The influence of meaning and memory consolidation on novel word learning

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Declaration of authorship

This thesis contains original work completed solely by the author under the supervision of Professor Kathy Rastle, with the co-supervision of Dr Duncan Astle for Study 1 and Study 2.

Signed:

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Abstract

The cognitive mechanisms underpinning adult word learning have become of great interest in recent years. Whilst knowledge about novel word forms and meanings can be acquired quickly, the integration of newly-learnt with existing words often requires offline consolidation after initial encoding. However, it remains relatively underexplored what factors contribute to the time-course and success of this process. A particularly interesting question concerns the role of semantics in word learning: whilst the provision of semantic information during the encoding of new words can benefit declarative memory, it may delay the lexicalization time-course. This thesis therefore investigated the dual influence of meaning and memory consolidation across different levels of spoken word learning in adults. The first question addressed was whether semantic information influenced phonological form learning, and the consequences of offline consolidation for this semantic effect. Study 1 and Study 2 investigated this using event-related potentials, in a learning paradigm in which novel words were learnt with and without consistent semantic associations. The results of these studies suggested that consistent semantic exposure could support the encoding of new phonological form representations, and that this learning benefit was stable following overnight consolidation. The second question was whether this semantic benefit transferred to the lexical integration of new with existing words. Study 3 tested the behavioural impact of semantic learning on lexical competition and observed no lexicalization following overnight consolidation, or at a long term follow-up, despite a semantic and consolidation benefit across other learning measures. The final study sought to address whether phonological attention during learning influenced the lexicalization time-course. Novel words acquired via phonological training engaged in lexical competition, with a time-course which was unaffected by semantic exposure. These data were interpreted in light of memory consolidation theories to discuss the extent to which encoding influences the offline consolidation process new words undergo.

Dissemination of Findings

The data from Study 2 were presented in the following paper:

Hawkins, E., Astle, D. E., & Rastle, K. (in press). Semantic advantage for learning new phonological form representations. *Journal of Cognitive Neuroscience*.

Data from this thesis were presented at the following conferences:

Study 1

Hawkins, E., Astle, D., & Rastle, K. (2012). *Information and processes in novel word learning.* Talk presented at Psycholinguistics in Flanders, the Netherlands, June 2012.

Study 2

Hawkins, E., Astle, D., & Rastle, K. (2013). *Consolidation-enhanced semantic influence on word learning.* Invited talk presented as part of the 'Linguistic Brain' session at Donders Discussions, the Netherlands, October 2013.

Hawkins, E., Astle, D., & Rastle, K. (2013). *Consolidation-enhanced semantic influence on word learning.* Poster presentation at the Form-to-Meaning Workshop, Newnham College, Cambridge, September 2013.

Hawkins, E., Astle, D., & Rastle, K. (2013). *Consolidation-enhanced semantic influence on word learning.* Talk presented at the 18th Meeting of the European Society for Cognitive Psychology, Budapest, Hungary, August 2013.

Hawkins, E., Astle, D., & Rastle, K. (2013). *Consolidation-enhanced semantic influence on word learning.* Poster presentation at the Experimental Psychology Society Meeting, Bangor, July 2013.

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1.1 Introduction

The relation of form to meaning is at the heart of language comprehension and, by extension, language learning. The acquisition of new words entails adding a new unit to the language system which can be accessed through its spoken and written form, related to its meaning, and can interact with existing lexical knowledge. A central challenge in acquiring a new word concerns its integration with existing stores of lexical knowledge. This thesis addresses how we acquire new spoken words as adults, and investigates specific factors influencing the learning and consolidation of newly-learnt words.

A long history of research suggests that adults are proficient word learners, but the last decade has seen a great increase in understanding the specific mechanisms underpinning word learning. It has come to be recognised that whilst factual knowledge about new words, such as their written or spoken form and meaning, can be rapidly acquired (e.g. Salasoo, Shiffrin, & Feustel, 1985; Whittlesea & Cantwell, 1987), the integration of newly-acquired words with known words often requires a longer period of time after initial encoding (e.g. Gaskell & Dumay, 2003; Tamminen & Gaskell, 2013). This period of memory formation after encoding is known as consolidation (e.g. Diekelmann, Wilhelm, & Born, 2009; McClelland, McNaughton, & O'Reilly, 1995). The term 'consolidation' encapsulates a range of processes that can overall produce beneficial and long-term changes to memory (e.g. Dudai, 2004). With specific relation to word learning, consolidation can enhance access to new word knowledge, aid its integration with existing knowledge, and facilitate its generalisation to new linguistic knowledge (Davis, Di Betta, Macdonald, & Gaskell, 2009; Dumay & Gaskell, 2007; Tamminen, Davis, Merkx, & Rastle, 2012).

Whilst the importance of consolidation in several aspects of word learning is becoming increasingly well understood, it is not yet well-established what factors contribute to the time-course or success of this process. A particularly interesting question concerns the role of semantics in the learning and consolidation of new words. Whilst the provision of semantic information during the encoding of new words can be beneficial in explicit recognition and recall (e.g. Forster, 1985; Rueckl & Dror, 1994), it has been observed to delay the integration time-course of new with existing lexical knowledge (e.g. Takashima, Bakker, van Hell, Janzen, & McQueen, 2014). It is thus relatively underexplored how semantic information influences the learning and consolidation time-course of newly-learnt word forms.

The present thesis is therefore driven by the overarching research question: how are new lexical representations established? This question can be considered in terms of the encoding of novel spoken words with semantic knowledge, and the subsequent effect of this encoding on the offline consolidation process these new words undergo. To first understand what establishing a new lexical representation entails, the following chapter reviews literature relevant to the architecture and mechanisms of language processing, and considers what it means to acquire a new word within this framework.

1.2 Lexical knowledge

A central feature of known words is the process they engage in during spoken word recognition, and understanding this process thus underpins what it means to establish a new lexical representation. Spoken word recognition involves the mapping of the speech signal onto internal representations of lexical knowledge. At its most basic level, learning a new word thus requires establishing a new internal representation onto which spoken (or written) input can be mapped.

Lexical knowledge consists of phonological, orthographic and semantic knowledge about individual words, and the relationships between words based on this knowledge. For example, on hearing the sentence "She went to the zoo and saw a /pɛ/", the final word segment /pɛ/ can be more quickly recognised as /pɛŋgwɪn/ than the less semantically coherent /pɛnsəl/, even though the input /pɛ/ is consistent with both possibilities. Marslen-Wilson (1987) suggested that this 'duality', whereby lexical representations could consist of both phonological and semantic knowledge, allowed the process of word recognition to mediate between an acoustic-phonetic analysis of the speech input, alongside accessing syntactic and semantic knowledge of the incoming speech. The core feature of this duality was allowing spoken word recognition to occur more quickly than it would on the basis of a bottom-up analysis of the speech input alone (e.g. Zwitserlood, 1989). The architecture of the language system, and spoken word recognition in particular, thus incorporates a representation of the speech input and a mapping of this input onto stored phonological and semantic knowledge.

Phonological knowledge constitutes representations of phoneme categories (e.g. Eimas et al., 1971; Liberman, Harris, Hoffman, & Griffith, 1957; Näätänen et al., 1997), whereby a phoneme category is a language-specific unit of sound which can meaningfully change a word (e.g. /k/ and /b/ are different phonemes in English, evidenced by /kæt/ and /bæt/ being different lexical items). Evidence for the presence of phoneme categories comes from studies suggesting that abstract linguistic representations constrain the processing of the speech signal. For example, Näätänen et al. (1997) tested the discrimination between /e/, /ö/ and /õ/ in Finnish and Estonian speakers, where /ö/ exists as a vowel in both languages but /õ/ is a vowel sound only in Estonian. Both Finnish and Estonian speakers discriminated between /e/ and /ö/ (measured by an ERP potential of auditory discrimination, the mismatch negativity), but only Estonian speakers discriminated between /e/ and /õ/. This suggested that discrimination between the phonemes was not driven by auditory differences, but was constrained by native language representations (see also Dobel, Lagermann, & Zwitserlood, 2009, for the assimilation of a trained non-native contrast to a native phoneme category). Phonological representations of words consist of sequences of phonemes, which can interact with each other during spoken word recognition (e.g. Luce & Pisoni, 1998; Marslen-Wilson, 1987).

