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Semantic and phonological schema influence spoken word learning and overnight consolidation

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Abstract
We studied the initial acquisition and overnight consolidation of new spoken words that resemble words in the native language (L1) or in an unfamiliar, non-native language (L2). Spanish-speaking participants learned the spoken forms of novel words in their native language (Spanish) or in a different language (Hungarian), which were paired with pictures of familiar or unfamiliar objects, or no picture. We thereby assessed, in a factorial way, the impact of existing knowledge (schema) on word learning by manipulating both semantic (familiar vs unfamiliar objects) and phonological (L1- vs L2-like novel words) familiarity. Participants were trained and tested with a 12-hr intervening period that included overnight sleep or daytime awake. Our results showed (1) benefits of sleep to recognition memory that were greater for words with L2-like phonology and (2) that learned associations with familiar but not unfamiliar pictures enhanced recognition memory for novel words. Implications for complementary systems accounts of word learning are discussed.

Keywords
Word learning; L1; L2; semantic; phonology; schema; consolidation; sleep

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Introduction

Word learning is a key aspect of language processing in our native tongue (L1) and during second language acquisition (L2). In both cases, we learn a novel sequence of speech sounds, map a meaning onto this phonological pattern and combine new words and existing language knowledge to comprehend or produce new words in context. However, L1 and L2 word learning differ in terms of whether the phonological sequences and meanings resemble previously learned words. In adulthood, we learn new words in our native language to denote novel concepts such as 'blog' or 'Internet'. However, the phonological form of these new words resembles existing words such as 'block' or 'international'. Conversely, when learning a new word in a new language, the meanings will already be familiar. Hungarian words such as 'szék' and 'répa' relate to the familiar concepts 'chair' and 'carrot', respectively. However, these words may have unfamiliar phonemes since English does not use a trilled/r/sound as in 'répa'. In this work, we consider whether and how existing phonological and semantic knowledge (schema) can support the learning of novel spoken words in these situations.

One theory of word learning from the perspective of the complementary learning systems (CLS) proposes that two separate neural systems contribute to initial acquisition and longer term retention of newly learned words (Davis &

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Gaskell, 2009; Lindsay & Gaskell, 2010; cf. McClelland, McNaughton, & O'Reilly, 1995). New words are initially encoded by the medial temporal lobe (MTL), which binds together representations of word form and meaning and is also involved in the retrieval of newly learned information (Breitenstein et al., 2005; Davis, Di Betta, Macdonald, & Gaskell, 2009; Mestres-Missé, Càmara, Rodríguez-Fornells, Rotte, & Münte, 2008). Longer term knowledge of familiar words and meanings is stored in neocortical networks; memory consolidation during sleep is responsible for re-encoding information initially learned by medial temporal systems for neocortical storage (Davis et al., 2009; Inostroza & Born, 2013; Laine & Salmelin, 2010; Rasch & Born, 2013). This proposal thereby explains behavioural (Dumay, N. et al., 2004; Dumay & Gaskell, 2007; Tamminen, Davis, Merkx, & Rastle, 2012; Tamminen & Gaskell, 2013) and neural (Davis & Gaskell, 2009; Gagnepain, Henson, & Davis, 2012; Takashima, Bakker, van Hell, Janzen, & McQueen, 2014) changes in spoken word recognition following sleep, and further that the magnitude of these overnight changes is linked to the frequency of slow-wave spindles (Tamminen, Payne, Stickgold, Wamsley, & Gaskell, 2010), or the number of rapid eye movement (REM) periods (De Koninck, Lorrain, Christ, Proulx, & Coulombre, 1989) during intervening sleep.

The first studies that suggest a role for consolidation during L1 word learning and that motivated the CLS framework used a lexical competition test of lexical integration. Gaskell and Dumay (2003) studied the emergence of lexical competition when participants learned new L1-like words that shared their initial (pre-uniqueness) segment with an existing L1 (English) word (e.g. cathedruke – cathedral). Once consolidated, these new words became a lexical competitor and delayed recognition for these L1 words. Strikingly, Gaskell and Dumay showed a temporal dissociation such that while lexical competition effects only emerged a week after training, two-alternative forced-choice recognition memory for trained words was good immediately. Similar results were obtained when lexical competition was assessed using pause detection and phoneme monitoring tasks (Dumay, Gaskell, & Feng, 2004; Gaskell & Dumay, 2003). Most importantly for the CLS theory, with a between-group (a.m.–p.m.) design, Dumay and Gaskell (2007) showed that the emergence of lexical competition between newly learned and existing words was associated with overnight sleep. Subsequent research has sometimes shown offline consolidation effects on trained rather than existing competitor words, for example, using recognition memory (Davis et al., 2009; Dumay & Gaskell, 2007), speeded repetition (Davis et al., 2009) or free recall tasks (Dumay & Gaskell, 2007; Dumay et al., 2004). However, consolidation effects are clearest in tasks that test lexical competition, since this is often only apparent following consolidation (although see Kapnoula, Packard, Gupta, & McMurray, 2015; Lindsay & Gaskell, 2013 for data consistent with pre-consolidation emergence of lexical competition for certain tasks or training protocols).

Overall, the results of these studies are consistent with the CLS model in suggesting that anatomically and functionally distinct neocortical and hippocampal systems contribute to word learning and recognition. The CLS framework further predicts that recognition of consolidated spoken words should be faster and more accurate than unconsolidated knowledge (Davis & Gaskell, 2009). This distinction is proposed to arise from MTL systems storing detailed episodic information that is accessed as wholes while neocortical areas acquire more abstract information that achieves more rapid integration of newly learned and existing word knowledge (see Brown & Gaskell, 2014 for illustrative data suggesting a decline in episodic information accompanying lexical integration).

