433	34	vəʊdʒ	2128	0	5
dəʊθ	31349	0	15	zeɪf	1431	0	3
sɜːk	40898	0	29	nɑːr	1439	4542	4
seɪt	43810	0	39	kuːdʒ	2508	747	11
weɪm	43069	0	27	zɜːb	1938	0	4
paɪt	47086	0	39	ʃuːb	3180	61	4
nɛv	65800	703	6	nuːr	345	1950	3

ðəʊn	42718	0	16	zɪr	244	1341	1
ðɪm	108449	450	8	gʊp	1851	342	5
ʃɪz	111449	1000	12	nʊf	101	596	3
gʌd	23545	1669	17	nɔɪp	1595	0	7
hɜːm	13901	0	24	vaɪg	2115	0	5
dɒf	31493	156	13	sʊg	1562	163	2
nʌv	3069	3069	12	pɛð	9776	565	5
fæm	44220	0	21	rɔːv	548	371	9
ðeɪn	92483	0	20	hʊtʃ	1092	40	5
fæs	36307	0	19	ræb	12591	0	26

[1] English diphone frequencies computed from Celex lexical database (diphone frequencies are weighted for the lexical frequency of the words within each diphone appears)

[2] Approximate French diphone frequencies from the phonetic database of French by Tubach & Boë (1990) (raw diphone frequencies, based on their frequency of appearance within the corpus of spoken French used for the construction of the database) (for this purpose, the English vowels / ʌ aː ʊ uː ɒ ɔː ɪ iː/ have been assimilated to the French vowels / ʌ ʊ ɒ ɪ/, respectively)

APPENDIX 2

Nonword stimuli used for the paired-associate learning task

HF nonword	French diphone frequencies [1] C_1V_1	V_1C_2	C_3V_3	V_3C_4	English diphone frequencies [2] C_1V_1	V_1C_2	C_3V_3	V_3C_4
kubtal	565	59	1320	2691	13282	229	4222	3447
mastɑ̃s	1030	2180	942	1806	39429	21909	0	0
ʒɛzkɔl	135	87	1305	635	0	9968	51421	26124
kiksɛ̃s	1524	1284	256	495	10699	37986	0	0

[1] French diphone frequencies from the phonetic database of French by Tubach & Boë (1990)

[2] Approximate English diphone frequencies taken from Celex for French diphones having similar or closely related English pronunciations (for this purpose, the French vowels /u a ɔ i/ have been assimilated to the English vowels / ʌ ʊ ɒ ɪ/, respectively)