In a similar way, stored semantic knowledge constitutes knowledge of word meanings and the relationship between them. One of the first theories of human semantic processing was the 'spreading activation' theory (Collins & Loftus, 1975), viewing semantic memory search as spreading from activated 'source' nodes (e.g. a word or concept), with this activation propagating through connected nodes in a semantic network. For example, responses to 'doctor' in a primed lexical decision task are faster when preceded by 'nurse' than when preceded by an unrelated word such as 'bread', suggesting the prime 'nurse' activates the semantically related 'doctor' in a way 'bread' does not (Meyer & Schvaneveldt, 1971). The role of semantic information in lexical access in such a way is well-documented (e.g. Tulving & Schacter, 1990; but see also Elman, 2004), and it is thus clear that lexical knowledge involves a representation of a word's phonology and semantics[1]. As such, the process of spoken language comprehension consists of mapping the acoustic-phonetic features of the speech input onto these internal representations of phonology and meaning.

[1] Note that knowledge about a word can include also its orthography, morphology, syntactic role, and such psycholinguistic factors as word frequency. 'Lexical knowledge' can thus be considered to incorporate each of these elements more extensively, but a full discussion of each component of lexical knowledge is beyond the scope of this thesis.

1.3 Architecture and models of spoken word recognition

Understanding the mechanisms of word recognition is thus central to defining what it means to add a new word to existing lexical knowledge. One key question in how we recognise spoken words is whether this process is interactive or autonomous (e.g. Norris et al., 2000; McClelland, Mirman, & Holt, 2006; McQueen, Norris, & Cutler, 2006). Early accounts of spoken word recognition were modular in nature (e.g. Becker, 1980), in which other sources of information, such as meaning, could not affect the recognition of the form-based representation of a word. Such models suggested that the speech input was mapped onto form representations, and meaning was accessed only after word recognition was completed. The meaning of a word could therefore not affect its form-based computation. Conversely, later models of spoken word recognition assumed an interaction between different sources of information during word recognition (McClelland & Elman, 1986; Marslen-Wilson, 1987; Gaskell & Marslen-Wilson, 1997).

Interactive accounts suggest that lexical knowledge can influence the online processing of a word, such that the perception of a phoneme within a word is impacted by lexical knowledge. For example, an ambiguous phoneme that may be perceived as either /g/ or /k/ is more likely to be perceived as /g/ if followed by –*ift*, and /k/ if

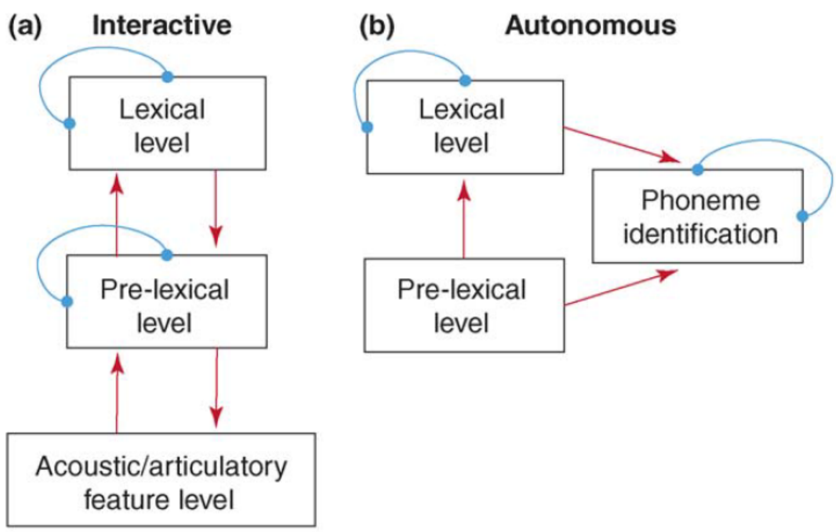

Figure 1. Schematics of interactive and autonomous models of speech perception.

The arrows indicate excitatory connections and the curved lines indicate within-level inhibitory connections. a) Interactive models incorporate bidirectional excitatory connections between levels, with phoneme identification occurring at the pre-lexical level. b) Autonomous models suggest feedforward excitatory connections from pre-lexical to lexical processing, with a separate phoneme identification layer. Note that in both classes of models there are mutually inhibitory connections between words at the lexical level. Figure from McClelland, Mirman, and Holt (2006).

followed by *–iss,* an effect known as the Ganong effect (Ganong, 1980). Conversely, autonomous models suggest that speech perception is bottom-up (e.g. driven only by acoustic-phonetic analysis of the speech signal, without the input of stored lexical knowledge), and lexical knowledge only affects post-perceptual decision processes in terms of lexical selection (Norris, 1994). A schematic of the information flow in interactive and autonomous models is shown in Figure 1. A body of experimental evidence broadly supports an interactive account of spoken word recognition, in which lexical knowledge can influence phoneme perception and the co-activation of semantic knowledge can facilitate lexical selection. This evidence will be discussed below in turn.

It is broadly agreed that spoken word recognition proceeds through the activation of multiple lexical candidates in parallel, in which the selection of one of these candidates emerges from the best fit for the spoken input based on the different activation levels of each candidate. The process of word recognition begins with a representation of the acoustic-phonetic features of the spoken input, which in turn activates multiple lexical candidates which are consistent with the spoken input at a given point in time. For example, on hearing the spoken segment /pɛ/, all candidate words in this word-initial cohort would be activated, such as /pɛnsəl/, /pɛŋgwɪn/ and /pɛzənt/ (*pencil, penguin* and *peasant*). The spoken input then accumulates such that one lexical candidate is selected, which culminates in word recognition. Notably, the *uniqueness point* of a word is the point at which only one lexical candidate matches the input; for example, on hearing /pɛŋgw/ the input can be recognised unambiguously as *penguin*, as there are no other candidate words matching this input. However, the *recognition point* of a word can often occur prior to its uniqueness point, due to coarticulation or other contextual information. Indeed, due to the speed of spoken word recognition, an early model of word recognition suggested that the process begins with an activation of stored lexical candidates matching the word-initial speech input (the Cohort model; Marslen-Wilson & Tyler, 1980), whereby this acoustic-phonetic analysis of the input was combined with stored semantic and syntactic information. The core idea of the Cohort model, and subsequent investigations of spoken word recognition, was thus that the incoming speech is processed continuously, with multiple lexical candidates which match the speech signal being activated in parallel.

It is therefore widely established that spoken word recognition involves a process of competition between multiple lexical candidates activated in parallel (e.g. Luce & Pisoni, 1998; Marslen-Wilson, 1987; McClelland & Elman, 1986). Critically,

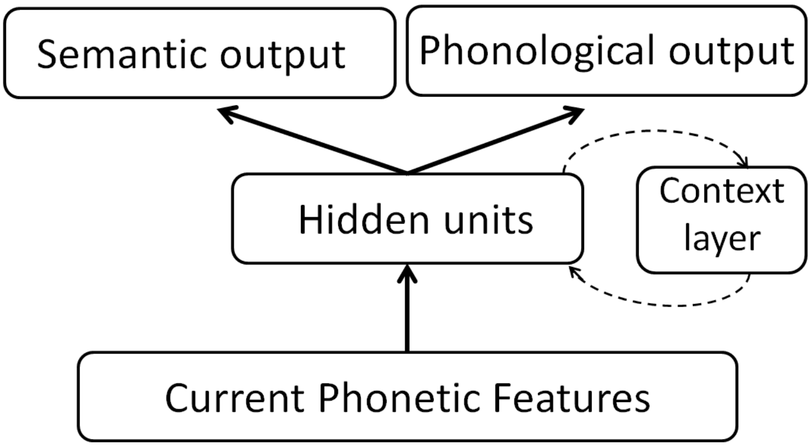

Figure 2. The Distributed Cohort Model of spoken word recognition.
Notably, this model differed from previous instantiations of the Cohort model (Marslen-Wilson, 1987; Marslen-Wilson & Tyler, 1980) by suggesting that lexical selection operated on a single distributed representation of phonology and semantics, rather than activating several localist word-level representations in parallel. Figure adapted from Gaskell and Marslen-Wilson (1997).

however, psycholinguistic properties of the cohort can affect the speed of word recognition. For example, word frequency has been established to affect the activation of lexical candidates (e.g. Forster & Davis, 1984), where more frequently used words are recognised more quickly than less frequent words. Moreover, words with high-frequency neighbours are responded to more *slowly* than words with lower-frequency neighbours, suggesting that higher-frequency words are more active during word recognition and thus have a greater inhibitory effect on phonologically overlapping words in their cohort (e.g. Marslen-Wilson, 1987). It has also been observed that the meanings of the multiple words in the word-initial cohort can be activated. These data come from cross-modal priming studies in which lexical decision responses to /kæpt/, for example, were equally facilitated by the visual presentation of the semantically related *guard* (consistent with /kæptɪv/) and *ship* (consistent with /kæptɪn/), suggesting that semantic correlates of lexical candidates are activated in parallel during word recognition (Marslen-Wilson, 1987; Zwitserlood, 1989). These findings are consistent with the proposal that word recognition combines a bottom-up analysis of the speech input with a top-down influence from stored lexical knowledge (such as word frequency and semantics).