While the initial experiments that led to the proposal of the CLS framework used L1-like novel words as stimuli, the CLS account also appears relevant for word learning in second language acquisition. One key distinction between L1 and L2 learning is that the latter typically occurs after learners have established knowledge of L1. In other domains, it has been shown that the period of time in which new knowledge remains dependent on MTL structures depends on whether it fits in with a pre-existing schema or knowledge base (Lindsay & Gaskell, 2010). Tse et al. (2007) found that for rats learning associations between odours and locations, the duration of hippocampal dependence was reduced if rats had learned a prior set of similar stimulus–location mappings. By extending this same principle, an L1 schema of form-to-meaning mappings already exists, and L2 learning could build on this, thus leading to a shorter-lived period of hippocampal dependence. On the other hand, the phonological schema for the L1 may be inappropriate for an L2 that contains different segments or phonological structures. This might lead to extended reliance on the hippocampus as a mediating structure. We will therefore review studies of these semantic and phonological aspects of second language word learning in turn.

Phonological aspects of word learning and consolidation

Studies addressing phonological aspects of second language acquisition found that learning new phonemes in isolation, novel phonotactic rules or novel word forms containing new phonemes are all more challenging than acquiring equivalent knowledge in L1. For example, in a Magnetoencephalography (MEG) study, Finnish-speaking participants learned the phonological forms of new words that either resembled their native language or were phonotactically different (Korean; Nora, Renvall, Kim, Service, & Salmelin, 2015). Participants were more accurate at both the recognition and repetition of L1-like new words compared to their L2 counterparts. In addition, L1-like items (perhaps due to their native phonotactic structure) evoked overall enhanced left temporal activation, whereas frontal activity during overt repetition was more pronounced for L2-like items. In an event-related potentials (ERP) study, Kimppa, Kujala, Leminen, Vainio, and Shtyrov (2015) found a rapid enhancement of activity in fronto-temporal brain regions following exposure to novel words, only if these followed the phonotactic rules and contained phonemes of their native language. This neural response further predicted the subsequent recall and recognition of the newly learned words. These findings are consistent with the proposal that different neural pathways are involved in word-form learning with L1 and L2 phonology and that novel words with native phonology benefit from pre-existing phonological representations.

Some aspects of L2 phonological learning have also been suggested to show CLS-like properties, for instance, effects of sleep-associated post-learning consolidation have been shown for learning phonotactic rules and new phonemes. For example, Gaskell et al. (2014) found that speech errors generated during generalization to new words were consistent with the placement of phonemes in trained words, if training and test were separated by a 90-min nap. However, if an equivalent time was spent awake, generalization to new items also included inconsistent errors. This suggests that sleep facilitates the integration of new phonotactic rules of a sort that might contribute to L2 learning. In learning individual phonemes, Earle and Myers (2015a) found that overnight consolidation promoted generalization across talkers in the identification of a Hindi dental–retroflex contrast. A further study suggested that sleep not only facilitated L2 phoneme learning but also protected against interference from perceptually similar native language phonemes (Earle & Myers, 2015b). The role of sleep was further supported by overnight improvements in non-native speech sound discrimination that were correlated with sleep duration (Earle, Landi, & Myers, 2017). Overall, these studies suggest that sleep-related consolidation may play an important role in phonological word-form learning, particularly for learning novel words that have L2-like phonemes or phonotactic structure. In our study, we set out to directly compare the effect of consolidation in learning L1- and L2-like words, exploring how the similarity of phonological forms to existing L1 knowledge interacts with the effect of sleep on performance.

Semantic aspects of word learning and consolidation

While L2 word learning may be made more difficult by the need to acquire novel phonological information, semantic information overlaps with L1 and hence could be readily associated with new L2 words. Based on the levels of processing framework (Craik & Lockhart, 1972), we would anticipate that more elaborate semantic processing during encoding will provide a mnemonic benefit to learning and remembering words. Indeed, previous results from L2 learners have confirmed that words that were learned with familiar pictures were better remembered compared to words learned without a picture (Bird, 2012). Here, we review studies that directly assess the role of associated semantic information in supporting word and meaning learning – in particular, considering whether pairing with novel or familiar semantic information makes a differential contribution.

Several studies have found that learning the phonological forms of L1-like novel words benefits from presentation of semantic referents (Cunillera T et al., 2010). Hawkins, Astle, and Rastle (2015) found that novel words were learned better when they were consistently associated with obscure novel objects during training than when word–object associations were inconsistent. Furthermore, in an ERP session on the same day as training, the mismatch negativity (MMN) effect, an electrophysiological measure of auditory discrimination, was also only present for words with consistent picture associations and was correlated with the accuracy of picture–word association knowledge. Similar behavioural benefits have been observed in two functional magnetic resonance imaging (fMRI) studies that also used L1-like novel words and novel object referents (Takashima et al., 2014, 2016).

Although the presence of a referent seems to improve memory for newly learned phonological forms, one study has reported that pairings with novel referents decreased the extent to which new words competed with existing words (Takashima et al., 2014). Furthermore, retrieval of picture-associated, relative to form-only, novel words showed greater activation of the hippocampal memory system, also suggesting reduced integration into neocortical systems. However, in a behavioural study, Hawkins and Rastle (2016) found equivalent lexical competition from picture-associated and form-only novel words if phonological forms are learned sufficiently well during training. They found that the presence of novel objects during learning did not interfere with lexical competition effects that emerged a week after training, when the training task emphasized phonological form rather than form-meaning learning.

Considering the effect of sleep on semantic referent learning, Kurdziel and Spencer (2016) taught participants highly infrequent words in their native language associated with their corresponding definitions. They found that the accuracy of cued recall (producing the newly learnt word when its definition is presented) decreased in a group that spent the subsequent 12 hr awake, but was maintained in the group that had a period of sleep between the two test phases. Polysomnography data from a subset of participants showed that the percentage of REM sleep correlated with the cued recall accuracy. Bakker, Takashima, van Hell, Janzen, and McQueen (2015) taught participants novel words that were phonologically similar to their native language and were associated with a definition, which provided a novel meaning. ERP data showed a neural correlate of semantic priming effects; an enhanced later positive component (LPC) for items preceded by a word related in meaning, both immediately and 24 hr after training. However, the difference between the N400 response to real and novel words was much reduced 24 hr as compared to immediately after training. These findings suggest that while newly learned words do not immediately acquire the same status as 'existing words' that are already integrated into the mental lexicon, novel meanings do immediately start to contribute to semantic processing.

The studies reviewed in this section have explored the role of novel and familiar semantic representations in supporting acquisition of spoken word forms with mixed results. Despite existing work showing enhanced retention of word forms following more elaborate, semantic encoding (Bird, 2012) these studies reviewed here have shown only inconsistent benefits of pairings with unfamiliar pictures. However, thus far, the effect of learning words associated with familiar and unfamiliar pictures have not been directly compared within a single study. Furthermore, interactions between these semantic or associative factors and phonological challenges in learning spoken forms remain unspecified.

In this study, we therefore assessed how object novelty and novel phonology impact on learning and consolidation of spoken words. We taught groups of Spanish-speaking participants novel spoken pseudowords that either followed the phonological structure of their L1 or were L2 (Hungarian) words. By comparing knowledge of L1 and L2 spoken items, we can study the impact of phonological novelty on word learning. Based on previous studies, we expect that participants will be faster and more accurate at learning and recognizing L1-like words than their L2-like counterparts. To assess how object familiarity impacts learning, for each participant we paired one-third of the words with pictures depicting everyday objects (*familiar picture*), one-third with pictures of unfamiliar objects (*unfamiliar picture*) and presented the remainder without a picture (*no picture*). This three-way comparison is critical to assess whether the benefit to word learning comes primarily from encoding novel words that are associated with visual information (in which case word learning can benefit from association with either unfamiliar or familiar objects), or from established conceptual knowledge (primarily available for familiar objects).

To explore the effect of sleep-associated consolidation on word learning, half of the participants were trained in the morning and tested 12 hr later (without intervening overnight sleep), and the remaining participants were trained in the evening and tested 12 hr after (with overnight sleep). This between-group design, similar to that of Dumay and Gaskell (2007), allowed us test for enhanced performance 12 hr after training for those participants who had an intervening period of overnight sleep (i.e. consolidation). For both groups of participants, we assessed knowledge of spoken phonological forms using a recognition memory test and word–concept associations using a word–picture matching task. Furthermore, participants performed a semantic priming task to assess whether the newly learned words would prime existing words and hence were semantically integrated into the mental lexicon (as used by Tamminen & Gaskell, 2013).

Methods

Participants

Sixty-eight Spanish-speaking healthy volunteers between the ages of 18 and 36 years ($M = 21.89$ years, standard deviation [SD] = 3.77 years) with normal or corrected-to-normal vision and normal hearing, and with no learning disabilities or psychiatric disorders, were tested. Three participants were excluded due to software failure therefore, 65 participants were included in the data analyses. Participants were divided into four experimental groups: (1) L1 −sleep ($N = 17$), (2) L1 +sleep ($N = 15$), (3) L2 −sleep ($N = 17$) and (4) L2 +sleep ($N = 16$). The groups were matched on verbal and non-verbal intelligence measured on the sub-scales of the Wechsler Adult Intelligence Scale III – Matrix reasoning: $F(3, 61) = 1.25$, $p > 0.3$, $\eta^2 = 0.06$; Similarities: $F(3, 61) = 0.32$, $p > 0.8$, $\eta^2 = 0.02$. Furthermore, there were no group differences in the number of languages spoken, $F(3, 61) = 0.22$, $p > 0.8$, $\eta^2 = 0.01$, and no participant had any previous exposure to Hungarian.

Materials

The 72 L1 and 72 L2 trained words as well as 144 L1 and 144 L2 untrained control items used in the memory tests were all between one and three syllables long. The items learned by each participant group were matched on syllable and phoneme length (syllable: $M_{L1} = 2.10$ [±0.47 SD], $M_{L2} = 2.10$ [±0.47 SD], $t(430) < 1$, ns; phoneme: $M_{L1} = 5.18$ [±1.03 SD], $M_{L2} = 5.02$ [±1.18 SD], $t(430) = -1.59$, ns). The L1 words were created based on real Spanish words by changing one or two phonemes (e.g. *bozal – cozal, casco – cosco*), while the L2 words were real Hungarian words (e.g. golyó, csíra). Hungarian has 44 phonemes, almost twice as many as the 22-24 phonemes is Spanish (depending on dialect). Nonetheless, Spanish also includes two phonemes that Hungarian does not. Thus, about half of the phonemes appearing in the Hungarian words were unknown for the Spanish participants. These phonological differences enabled us to study how the familiarity of the phonological system of the novel words can affect word learning.

Each of the four groups learned words in three experimental conditions: (1) familiar picture (n=24), where the novel word was presented with a colour photograph depicting a known, everyday object; (2) unfamiliar picture (n=24), where the novel word was presented with a colour photograph of an unknown object; and (3) no picture (n=24), where the novel word was presented in the absence of a picture. Familiar object pictures were taken from colour photographs collated and pre-tested by Lolly Tyler's research group at the Centre for Speech and Language in Cambridge, UK. We refer the reader to previously published functional imaging research using this picture set for a brief description of pre-test data from these materials (Bright, Moss, & Tyler, 2004; Tyler et al., 2004) Novel object pictures (see Supplementary material) were selected from a photo objects database and were used in a previous object-name learning study (Taylor, Rastle, & Davis, 2014).

Procedure

The training phase involved the randomly ordered presentation of the 48 word–picture pairs from the familiar picture (n=24), unfamiliar picture (n=24) and no-picture condition. Participants were instructed to pay attention to the words and word–picture pairs and to learn as many of them as possible. All the words and word–picture pairs were presented five times, once in each of the training runs. Assignment of spoken words to familiar/unfamiliar/no-picture conditions was counterbalanced over participants so that all words were learned in all training conditions. During training, the picture appeared 500 ms before the auditory presentation of the word and remained on screen for a total of 3500 ms. Between each word–picture pair, a fixation cross was displayed for 500 ms. To provide an online measure of word learning, an auditory recognition memory test was administered after each run. Participants were presented with the spoken forms of 18 of the trained words (6 from the familiar picture condition, 6 from the unfamiliar picture condition and 6 that were learned in isolation) as well as 18 untrained foils (different items after each run) and had to judge whether each item was one they had learned.