Computational instantiations of the Cohort model extended these behavioural findings to provide an architecture and processing mechanism for the activation of multiple word candidates. In the Distributed Cohort Model (DCM; Gaskell & Marslen-Wilson, 1997) lexical knowledge is represented on a single distributed layer of units, which encode information about the phonological form and meaning of words (Figure 2). A lexical representation consists of a specific pattern of activation of units across the phonological and semantic output units. In the DCM, the speech input is first mapped onto a set of units representing phonetic features, which feedforward to a layer of hidden units; these hidden units have recurrent connections with context units to model the short-term store of the ongoing speech input in phonological short term memory. The hidden units then have feedforward connections onto the single representational output layer encoding phonological and semantic information. Word recognition corresponds to a stable pattern of activation across the representational output layer, which matches a (stored) lexical representation; in the DCM, a lexical representation is thus modelled as a specific pattern of activity across the output units.

Importantly, the DCM was able to simulate evidence of lexical competition, the cardinal property of which is that words with more phonologically overlapping neighbours in the word-initial cohort are recognised more slowly than words with fewer phonologically overlapping neighbours (e.g. Allopenna, Magnuson, & Tannenhaus, 1998; Luce & Pisoni, 1998; Marslen-Wilson, 1987; Zwitserlood, 1989)[2]. To assess lexical competition in the DCM, Gaskell and Marslen-Wilson (1997) tested how successfully the model represented competing lexical items with different cohort sizes. This was measured as the difference between the target activation and actual activation (the root mean squared error of the difference, or RMS error), where activation corresponded to setting the value of the units in the distributed output layer. The difference between the target activation and actual activation of these units increased with an increase in cohort size (that is, the size of the RMS error increased), suggesting the model could not distinguish cohort members from phonologically similar words in larger cohorts, but could successfully do for words in so in smaller cohorts. The DCM thus provided a behaviourally realistic model of spoken word recognition (see also Gaskell & Marslen-Wilson, 2002), which represented lexical knowledge as a specific pattern of stable

[2] It is noteworthy that lexical competition from phonologically overlapping neighbours is implied to be directional, whereby most models of spoken word recognition imply that onset-matched words (the word-initial cohort) compete more strongly for activation than offset-matched words (e.g. Allopenna, Magnuson, & Tanenhaus, 1998; Gaskell & Marslen-Wilson, 1997; Marslen-Wilson, 1987). Such an assumption is consistent with the notion that spoken word recognition proceeds in a time-dependent manner, in which fewer words are compatible with the speech input as it unfolds and fewer lexical candidates are engaged in competition (this view is particularly instantiated in the Cohort model). Models such as TRACE (McClelland & Elman, 1986) and Shortlist (Norris, 1994) incorporate lexical competition for overlapping words in general, including offset-matched words (e.g. Luce & Pisoni, 1998; McQueen, Norris, & Cutler, 1995; Norris, McQueen, & Cutler, 1994), but nonetheless suggest that the speed of word recognition is most strongly determined by onset-matched words.

activation across a distributed set of output units.

An influential alternative model is the TRACE model of spoken word recognition (McClelland & Elman, 1986). TRACE has an interactive architecture whereby different sources of information can interact to influence word recognition. Whilst the DCM does not have a hierarchical structure and has a feedforward flow of information, the architecture of TRACE is interactive and hierarchical, with an explicit ordering of information types. The TRACE model consists of units organized into three layers: *feature*, *phoneme* and *word* levels (Figure 3). Each layer consists of processing units (for phonetic features, phonemes, and words, respectively) which represent the possibility of the presence of a particular linguistic feature in the unfolding speech signal at a particular point in time, based on the overall activation across each of the three levels. There are bidirectional excitatory connections between levels, and inhibitory connections within each level. At the phonetic *feature* level, seven sets of feature detectors code for the different dimensions of speech sounds, and these sets are replicated for each of several successive moments as the spoken word unfolds in time. The phonetic feature units have mutually excitatory connections with units at the *phoneme* level, whereby a set of features corresponds to a particular phoneme. The phoneme level consists of detectors for fifteen phonemes, whereby these phoneme detectors have inhibitory connections between each other, with excitatory connections between both the feature and word levels. The *word* level consists of detectors for each word, in which the activation of each detector represents a hypothesis about word identity. Word units receive excitatory input from their corresponding phoneme units at the phoneme level. Critically, however, the model includes inhibitory connections between words; this means the word units activated by the phoneme level input mutually inhibit each other. Word recognition in TRACE manifests as the maximal activation of a unit at the word level, whereby this maximal activation is constrained by both bottom-up input from the phoneme level and intra-level inhibition with other units at the word level.

Evidence for this word level competition in TRACE comes from the established finding that words with more neighbours are recognised more slowly than words with fewer neighbours, suggested to be due to a higher level of inhibition from competing words with phonological overlap (e.g. Luce & Pisoni, 1998; Marslen-Wilson, 1987; Zwitserlood, 1989). The hierarchical structure of TRACE and existence of a pre-lexical phoneme level has been supported by findings suggesting a lexical influence on speech perception, such as the Ganong effect described above (e.g. Davis et al., 2005; Ganong, 1980; Kraljic & Samuel, 2005; McQueen et al., 2006; Norris et al., 2003; Samuel, 2001). Conversely, whilst the DCM lacks any pre-lexical integration of phonological knowledge, it can better account for data suggesting the parallel activation of meaning for multiple cohort members which are consistent with the speech input at a given point in time (e.g. Zwitserlood, 1989). Note, however, that the existence of a pre-lexical level is relatively controversial (for example, cf. Marslen-Wilson & Warren, 1994; McClelland et al., 2006; McQueen et al., 2006). Rather than making a theoretical commitment regarding any pre-lexical level, the key point regarding TRACE and DCM is the presence of competition between multiple lexical candidates evoked by the speech input, whereby multiple sources of information are integrated to hypothesise about the most likely lexical candidate for spoken word recognition (but see also McQueen et al., 2006, for an alternative account of these findings).