Longer term retention was assessed 12 hr (±1 hr) after the training phase. To evaluate the effect of sleep on word learning, two groups were trained in the morning (8-10 a.m.) and tested in the evening (8-10 p.m.; −sleep groups), and two groups were trained in the evening (8-10 p.m.) and tested in the morning the following day (8-10 a.m.; +sleep groups). In the testing phase, three tasks were administered in the following order to avoid further repetition of the trained items influencing recognition memory: (a) a recognition memory test to evaluate learning of the phonological form of the trained words, (b) a four-alternative picture selection task to evaluate associative learning of the word–picture pairs and (c) a semantic priming task to assess integration of words and meanings from the familiar picture condition into the mental lexicon (Figure 1).

- *(a) Recognition memory test*. Participants were presented with the spoken forms of the 72 trained and 72 untrained control items (without pictures) in a randomized order and were asked to make an old–new judgment by pressing a button. There was a 3-s time limit on responses after which the next trial was presented.
- *(b) Four-alternative forced-choice word–picture matching task.* The spoken form of one trained word associated with a (familiar or unfamiliar) picture was presented with four trained pictures (the correct associated picture and three trained ones). Participants were asked to choose which picture was paired with the word that they had heard, by pressing one of four buttons on the keyboard. There was a 3-s time limit on responses. The items from the unfamiliar and familiar object conditions were tested in separate blocks, so that all four pictures on a given trial depicted either unfamiliar or familiar objects.
- *(c) Semantic priming task.* To evaluate whether novel words from the familiar object condition were integrated with existing semantic memory participants performed a semantic priming task. Primes were the 24 spoken words (with L1 or L2 phonology for different participants) that were associated with pictures of familiar objects. After a 500-ms fixation cross, the auditory prime stimulus was presented, followed by a 150-ms visual presentation of a written target item that stayed on screen for 2 s, or until the participant made a lexical decision (whichever was sooner). The target items were (a) the Spanish translation of the prime (related condition), (b) a real Spanish word completely unrelated to the meaning of the prime (unrelated condition) or (c) a Spanish pseudoword (filler trials). Each prime word was presented four times, once with a related target, once with an unrelated target and twice with different pseudoword fillers, and item presentation was fully randomized. Lexical decision response times were compared following related and unrelated prime trials. Prior to training, each participant also completed an equivalent semantic priming task using semantically related or unrelated Spanish words as primes with the same experimental set-up. This allowed us to compare the magnitude of translation priming for

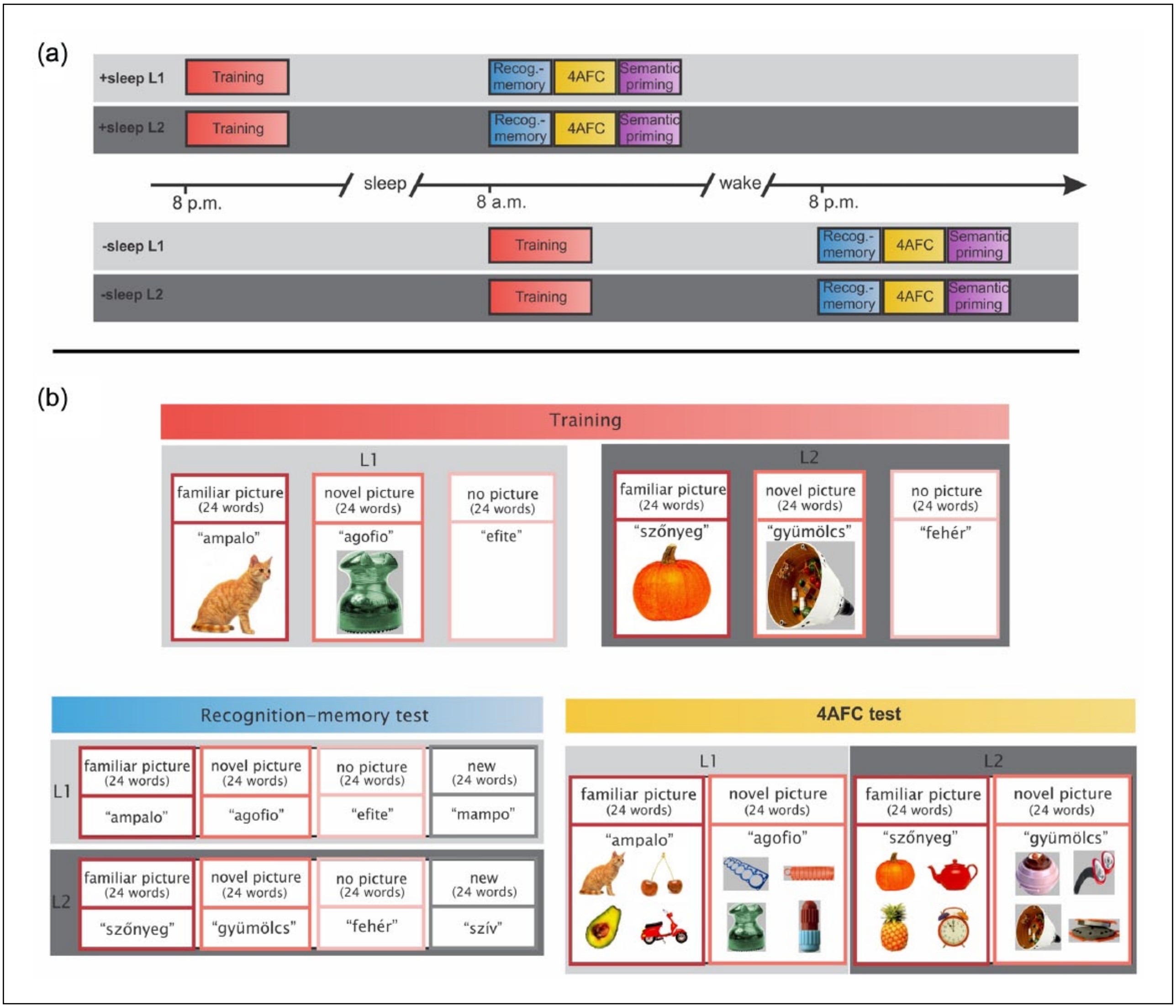

Figure 1. Overview of the experimental procedures and paradigm: (a) time course of the training and memory tests for the four experimental groups and (b) example stimuli for both novel phonological forms and pictures for each experimental condition and task.

newly learned spoken words to the magnitude of semantic priming for the native language.