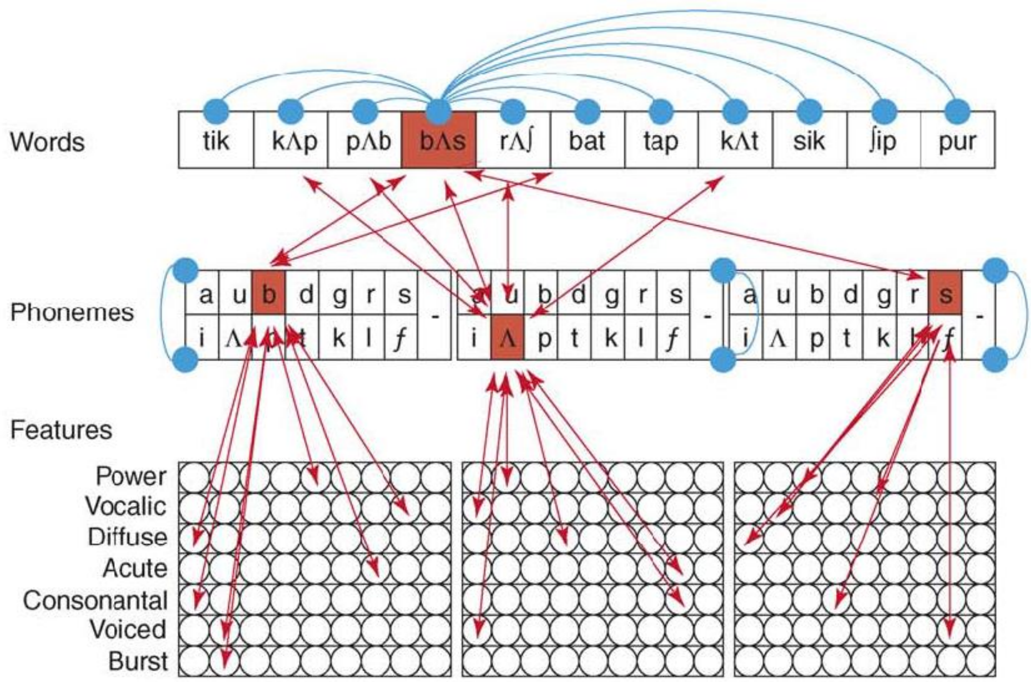

Figure 3. The TRACE model of spoken word recognition.

Note that TRACE (McClelland & Elman, 1986) differs from the Distributed Cohort Model (Gaskell & Marslen-Wilson, 1997) primarily by a) an explicit ordering of feature, phoneme, and word levels of representation, b) interactive information flow between each level, whereas information flow in the DCM is feedforward only, c) a pre-lexical representation of phonological knowledge at the phoneme level, whereas the DCM models selective access to phonology as partial activation of the distributed output units, and d) word-level/ lexical knowledge consisting of localist representations with mutually inhibitory connections, where the DCM models lexical knowledge as the blend of activation across the distributed output units. Figure from McClelland, Mirman, and Holt (2006).

In sum, the above data and models firstly suggest two complementary ways of thinking about lexical representations. A lexical representation can be considered a stored representation of knowledge about a word which influences the recognition of related phonological and semantic knowledge. Secondly, it is evident that word recognition is an interactive and competitive process, where interaction can be between phonological and lexical-level knowledge (as in TRACE, McClelland & Elman, 1986) or between the relative activation of phonological and semantic knowledge (as in DCM, Gaskell & Marslen-Wilson, 1997). These models of spoken word recognition thus provide a framework for considering what it means to establish a new lexical representation in the language system.

1.4 Adding a new unit to the language system

From the above models of spoken word recognition a case can be made for delineating between new phonological knowledge of a spoken word form, and the engagement of this phonological knowledge in competition. Such a distinction between the acquisition of new word representations, and the *interaction* between new and existing representations, was operationalized by Leach and Samuel (2007) in terms of what they referred to as 'lexical configuration' and 'lexical engagement'. Lexical configuration referred to factual knowledge about a word form (such as its phonology, orthographic form and meaning), whilst lexical engagement referred to a new word interacting with existing lexical knowledge. As described above, a prime example of lexical engagement is the lexical competition process, in which multiple lexical candidates activated by the input compete with each other during word recognition, resulting in slower recognition latencies for words in high-competition cohorts. Both TRACE (McClelland & Elman, 1986) and the DCM (Gaskell & Marslen-Wilson, 1997) incorporate a) a representation of the phonological forms of words, and b) a mechanism for competition between these representations during spoken word recognition. It is thus possible to distinguish between phonological knowledge and the engagement this phonological knowledge in competition within the framework of these models.

Recall that in the architecture of TRACE the speech input is first mapped onto feature units which feedforward to the phoneme level, which maps onto representations of known words at the word level. At the word level, each word unit has mutually inhibitory connections with other word units, and this inhibition mechanism simulates slower recognition speed for words in larger cohorts. A novel spoken word can thus be mapped onto the feature level, which will feed into phonemes at the phoneme level accordingly; however, as this novel word would have no corresponding unit of representation at the word level, no word unit would be activated after the phoneme level. Because maximal activation of a unit at the word level corresponds to word recognition, and each unit at the word level has inhibitory links with phonologically overlapping word units, this implies that learning a new word requires establishing a new unit at the word level which has inhibitory connections with existing word units, and thus engages in lexical competition during word recognition. The engagement of a new word in lexical competition would therefore mean that a) other lexical items would affect the recognition of the new word, and b) the new word could impact on the recognition of existing words (Gaskell & Dumay, 2003).

Within the architecture and processing mechanism of TRACE it is thus possible to distinguish between a word having a *phonological* representation and a *lexical* representation. The core property of a *lexical* representation may be its engagement in lexical competition, and within TRACE a lexical representation could therefore consist of a new unit at the word level, with mutually inhibitory connections within this level. A representation of *phonological* knowledge of a new word is less clearly defined. In TRACE, one possibility is that phonological knowledge of a novel word may either correspond to activation at the phoneme level only, or be a weakly established unit at the word level *without* inhibitory connections with other units at that level. The critical point is thus that phonological knowledge can engage a phoneme or word-level representation but *without* any inhibitory connections to other words, whereas a lexical representation has established a new word-level unit *with* inhibitory connections that can affect the processing of other words during recognition. The development of inhibitory connections with existing words being a key property of lexical representations is supported by a growing body of evidence, which suggests that new words often do not establish these inhibitory connections immediately after learning but rather require time (e.g. Davis et al., 2009; Dumay & Gaskell, 2007; Dumay & Gaskell, 2012). For example, Dumay and Gaskell (2007) found that exposure to new spoken words resulted in high recognition immediately after learning (~88%), but did not slow down processing of existing words until after a night of sleep. This evidence will be discussed comprehensively in the following chapters, but is concurrent with the idea that phonological knowledge of a new word is accessible immediately, and distinct from the slower development of a lexical representation which engages in competition.

In the DCM (Gaskell & Marslen-Wilson, 1997) recall that a lexical representation is modelled as a specific pattern of activation across the output layer, which consists of units representing phonological and semantic knowledge. Because phonological form perception occurs in parallel with semantic access, the DCM provides a single basis for the representation of both known words and novel words. One of the key principles of the DCM is thus that it models the *retrieval* of phonological and semantic knowledge, where word recognition is a by-product of phonological form perception and semantic access occurring in parallel, rather than an explicit aim of this process. Gaskell and Marslen-Wilson (1997) therefore suggested that the difference between the perception of words and nonwords is in the types of information available during the retrieval process and the activation of the distributed output units as a result. Phonological, semantic and syntactic information can be accessed for a known word, whilst nonwords can access the same representational layer but with the retrieval of only phonological information. Nonword perception is therefore modelled as *partial* activation of the representational output layer, whereby this activation does not correspond to a stored lexical representation (that is, a specific pattern of activation across the output units). This would therefore suggest that, within the context of the DCM, learning a new word requires learning a new pattern of activation across these output units.

However, the retrieval of phonological and semantic information in the DCM also incorporates lexical competition (Gaskell & Marslen-Wilson, 1997; Gaskell & Marslen-Wilson, 2002). This again suggests that for a novel word to become like a known word it must engage in lexical competition, by slowing down the recognition of existing items. Because word recognition is the by-product of the activation of phonological and semantic information on the distributed layer, this implies that a newly-trained novel word can be recognised via a phonological representation, without necessarily having a complete representation which engages in competition. The single distributed representational layer in the DCM further suggests that a phonological representation of a new word (the activation of phonological output units, without any engagement in lexical competition) and lexical representation (the activation of phonological and potentially semantic output units, with an engagement in lexical competition) may be along a continuum of the activation level of the output units.

In sum, in terms of models of spoken word recognition at least, it seems that adding a new word to the language system requires establishing a new word unit with mutually inhibitory connections with other word units (TRACE), or a specific pattern of activation across a distributed set of units (DCM) corresponding to a representation which can reduce the ease of recognition for phonologically overlapping words. Whilst both models differ in their architecture and means of characterising lexical knowledge, the important commonality is the distinction between a representation of phonological knowledge (i.e. allowing the recognition of a newly-trained novel word from a phonologically similar untrained word) and the engagement of this new phonological representation in lexical competition (i.e. slowing the recognition of phonologically overlapping existing words)[3].

1.5 Memory systems and word learning

In parallel with what it means to learn a new word in terms of models of spoken word recognition, a central consideration is the memory systems involved in this process. Memory can be understood in terms of three temporally related processes of encoding, consolidation and retrieval (e.g. Diekelmann, Wilhelm, & Born, 2009). Encoding refers to the acquisition of new knowledge (such as exposure to a new word); consolidation is the process whereby these memories are strengthened and integrated with existing knowledge; retrieval is then the successful recall of these memories. The functional structure of memory can be understood by delineation into meaningful subsystems, the most established of which is the distinction between declarative and non-declarative memory (Squire & Zola, 1996; Tulving, 1985), as shown in Figure 4.

Declarative memory can be considered memory which can be consciously accessed and articulated, and is thus a form of *explicit* memory. It can be further delineated into episodic and semantic memory. Episodic memory constitutes knowledge or experiences which have a specific context associated with them, such as a spatial or temporal context (Tulving, 1985). Conversely, semantic memory is a form of memory which can be explicitly recalled, such as a conceptual knowledge of objects, places and events and the relationship between them, but is free of any associated context. An example of episodic memory would be recalling that you learnt the French word for jam, *confiture*, whilst ordering a croissant in Paris on holiday; an example of semantic

[3] An additional consideration here concerns the different characterisation of lexical knowledge in these models. The presence of word-level units in TRACE implies that learning of a new word form requires adding a distinct word-level entry with inhibitory connections to other lexical entries. Conversely, the distributed representation layer in DCM implies that the learning of a new word form involves the *reorganisation* of existing phonological representations on this distributed layer, rather than the *addition* of a new unit per se. However, the critical commonality is that such engagement of a new phonological form should exert an observable effect on the behaviour of existing phonological forms during recognition.

memory would be knowing that Paris is the capital of France, but not recalling how or when you acquired that knowledge. The neural basis of declarative memory formation is understood to be dependent on medial temporal lobe structures, and the hippocampus in particular (e.g. Eichenbaum, 2000). Conversely, non-declarative memory encapsulates knowledge that is regarded as non-conscious, such as procedural memory (Squire & Zola, 1996), and is thus a more *implicit* form of memory (for example, knowing how to ride a bike). The encoding of non-declarative memory is considered less dependent on medial temporal lobe structures (e.g. Walker & Stickgold, 2004). Whilst this declarative and non-declarative distinction is useful, it is important to recognise that these memory systems are often used in parallel; a prime example of this is in language use and word learning.

Knowledge of existing words draws on both declarative semantic memory, and non-declarative aspects of memory such as procedural skill. For example, whilst knowing that Paris is the capital of France is a form of semantic memory, being able to articulate /pærɪs/ in speech is a non-declarative procedural skill; the use of *Paris* in a sentence similarly requires non-declarative memory of grammatical rules. Correspondingly, learning a new word initially engages the declarative episodic memory system, and the hippocampus in particular. Evidence for this comes from a body of studies implicating the hippocampus during the encoding of novel words (e.g. Breitenstein et al., 2005; Davis et al., 2009.; Takashima et al., 2006; Takashima et al., 2014), with the magnitude of the hippocampal response being positively correlated with word learning ability (e.g. Breitenstein et al., 2005). A large body of adult word learning literature also suggests that whilst factual knowledge about new words (such as their form and meaning) can be rapidly acquired, these early representations require more time or training to have the same degree of automaticity of processing as known words, in tasks of non-declarative

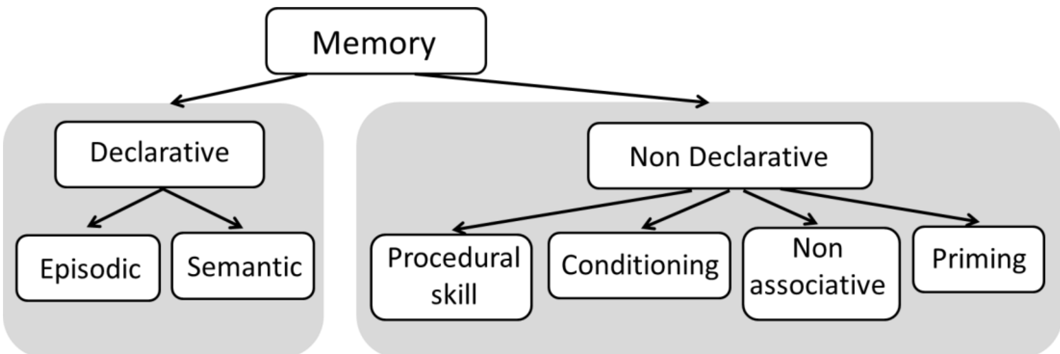

Figure 4. The categorisation of human memory into declarative and non-declarative subsystems. This figure is adapted from Walker and Stickgold (2004).

memory such as priming; this literature will be reviewed in Chapter 2. Moreover, there is an emerging field of evidence suggesting that newly-learnt words can be transferred from an episodic mode of representation, mediated by the hippocampus, to a neocortical representation which is *abstracted* from the episodic context in which it was learnt. Importantly, this process occurs during the consolidation stage of memory formation; this literature will be reviewed in Chapter 3. One suggested mechanism for this consolidation process is to transform the initial episodic memory representation such that it becomes redistributed over the memory network, and consolidated words may thus draw on the semantic and non-declarative memory subsystems. Likewise, the processing of known words thus draws on semantic and non-declarative memory, with almost no reliance on episodic memory. Understanding the learning of new words therefore critically requires understanding how they are transferred from an episodic memory store to representation by non-episodic memory systems.

To return to word learning in the context of models of spoken word recognition, the relationship between memory systems suggests two key points. The first of these is that for a representation of *phonological knowledge*, whereby a newly-trained word can be recognised but without engaging in lexical competition, an episodic mode of representation is sufficient (although note that different test tasks may also draw on non-declarative memory, such as in shadowing or priming tasks). The second and most interesting point is that for a new phonological form to establish a new lexical representation, such that it engages in lexical competition through inhibitory connections with other words (TRACE; McClelland & Elman, 1986) or a specific pattern of activation which interferes with the recognition of existing lexical representations (DCM; Gaskell & Marslen-Wilson, 1997), non-episodic memory systems seem to be required. This suggests that the integration of new with existing words may involve distinct stages of word memory formation, which draw on specific memory subsystems.

1.6 Conclusions and themes of this thesis

In considering what is required to add a new word to the language system, models and data from spoken word recognition suggest a distinction between learning new phonological knowledge of a word, and this word engaging in lexical competition. It is also clear from behavioural studies that newly-learnt words can be recognised at above-chance levels without engaging in lexical competition; rather, new words often require a period of time before slowing down the recognition of existing words, a finding which has been widely replicated (e.g. Davis et al., 2009; Dumay & Gaskell, 2012; Gaskell

& Dumay, 2003; Takashima et al., 2014). It therefore seems possible to have familiarity with the phonological forms of new words, in terms of distinguishing them from phonologically similar untrained items, but that these new words do not slow down response latencies to phonological neighbours (suggesting no lexical competition) until a later point in time under most circumstances. In terms of the above models of spoken word recognition, for a new word to have a *phonological* representation, it may therefore a) activate the phoneme level, or be weakly represented at the word level but without inhibitory connections (TRACE), or b) activate phonological units on the distributed representational output layer, but not have established a specific pattern of activation across the output units which is involved in lexical competition (the DCM). This thesis is therefore working within a framework in which a *phonological representation* refers to familiarity with and recognition of a novel phonological form, whereas a *lexical representation* is a new phonological representation which can compete with existing words during recognition, and thus interact with existing lexical knowledge. The process of moving from a phonological representation of a new word to a lexical representation which competes with existing words during the online process of spoken word recognition is thus referred to as *lexicalization*.