Results

For all analyses of variance (ANOVAs), post hoc tests were conducted to determine the source of any significant main effects for factors with more than two levels and for any interactions. Differences between conditions that were significant at $p<0.05$ with Bonferroni correction were considered reliable. Given that the specific items in each condition were counterbalanced across subjects, item-specific factors cannot explain any differences observed between learning of spoken words with and without pictures or effects of sleep. Therefore, ANOVAs by participants sufficed to assess effects of these within-group factors (cf. Raaijmakers et al., 1999). Furthermore, given our between-participant manipulation of language, between-item and between-participant variance contributes equally to effects of L1 versus L2 in by-participant analyses; therefore, these by-participant ANOVAs are suitably conservative for assessing effects of language.

Training

To assess recognition memory performance during training sessions, we computed d′ measures of sensitivity (cf. Snodgrass & Corwin, 1988) for each participant, after each training run and for each picture condition. To check that time of day did not affect the rate and efficacy of learning, we conducted a mixed-design ANOVA on d′ values from the recognition memory test that followed each

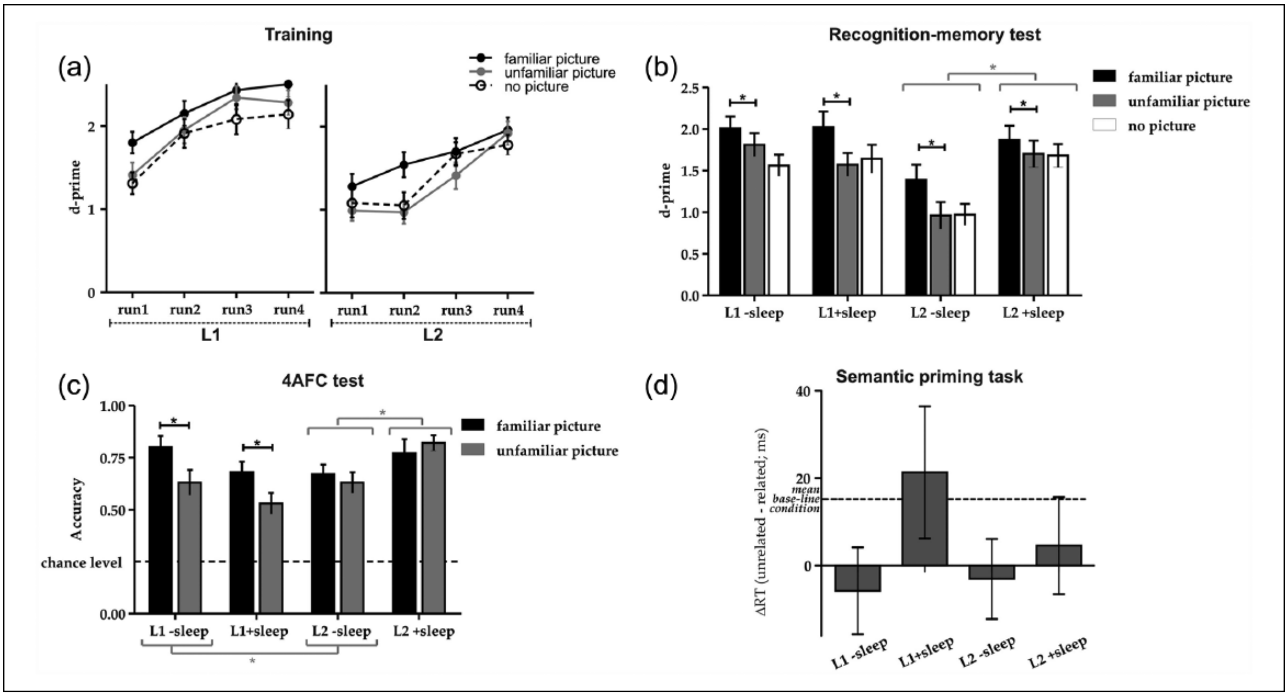

Figure 2. Results of the recognition-memory task: (a) during training runs and (b) 12 hr after training. (c) Results of the four-alternative forced-choice word–picture matching task and (d) results of the semantic priming task. Results are expressed in (a, b) d′ values, (c) percentage accuracy and (d) differences in response times between related and unrelated trials (ms).
*$p<0.05$. Error bars show the standard error of the mean after between-subject variance has been removed, suitable for repeated measures comparisons (Loftus & Masson, 1994).

run of training. This analysis had the within-subject factors *picture* (familiar picture, unfamiliar picture, no picture) and *run* (runs 1, 2, 3, 4) and the between-subject factor *time* (morning training session = −sleep groups, evening training session = +sleep groups). Results show a main effect of picture, $F(2,122)=15.00$, $p=0.0001$, partial $\eta^2=0.20$, and run, $F(3,183)=24.83$, $p=0.0001$, partial $\eta^2=0.29$, but no main effect of time, $F(1,61)=0.02$, $p=0.885$, partial $\eta^2<0.001$, and no interactions involving this factor. This result shows that there were no significant time-of-day effects on initial learning, suggesting that the differences between the +sleep and −sleep groups in subsequent analyses were probably not driven by effects of time-of-day on the efficacy of learning. Our favoured interpretation is that subsequent differences are due to the presence or absence of post-learning overnight consolidation. However, we cannot exclude the possibility that differences in performance between the morning and evening group were due to time-of-day effects during the testing phase.