This thesis is concerned with how we add a new unit to the language system, and the overarching question posed is how a new word establishes a lexical representation. This broad research question can be segregated into two main themes. The first theme is how the knowledge acquired during the acquisition of novel words impacts upon earlier and later stages of word memory formation; this will be investigated in terms of the acquisition of semantic knowledge. The second theme concerns the role of offline memory consolidation, and the factors that influence the time-course and success of the lexicalization process. The following two chapters thus review the relevant literature for these issues. Chapter 2 reviews the literature on adult word learning and what factors impact on the acquisition of new word knowledge, whilst Chapter 3 reviews the memory consolidation literature with specific reference to word learning.

Chapter 2: Novel word learning in adulthood

2.1 Introduction

Whilst learning new words is an ability often associated with children (Bloom, 2001) there is now a strong foundation of empirical evidence to indicate that adults are also proficient word learners. In recent years a theoretical framework has emerged suggesting that factual knowledge about a novel word form and meaning can be rapidly acquired (Leach & Samuel, 2007), and that a longer period of time is often required for new words and meanings to engage with existing stores of knowledge (Davis & Gaskell, 2009). The different time-courses of these two aspects of word memory formation – the relatively quick acquisition of knowledge about the form and meaning of a new word, and the slower lexicalization of this new word knowledge such that it engages in lexical competition – have been primarily understood in terms of the acquisition of new phonological forms or meanings separately (e.g. Gaskell & Dumay, 2003; Dumay & Gaskell, 2007; Tamminen & Gaskell, 2013), with less investigation of the interaction between meaning acquisition and the lexicalization process for new words (Dumay, Gaskell, & Feng, 2004; Takashima et al., 2014). It thus remains less well understood how the acquisition of meaning may impact upon both the formation of new phonological form representations relatively early in learning, and what the consequences of this may be for the slower lexicalization of these new forms. As such, whilst the time-course of both spoken word learning and meaning acquisition have now been investigated, understanding any semantic impact on the time-course of spoken word learning remains relatively underexplored.

The following chapter will thus first review the adult word learning literature pertaining to the immediate learning of phonological and semantic knowledge about new words, and address what factors are currently understood to influence this process. The immediate learning of new words is defined as knowledge about new words directly after training, before any period of offline consolidation. Whilst some of the below studies incorporate testing delays (e.g. to assess the stability of new word representations one week after training), they do not partial out the effect of consolidation from effects such as repeated testing, and are thus on the whole interpreted in terms of the acquisition of factual knowledge about new words.

2.2 Learning the form and meaning of novel words

2.2.1 Immediate learning of new word forms

The acquisition of knowledge about new spoken and written words can occur rapidly. To assess whether a novel word has acquired a representation akin to known words it is helpful to test for characteristic behaviours of existing lexical items. One such behaviour is the word superiority effect, in which letters within known words are identified more quickly than letters within nonwords (Reicher, 1969; Wheeler, 1970). An early demonstration to suggest that novel words could develop such a representation quickly was from Salasoo et al. (1985). Training consisted of the presentation of existing and novel written words, followed by a mask. Participants' task was to identify what was presented, and in this perceptual identification task it was predicted that existing words should be identified more quickly and with a higher accuracy than novel words, showing a word superiority effect. Interestingly, whilst this was initially the case it was observed that after six exposures to the novel words participants' identification speed for the novel words matched that of the existing words, and this performance was stable over one week of training. Salasoo et al. (1985) interpreted this result as the process of 'codification', whereby the novel words rapidly developed a 'code' corresponding to a lexical representation. Strikingly, in a test one year later the novel words continued to be identified as quickly as the real words. Whilst these data do not address whether the novel words had fully acquired the properties of existing words in terms of engaging in lexical competition, it does suggest that the novel words could quickly develop a representation that could facilitate their identification speed, such that performance was comparable to that of existing words and stable over one year with no additional training.

Another method used to measure whether novel words have attained a word-like status is masked repetition priming. In the masked repetition priming paradigm a target in a task (e.g. lexical decision, reading aloud, or semantic categorisation) is preceded by a prime that is both pre and post-masked. Forster and Davis (1984) used masked repetition priming in a lexical decision task in which participants were required to report whether the target was a real word or not, and the prime could either match or not match the identity of the target word. They found that masked repetition priming facilitated faster responses for known words but not for unfamiliar novel words, and masked repetition priming was thus interpreted as a lexically-driven effect, as nonwords do not reliably lead to such priming. One possibility was then that if novel words have achieved a lexical status similar to known words, the responses to novel words should be facilitated to an equivalent degree to known words in a masked repetition priming task.

Forster (1985) tested this by asking whether novel written word targets could come to be primed in a masked repetition priming task. The novel words were obsolete real words (e.g. *holimonth*), and initially acted like nonwords in producing no identity priming effect. However, after participants were trained on the meanings of these words and, critically, were instructed to treat them like real words, masked repetition priming facilitated responses to the novel words. Rajaram and Neely (1992) extended these results by training participants on novel words on either an intentional learning task or incidental learning task. They observed that prior exposure to novel words from both learning tasks could result in masked repetition priming of the novel words, although interestingly the magnitude of the priming effect was greater for words learnt in the intentional learning task. Given that masked priming is generally considered to reflect automatic processes, from these findings it could be inferred that very little training is required for the identification and activation of newly-learnt words to behave in an automatic way akin to known words.

Whilst the word superiority effect in perceptual identification and the fact that nonwords do not reliably elicit priming in masked repetition priming means that these results are informative about novel words acquiring some similar properties to known words, these rapidly formed representations may not have the same precision or automaticity of processing as real words. At least for the skilled, speeded orthographic processing of newly-learnt written words, it is possible more extensive training is required. In a study by McCandliss, Posner, and Givon (1997) participants learnt novel words over the course of five weeks, on tasks associating written words with pictures. The test of new word knowledge was a task in which participants categorised pairs of letter strings, briefly presented one after the other, as the same or different. Due to the brief presentation time and similarity of the letter strings, a high level of accuracy on this task required more precise orthographic representations than the perceptual identification or masked repetition priming tasks. After five weeks of training participants categorised the trained novel words more quickly than untrained words, with accuracy and response speed approaching that for known words. Because this test was potentially more demanding on well-specified orthographic representations than those of Salasoo et al. (1985), Forster and Davis (1984) and Forster (1985), it suggests that the skilled orthographic processing of novel written words may require more extensive practice or time than these previous studies would suggest.

For spoken word learning there is evidence that exposure to both novel words and existing words can also lead to faster processing at a later point in time, from long-term auditory repetition priming studies. Church and Schacter (1994) trained participants on novel spoken words. Implicit and explicit knowledge of the trained words was tested several weeks later on tasks of word identification and stem completion, with identity priming of the target novel word. When the test stimuli were acoustically identical to the training phase there was significant identity priming of the novel words, and this faster processing for the novel words after a single training session suggested that limited training could lead to a stable phonological representation. Crucially, however, Church and Schacter (1994) found that when the training and test items differed acoustically (in terms of a speaker change, fundamental frequency or intonation change) there was a significant reduction in the magnitude of priming effect in the identification and stem completion tasks. This suggested that the novel spoken words were priming episodic phonological representations of the new words, suggesting the underlying representations were not yet abstracted from the surface detail of the speech. However, acoustic changes between training and test did not consistently impair explicit recognition and recall, suggesting that explicit knowledge of the novel words was more robust. Church and Fisher (1998) further found this long-term auditory priming for existing words in 2-3 year-olds, which reinforced the possibility that a fast phonological encoding ability could be a word-learning mechanism throughout the lifespan.

In sum, the above findings suggest that adults can rapidly acquire a degree of knowledge about both written and spoken novel words, and these representations can behave in a similar way to known words in terms of priming when tested after a range of time delays. However, given that these novel word representations seem to be both underspecified (e.g. McCandliss et al., 1997) and sensitive to acoustic differences between training and test (Church & Schacter, 1994) a key question is the degree to which these early novel word representations are episodic in nature (e.g. Goldinger, 1996) or constitute non-episodic lexical representations.