As there was no effect of the time of training on initial learning, the +sleep and −sleep groups were collapsed for further analyses of recognition memory performance during training. Figure 2a shows mean d′ values for each training run, language and picture condition averaged over +sleep and −sleep conditions. A mixed-design ANOVA was conducted with the within-subject factors picture and run and the between-subject factor *language* (L1, L2 phonology). This analysis showed that spoken words that were associated with familiar pictures were easier to learn than words with no pictures or pictures of unfamiliar objects. We found a main effect of the picture condition, $F(2,122)=15.55$, $p=0.0001$, partial $\eta^2=0.20$; subsequent post hoc analysis with Bonferroni correction showed a significant difference between the familiar picture versus unfamiliar picture and familiar picture versus no-picture conditions ($p=0.001$); we found no differences between the unfamiliar picture and no-picture condition ($p=0.9$). The significant main effect of *run* ($F(3,183)=25.71$, $p=0.0001$, partial $\eta^2=0.30$) shows that recognition improved over the course of training, and the effect of *language* ($F(1,61)=24.38$, $p=0.0001$, partial $\eta^2=0.29$) confirmed that participants had more difficulty in acquiring novel words from a phonologically different language (L2 – Hungarian). No significant interaction effects were obtained) picture × language: $F(2, 122)=1.59$, $p=0.209$, partial $\eta^2=0.03$; run × language: $F(3, 183)=2.28$, $p=0.086$, partial $\eta^2=0.04$; picture × run: $F(6, 366)=0.625$, $p=0.708$, partial $\eta^2=0.01$; picture × run × language: $F(6, 366)=1.163$, $p=0.327$, partial $\eta^2=0.02$).

Recognition-memory task

The recognition-memory task administered 12 hr after training revealed better than chance performance in all conditions (d′ scores greater than zero). However, we also see between-group and within-group differences in recognition memory as depicted in Figure 2b. An ANOVA on d′ values with *picture* (familiar, unfamiliar, no picture) as a within-subject variable and *sleep* (+sleep, −sleep) and *language* (L1, L2) as between-subject variables showed significant main effects of all three factors – picture: $F(2,120)=22.25$, $p=0.0001$, partial $\eta^2=0.27$; language: $F(1,60)=6.06$, $p=0.017$, partial $\eta^2=0.09$; sleep: $F(1,60)=4.58$, $p=0.036$, partial $\eta^2=0.07$. Post hoc analysis showed that participants were more successful at recognizing words trained in the familiar picture condition than from the other two conditions (both $p<0.001$; which did not differ from each other; $p>0.9$), even though the task only required recognition of phonological forms. In addition, participants were more successful at recognizing L1 words than L2 words, and there was a beneficial effect of sleep on recognition. However, an interaction between language and sleep was also observed, $F(1,60)=6.30$, $p=0.015$, partial $\eta^2=0.10$, indicating that these two effects did not combine in an additive fashion. Post hoc analyses revealed a beneficial effect of sleep in the groups that studied L2 words ($p=0.001$), but not in those that studied L1 words ($p=0.79$). As the maximum possible d′ value for this task was 4.07 (equivalent to 100% correct hits without any false alarms), we can exclude the possibility that the absence of a sleep effect in the L1 groups was due to a ceiling effect (d′ values: L1 +sleep, $M=1.81$, standard error [SE]=0.14; L1 −sleep, $M=1.74$, $SE=0.17$). On average, participants in the L1 groups made 75% correct hits and 18% false alarms further confirming that performance is well below ceiling. Post hoc analyses also demonstrated that the effect of language was only present for the −sleep groups; the L2 +sleep group performed equivalently to the two L1 groups. The picture × language × sleep interaction was marginally significant – $F(2,120)=2.54$, $p=0.084$, partial $\eta^2=0.04$; all other interactions were non-significant – picture × language: $F(1,120)=0.446$, $p=0.641$, partial $\eta^2=0.01$; picture × sleep: $F(1,120)=1.136$, $p=0.325$, partial $\eta^2=0.02$.

Four-alternative forced-choice word–picture matching task

Mean accuracy rates in the four groups of learners (L1/L2, +/−sleep) for words associated with unfamiliar and familiar pictures are shown in Figure 2c. A similar mixed-design ANOVA was conducted on accuracy in the four-alternative forced-choice task (within-subject factor: *picture* [familiar picture, unfamiliar picture], between-subject factors: *language* [L1, L2] and *sleep* [+sleep, −sleep]). A significant main effect of picture, $F(1,61)=15.55$, $p=0.0001$, partial $\eta^2=0.20$, and two-way interactions between language and picture, and language and sleep were found, language × picture: $F(1,61)=16.22$, $p=0.0001$, partial $\eta^2=0.21$; language × sleep: $F(1,61)=16.22$, $p=0.01$, partial $\eta^2=0.10$. Post hoc analyses showed that as in the recognition-memory results, a beneficial effect of sleep was present for L2 ($p=0.038$) but not L1 learners ($p=0.128$). In addition, an effect of language was present only for the +sleep groups ($p=0.010$), within which performance was in fact better for L2 learners; in the −sleep groups, L2 and L1 learners performed equivalently ($p=0.338$). With regard to the interaction between picture and language, the beneficial effect of a familiar relative to an unfamiliar picture was only present for L1 learners ($p=0.028$) and not L2 learners ($p=0.952$), unlike in the recognition memory task where accuracy was higher for the familiar picture items for both L1 and L2 groups. In addition, the effect of language was only present for unfamiliar ($p=0.007$) and not familiar pictures ($p=0.731$). All other interactions were non-significant – picture × sleep: $F(1,61)=1.84$, $p=0.180$, partial $\eta^2=0.03$; picture × language × sleep: $F(1,61)=0.855$, $p=0.359$, partial $\eta^2=0.01$.

Semantic priming task

Confirming that our experimental set-up was adequate to examine semantic priming, we found that Spanish target words were responded to significantly faster when preceded by a related than an unrelated auditory Spanish real word – related: $M=651$ ms, $SE=9$ ms, $SD=73$ ms; unrelated: $M=667$ ms, $SE=10$ ms, $SD=78$ ms, $t(61)=-3.08$, $p=0.003$. However, when we examined the results from the semantic priming task with trained item primes, we did not find any significant priming effects in any of the conditions. A mixed-design ANOVA (within-subject factor: *relatedness* [related, unrelated], between-subject factors: *language* [L1, L2] and *sleep* [+sleep, −sleep]) obtained no significant main effects ($p>0.2$, partial $\eta^2<0.025$) and only found one significant interaction that was unrelated to priming – sleep by language: $F(1,61)=8.18$, $p=0.006$, partial $\eta^2=0.118$. Post hoc analyses revealed that the L1 −sleep group performed the task faster compared to the L1 +sleep group ($p=0.005$, partial $\eta^2=0.121$). All other interactions were statistically non-significant ($p>0.1$, partial $\eta^2<0.04$). The lack of priming effects could indicate that the trained words were not yet sufficiently integrated into the semantic system or could be due to the small sample size. This is possible given that the difference between RTs in the related and unrelated condition even in the native language task was small ($M_{\text{difference}}=16$ ms, $SE=4.94$, $SD=38.93$). As shown in Figure 2d, we did observe a numerical trend in the priming task with the trained items that would benefit from further investigation: the magnitude of semantic priming was largest for the L1 +sleep group (21.34 ms) and in this condition alone approached statistical significance ($p=0.075$).

Discussion

We studied the initial acquisition and overnight consolidation of new spoken words in L1 and L2 that were associated with a familiar or unfamiliar object, or with no picture, to determine the generality of CLS account of word learning. Each of our three experimental manipulations – (1) sleep, (2) association with object pictures and (3) familiar (L1) phonology – affected the acquisition and retention of word form and meaning knowledge. We will discuss these three findings before summarizing implications for CLS accounts.

Overnight Consolidation

Sleep produced significant benefits to recognition memory and associative knowledge of recently learned spoken words. However, these beneficial effects of sleep were confined to groups trained on L2 spoken words. The lack of an advantageous effect of sleep for L1 words seemingly contradicts findings from previous word learning studies showing effects of overnight consolidation in L1 (Clay, Bowers, Davis, & Hanley, 2007; Davis et al., 2009; Dumay & Gaskell, 2007). Even though these studies have often tested lexical competition (i.e. competition between newly learned and existing words, cf. Gaskell & Dumay, 2003), sleep effects were found on free recall and recognition memory tasks as well (Dumay & Gaskell, 2007), and there is some debate as to the types of task that should show greatest sleep-related enhancements (see Diekelmann, Wilhelm, & Born, 2009 for review). Thus, further research is necessary to clarify the conditions and tasks under which consolidation effects are observed for words with L1-like phonology.

It is possible that we only obtained consolidation effects for L2 words due to better performance overall for the L1 items. While recognition accuracy of L1 words appears to be below ceiling (75% hit rate and 18% false alarms), there may nonetheless have been less opportunity for overnight improvements in retention (i.e. consolidation) for items with L1 phonological forms. Drosopoulos, Schulze, Fischer, and Born (2007) found similar results in a sleep-associated declarative memory consolidation study where participants learned lists of word pairs. The sleep-related enhancement of memory retention was greater for weaker associations.

Familiar object association

Pairing novel words with pictures of familiar objects enhanced recognition memory for spoken words. This beneficial effect was present for recognition of trained phonological forms during and immediately following initial learning and when retention was tested 12 hr later. This result is consistent with the proposal that more elaborate semantic processing during learning aids subsequent memory (cf. Balass, Nelson, & Perfetti, 2010; Bird, 2012; Cunillera, Camara, Laine, & Rodríguez-Fornells, 2010). However, the present results extend these previous findings, by showing that words paired with pictures of unfamiliar objects did not show any advantage compared to words learned in isolation. Hence, the beneficial effect of association with object pictures is limited to pictures that depict familiar objects and is not due to mere pairing of words with pictures. A further effect of object familiarity was also seen for participants' performance in choosing the correct referent for a recently learned word. However, in this case, familiar object pictures only had a beneficial effect for L1 words. As we will discuss later, these results suggest that association with existing knowledge schema (for items with familiar phonological structure and items paired with familiar objects) seems to enhance associative learning compared to items for which only one or neither of these forms of knowledge are supported by existing representations.

One notable difference between familiar and unfamiliar object pictures is that only the former has an existing label in the language learner's L1. It might be that phonological knowledge of this existing word could have influenced the word learning process (as well as, or instead of the direct association with a meaningful picture). Participants might have adopted the strategy of associating the new word with the L1 word, not only the picture. Unfortunately, we do not have information from our participants to indicate whether or not this was the case.

Another possibility is that greater cognitive resources may have been required to interpret unfamiliar object pictures. Encountering and memorizing a picture of an unfamiliar object might present a significant cognitive load that could detract from the process of encoding the spoken words and hence make word learning more difficult. However, if this were the case, participants should have been worse at learning word forms paired with unfamiliar objects than word forms presented in isolation, which, like Hawkins and Rastle (2016), we did not observe. We therefore suggest that our results reflect a positive effect of learning spoken words associated with familiar object pictures rather than difficulties with processing unfamiliar object pictures.

Phonological familiarity

Our findings demonstrate the additional difficulty of learning spoken words in a second language: L1 word forms were learned more effectively and better remembered than L2 words in same-day tests of auditory recognition memory. L2 words may have been more difficult to learn due to either the presence of unfamiliar phonological elements (novel segments) or infrequently heard sequences of familiar elements (low phonotactic probability). Consistent with this latter explanation, McKean, Letts, and Howard (2013) reported that children were more accurate at a fast-mapping task when the novel words to be learned had a high phonotactic probability in their native language.