Evidence to suggest that novel word representations have a lexical basis from a few instances of training comes from studies examining the ability of recently-learnt novel words trained in one modality to act as primes for novel words presented in the other modality. Johnston, McKague, and Pratt (2004) tested this by asking whether the phonological representations of newly-learnt spoken words could generalise to orthographic representations to produce masked repetition priming. This tested two properties of non-episodic lexical representations: the ability of novel word representations trained in one modality to generalise to an untrained modality, and whether representations in this untrained modality can facilitate masked repetition priming, which is elicited for words but not for nonwords. Johnston et al. (2004) taught participants novel spoken words along with definitions, and tested participants on a priming task with orthographic representations of the newly-learnt words. Because the prime words were orthographic (in the visual modality) and the targets were spoken words (in the auditory modality), the priming task was crossmodal; this tested whether the trained spoken words had developed (untrained) orthographic representations which could prime the trained spoken words. Crossmodal masked repetition priming was present, whereby the novel spoken words primed by their orthographic form were responded to more quickly than novel words not preceded by their orthographic form. However, the new orthographic representations were underspecified: orthographic primes which differed from the spoken word target by up to two letters were able to facilitate responses, and this effect was not observed with real words. The findings of Johnston et al. (2004) thus indicate that phonological training can give rise to orthographic representations able to enter into crossmodal priming immediately after training, but that these orthographic representations may be underspecified compared to real words. As Johnston et al. (2004) did not include an auditory priming condition to test the specificity of the trained *phonological* forms, it is possible that this orthographic underspecification could reflect a general property of the new word representations being underspecified, rather than being specific to the transfer to a different modality. However, given the findings of McCandliss et al. (1997) suggesting several training sessions over time are required for specified orthographic representations, it is possible the orthographic underspecification of Johnston et al. (2004) could be a property both of the crossmodal transfer and additional time and/or training required to establish representations as highly specified as real words.

The evidence reviewed thus far suggests that knowledge about novel words can be rapidly acquired, but further training and time may be required for these new representations to have the same orthographic specification and phonological stability of known words. Notably, these studies are all relatively simple learning circumstances in which individually presented novel words are learnt. In real-world learning situations the learner is rarely presented with new words in such a pared-down context; the next question to address is thus what success adults have learning words in more demanding paradigms.

A more challenging task comes from the word segmentation literature, in which participants are required to acquire novel words through the segmentation of a continuous speech stream via statistical learning of phoneme co-occurrences as indicators of word boundaries. Saffran, Newport, and Aslin (1996) used this task to train adult participants on six novel words which were phonologically legal but phonologically unrelated to existing words (e.g. *babupu*). Participants heard these words in a continuous speech stream in which the cue to word segmentation was syllable co-occurrence probability (e.g. the final syllable of one word and first syllable of the following word co-occurred infrequently). In a two-alternative forced-choice recognition task immediately after training participants were able to discriminate between the novel words from the speech stream and foils generated using the same syllables, and this above-chance performance persisted when the foils differed from the trained items by only one syllable. Although the 2AFC task may be prone to ceiling effects, these findings suggest that adults can successfully acquire explicit knowledge of new spoken words from a word segmentation task. Furthermore, Saffran, Aslin, and Newport (1996) observed that 8-month-olds possessed the same statistical learning mechanism, suggesting that it could also be present across the lifespan. Fernandes, Kolinsky, and Ventura (2009) and Szmalec, Page, and Duyck (2012) further trained adult participants on novel words in a continuous syllable stream and observed that they could be recognised from similar foils immediately after training; however, as these two studies primarily concern lexical consolidation they will be discussed in more detail in the next chapter.

These data thus provide evidence suggesting that adults can learn novel phonological forms from a continuous speech stream in implicit statistical learning paradigms. These findings raise a similar issue to findings obtained from word learning in isolation, however: whether the representations established from this learning paradigm are primarily episodic in nature, particularly as the 2AFC and recognition test tasks require declarative memory. Dahan and Brent (1999) suggested that lexical representations were not necessary for successful performance on recognition and lexical decision tasks, and that these tests of word knowledge could be performed on episodic knowledge alone, particularly as these test tasks required an explicit metalinguistic judgement. They proposed the INCDROP model in which learning mechanisms for word segmentation were based on knowledge of existing words rather than statistical learning: novel words could be segmented from speech by recognising known words as familiar units, and subsequently treating the leftover sequences as novel words to be learnt. Although both bottom-up statistical learning and top-down lexical segmentation mechanisms have been suggested to facilitate word learning from a continuous speech stream in both children and adults (Cunillera, Camara, Laine, & Rodriguez-Fornells, 2010), it is difficult to see how an episodic mechanism of this kind could account for the Saffran et al. (1996) findings, because the speech stream contained entirely novel sequences.

However, a means of probing new word representations without recourse to declarative memory is with event-related potentials (ERPs), which provide an implicit measure of the online processing of a stimulus. For example, Sanders, Newport, and Neville (2002) measured the ERPs evoked to speech streams of novel words before and after a learning phase in which participants explicitly learnt the novel words. Sanders et al. (2002) were specifically looking at the N100 elicited by novel word onsets as a marker of listeners segmenting novel words from the speech stream, whereby the N100 is an ERP component elicited approximately 100ms after stimulus onset, with its magnitude reflecting the predictability of a stimulus. In continuous speech the N100 was found to be larger in response to word onsets than when ERPs were measured in response to later word syllables, and was thus interpreted as an electrophysiological marker of speech segmentation (Sanders & Neville, 2003). Interestingly, Sanders et al. (2002) observed that the N100 magnitude for novel word onsets was larger after training than before training, but only for participants with above-chance accuracy in the behavioural recognition test. This rapid acquisition of an ERP signature of novel word learning is also possible for items with a high degree of phonological overlap with existing words: Shtyrov, Nikulin, and Pulvermüller (2010) exposed participants to a continuous stream of known words interspersed with novel words which were minimal pairs of existing words (such as *pipe-pite*) in an auditory oddball task. The measure of novel word learning was the mismatch-negativity (MMN), a measure of change detection that is elicited after the recognition point of a word if it is discriminated from the baseline stream of known words. After 160 exposures to the novel words in this oddball task (14 minutes of exposure) the novel words elicited an MMN that was statistically indistinguishable from the magnitude of the MMN elicited by known words. Similar to Sanders et al. (2002), Shtyrov et al. (2010) thus suggested that novel spoken words could rapidly acquire new phonological representations.

Overall, the above studies suggest that adults can acquire new orthographic and phonological representations after a single training session, and continue to do so under more challenging learning conditions. It nonetheless seems that these representations acquired in a single training session are underspecified in the case of orthographic word learning (e.g. Johnston et al., 2004; McCandliss et al., 1997), in terms of novel word primes differing by two letters from a target novel word eliciting a priming effect of similar magnitude to identity priming, an effect not observed with real words. For spoken word learning, after a single training session new words are also not stable under a range of acoustic differences between training and test (e.g. Church & Schachter, 1994), whereas this acoustic sensitivity is not observed for known words. Accordingly, it is an important question whether further specification and stability of these early representations is a precursor to, or part of, the full lexicalization process for these new phonological and orthographic forms to engage in lexical competition with existing words. Whilst these low-level representations may remarkably have a degree of stability over long intervals between training and test (e.g. Salasoo et al., 1985), it is unclear to what extent this immediate learning of new word form knowledge impacts upon the lexicalization process. This question will be returned to in the next chapter; the following section first turns to how adults acquire knowledge of new word meanings.

2.2.2 Immediate learning of new word meanings

The acquisition of word meaning involves the mapping of specific phonological and/or orthographic representations onto concepts. Church and Fisher (1998) suggested that in the case of children, the development of phonological representations must at least partially occur before acquiring meaning, due to the necessity of identifying cross-situational uses of a word for mapping its corresponding meaning. However, children are able to acquire knowledge of word meanings at a similar pace to word forms (e.g. Bloom, 2001); given the speed of word form learning in adults it is therefore a key question whether knowledge of new word meanings can also be established as efficiently.

Early semantic learning studies aimed to teach participants associative links between unrelated word pairs, and hypothesised this associative link should then lead to priming whereby one word of the pair facilitated responses to the other target word. Neely (1977) used these pairings of familiar words to train participants on arbitrary associations. In the test phase priming was present at longer prime durations; however, there was no priming effect at shorter prime durations, when any activation of associative links would be more automatic. Data from Pecher and Raaijmakers (1999) suggested that additional training and/or time was required for this kind of arbitrary associative learning: after participants learnt unrelated existing word pairs 11 times per day over three days, priming was observed at a 40ms prime duration. Similarly, Dagenbach, Horst, and Carr (1990) obtained associative priming after five weeks of 15-minute training sessions on unrelated existing word pairs. This requirement of additional training and/or time to obtain associative priming at prime durations that would suggest automaticity implies that, at least in terms of associative learning, participants are unable to establish new associative links immediately.