One novel observation in this study is that overnight consolidation significantly benefits knowledge of L2 phonological forms. For participants who were tested after overnight sleep, auditory recognition memory was equivalent for L1 and L2 words, and picture selection for L2 words exceeded L1 accuracy. Such findings are consistent with a contribution of consolidation to phonological learning suggested by prior research, but not previously confirmed as associated with overnight sleep (see Earle & Myers, 2014 for a review). For example, Warker (2013) showed that associations between phoneme identity and syllable position are only established on the second of two successive days of testing. However, Warker's design leaves unspecified whether this change was due to the passage of time, repetition of the test or an influence of offline consolidation. As reviewed in the introduction, Gaskell et al. (2014) found that sleep benefits the integration of new phonotactic constraints into the speech-production system. Our design adds convergent evidence for consolidation of novel phonological patterns in recognition memory rather than in speech production. We suggest that our findings are consistent with a greater influence of sleep-associated consolidation on recognition memory for phonological forms of novel words in L2 than seen in L1. However, we also note that the present design does not completely rule out the possibility of circadian effects on our test tasks. Further research to rule out this circadian confound or to demonstrate an association with sleep parameters (e.g. spindle density, cf. Tamminen et al., 2010) would be valuable.

Implications for CLS accounts of word learning

A key prediction of CLS accounts is that the contrasting computational requirements of initial learning and longer term retention of spoken words (as for other domains) lead to a specific division of labour. Initial learning of novel items is supported by medial temporal lobe systems that achieve greater plasticity by encoding recent episodes into sparse, or non-overlapping, representations. Only following consolidation is new knowledge fully encoded into neocortical systems that store novel and existing items in overlapping representations (Davis & Gaskell, 2009; McClelland et al., 1995). This study lends further support to this account through evidence of overnight consolidation in learning situations modelled after L1 and L2 learning. By manipulating similarity between novel and pre-existing word forms and associated objects, we have also gained new insights into how existing knowledge schema supports initial learning and influences later consolidation.

Critically, a consolidation-induced enhancement of recognition memory for spoken words was only evident for phonological forms that were dissimilar to previously known words (i.e. L2 items). Forced-choice picture selection similarly only showed consolidation effects for words with novel phonological properties. The lack of consolidation effects for conventional L1 pseudowords combined with their significantly more rapid initial acquisition points to a beneficial effect of familiar phonological structure in assisting episodic learning of spoken words.

Effects of similarity between new words and existing knowledge were also seen when words were paired with familiar or unfamiliar objects. Spoken words were learned more rapidly if they were paired with familiar objects, but pairing with unfamiliar objects provided no benefit to learning or retention. Furthermore, pictures of familiar objects were more accurately selected after association with L1 pseudowords than were pictures of unfamiliar objects. Hence, it is easier to associate the phonological form of new spoken words with familiar object pictures (that also have existing labels) than with pictures of unfamiliar objects.

Thus, both phonological and semantic aspects of word learning are enhanced by similarities between new and existing knowledge. Memory is enhanced for items that are related to existing schema (cf. Bartlett, 1932; van Kesteren, Ruiter, Fernández, & Henson, 2012). According to the definition in van Kesteren et al. (2012), a schema is a network of neocortical representations that are strongly interconnected and that can affect online and offline information processing. In this sense, a picture of a familiar object will activate cortical networks related to the object that is depicted (including properties of the object, its use and the word used in L1 to refer to that object). This simultaneous activation of neocortical representations can be considered a schema and appears helpful in the acquisition of novel spoken words. In the case of novel words with familiar phonological structure, phonotactic properties of the language and phoneme representations will also be activated and will aid the language learner to encode novel spoken words. The phonological or phonotactic schemas and schemas relating to object recognition are likely processed by different neural networks. Nonetheless, there seems to be a common underlying principle at work. Existing representations that facilitate the integration of novel information into familiar schemas appear to support encoding and retention of new information in memory networks. In contrast, schema-inconsistent knowledge (such as the phonological form for an L2 spoken word, or a picture of an unfamiliar object) is more difficult to learn and might be more dependent on overnight consolidation.

In this description, word learning shows schema-related benefits similar to those seen in other domains, and for other species. For example, structured knowledge of the first part of a movie enhances encoding of the second half of a movie on a subsequent day (van Kesteren, Fernández, Norris, & Hermans, 2010). Rats show more rapid consolidation of novel place–food associations if they have previously learned similar associations (Tse et al., 2007). In both cases, connections between medial temporal and ventro-medial prefrontal cortex may contribute to encoding advantages for schema-associated knowledge (see van

Kesteren et al., 2012 for discussion). Neuroimaging studies will be required, however, to assess whether these same systems contribute to schema-supported learning for spoken words, rather than the lateral and medial temporal systems highlighted by existing neuroimaging studies of word learning (Breitenstein et al., 2005; Davis et al., 2009; Takashima et al., 2014).

In the context of CLS, these findings illustrate how similarity between new knowledge and existing cortical representations enhances learning and influences consolidation. Initial learning, which is dependent on medial temporal lobe systems, is most effective when existing knowledge of familiar items (presumably already encoded in neocortical representations) can be used to support the learning of new items. When learning words with L2 phonology, neocortical systems can only activate an approximate representation of a new phonological form and hence are less effective in supporting hippocampal encoding. Overnight consolidation might help generate more accurate neocortical representations of the novel phonological aspects of L2 words; thus, tests of recognition memory on subsequent days show enhanced episodic memory for L2 words learned the day before. In contrast, L1 items are encoded into the hippocampus using appropriately structured neocortical representations, and hence episodic memory receives a more limited gain from consolidation. One exception to this pattern, however, is that retrieval of pictures associated with L2 words showed no effect of object familiarity when tested on the same day or following sleep. This might suggest a knock-on effect of schema-inconsistent phonological forms; encoding these phonological forms might require more cognitive resources, and thus participants were less efficient in recognizing the word–picture pairs regardless of the familiarity of the depicted object.

In conclusion, then, our findings provide additional support for a role of overnight consolidation in word learning, showing sleep-associated benefits to learning L2 phonological forms. Furthermore, initial learning was enhanced for L1 phonological forms and assisted by pairing with pictures of familiar object. These findings illustrate how word learning benefits from the supportive influence of existing phonological and semantic schema. Educational methods that build on existing phonological or object picture schema are likely to be effective in teaching new words and meanings in L1 and L2.

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Supplementary material

Supplementary Figure A1 is available at: http://journals.sagepub.com/doi/suppl/10.1080/17470218.2017.1329325

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