However, it is important to recognise that this kind of arbitrary associative learning between existing words, already with their own semantic concepts, may be substantially more challenging than learning a new meaning for a new word – that is, something to be treated as a functional addition to the mental lexicon. Forster (1985) observed that unfamiliar written words only entered into masked repetition priming when participants learnt their meaning and were instructed to treat them as real words, suggesting that the meaningfulness of the learning task or task goals may play an important role in the ability to learn new word meanings. More recent studies of adult meaning acquisition have addressed this by pairing novel words with a meaning and testing knowledge of both the word and its meaning.

Gupta (2003) trained participants on novel words which corresponded to pictures of imaginary animals (Experiment 1) or cartoon drawings of aliens (Experiment 2). The test of learning was for participants to name the pictures. This task therefore required both the recall of the words, and correct mapping of these names to the pictures from the training task. Accuracy on this task indicated participants had acquired the names, with 78% of pictures named accurately for the imaginary animals and 46% of the cartoon aliens named correctly. The main goal of the two experiments was to test for a correlation between this referent learning ability (referred to as ‘word learning’), nonword repetition, and immediate serial recall. A positive correlation was found both between naming accuracy and nonword repetition, and between naming accuracy and immediate serial recall. From these data Gupta (2003) suggested that more accurate nonword repetition supported more accurate learning of referents and names (similar findings were obtained by Baddeley, Gathercole, & Papagno, 1998). In a similar paradigm, Breitenstein and Knecht (2002) trained participants on associations between novel spoken words and line drawings of existing objects (e.g. *enas* corresponding to a line drawing of a tree). Participants had to respond as to whether the novel word-object pairing was correct or incorrect, and learnt the associations through cross-trial co-occurrences of novel words with their 'correct' drawings occurring more frequently than with 'incorrect' drawings; no feedback was provided during training. After one training session per day over five days participants learnt 90% of the novel word-object pairings correctly, based on the percentage of correct responses in the learning task. This level of performance stayed constant at follow-up training sessions one week and one month later, suggesting that participants were able to retain the novel words and associated meanings over a longer time period.

The studies of Gupta (2003) and Breitenstein and Knecht (2002) suggest that adult learners can quickly acquire explicit knowledge about novel words and their meanings, and that this explicit knowledge can be reliable up to one month after initial training. An interesting related question concerns whether participants can learn new meanings for existing words. The ability to update existing word representations with a new semantic meaning is a skill often required throughout the lifespan. For example, an instance given by Rodd et al. (2012) is in recent years learning that '*tweet'* is not only the sound made by a small bird but also a posting made on a social networking site. The acquisition of new meanings for existing lexical items was therefore probed by Rodd et al. (2012) across three experiments, in which the key question was whether it was easier to acquire new meanings related to the original meaning of the word than unrelated meanings (the relatedness effect). Participants learnt new meanings by reading paragraphs that contained uses of existing words with a dominant meaning (e.g. "ant") in contexts indicating an additional meaning. The new meaning could either be related to the dominant meaning of the word or unrelated. Explicit knowledge of the meanings was tested in a cued-recall task, and the online processing of the existing words was tested in a lexical decision task which assessed the implicit knowledge of the new meanings and their ability to affect word recognition. In the cued-recall task, participants were presented with the word and asked to type as many properties of its new meaning as they could remember. In this task it was predicted that participants would recall more properties of word meanings for words with semantically related than unrelated meanings, based on the familiar association between the word form and its existing meaning acting as a potential retrieval cue. In the lexical decision task two hypotheses were made: firstly, a benefit also for words with a related new meaning, indexed by faster responses for words with semantically related meanings (although note that the relatedness effect extending to a lexical decision task is contentious e.g. Lupker, 2007, as cited in Rodd et al., 2012). The alternative hypothesis was that the semantic relatedness of the new meanings would not influence lexical decision performance; this was based on the interesting possibility that the acquisition of new meaning knowledge was dissociable from the subsequent longer-term integration of this knowledge with existing word representations in such a way as to affect online recognition processes. Cued recall was tested in Experiment 1, in which there was a significant relatedness effect in the ability to recall properties of the newly-learnt meanings (70% for related meanings, 26% of unrelated meanings). Training was extended across 6 days in Experiment 2, and participants were tested on the cued-recall and lexical decision tasks one day after the final training session. The same relatedness effect in cued recall was observed as in Experiment 1, but there was no relatedness effect on lexical decision response times.

To promote a relatedness effect in lexical decision responses, Experiment 3 modified the training regime such that participants both explicitly focused on learning the new meaning-word mappings, and semantically engaged with the new meanings. The cued-recall results showed more ‘correct’ responses (e.g. a response given corresponding to the new meaning) for related than unrelated words, but no effect of relatedness on the number of properties which could be recalled for each word; that is, for the words which were responded to the relatedness of their new and existing meanings did not affect the number of correct semantic properties which were recalled. In the lexical decision task, however, there was a significant effect of relatedness on reaction times, in which words trained with a related meaning were responded to more quickly than to words with unrelated meanings. These data suggest two key points: firstly, adults are able to successfully learn a new meaning for existing words with dominant meanings, although this can be more challenging when the new and existing meaning are not semantically related (from the cued recall data). Secondly, new related meanings are able to affect the online processing of existing words (Experiment 3 lexical decision data), but potentially only when there is a high level of semantic engagement with the new meanings during training: as Experiments 2 and 3 took place over similar timeframes (one week in Experiment 2, and five days in Experiment 3), it is possible that the higher level of semantic engagement during training in Experiment 3 was required for the new word meanings to influence online processing. The data of Rodd et al. (2012) do not address whether these effects are retained over time – for example, it may be the case that as the new meanings were subordinate they needed to be recently encountered to affect online word processing, or because the meanings were recently encountered they affected processing but would not do so in subsequent everyday uses of the words – but nonetheless suggest that participants can successfully acquire new meanings for existing words, and this learning can be influenced by semantic relatedness.

Finally, a related question concerning meaning acquisition is whether existing semantic representations can be updated to include novel words: that is, whether novel words with a trained meaning that matches an existing word can be acquired as names for existing semantic concepts. Dobel, Junghöfer, et al. (2009) extended the study of Breitenstein and Knecht (2002) by measuring the effect of newly-learnt words on existing semantic concepts via crossmodal priming. Dobel, Junghöfer, et al. (2009) used the same learning paradigm as Breitenstein and Knecht (2002), in which participants learnt the association between novel spoken words and pictures of existing objects via their statistical co-occurrences. The measure of the novel words being linked to existing semantic representations was the magnitude of the N400m. The N400m is an MEG response considered to reflect post-lexical semantic integration, where the N400m magnitude is reduced for semantically congruent stimuli. In the crossmodal priming task the existing object pictures used during training were preceded by a spoken word that was the existing picture name, an existing word semantically related to the existing picture name, the novel trained word as a new label for that object, or a novel word which was exposed during training but had no new meaning. The N400m was measured in response to the target picture. For the newly-learnt novel names priming condition, the N400m was significantly reduced after training relative to before training; after training, it was only the novel words with no learnt association that elicited an N400m, indicating that this effect was modulated by the acquisition of meaning and not simply exposure to word forms during training. However, the post-training N400m for the novel word primes was still significantly larger than that elicited by the existing picture names, and existing words which were semantically related to the target picture. This pattern of results suggested that the novel words had been acquired as names for existing meanings, such that they could prime the objects and reduced the N400m potential, but not to the same extent as known words. Importantly, however, whilst these data indicate learning of the mappings between the novel words and trained objects, it is possible that the priming effect with the novel words as new names was simply a case of associative rather than semantic priming, due to the target pictures being the same as those used in training rather than semantically related objects (e.g. if a *tree* was the trained object, using a *flower* as the semantically related target object in the crossmodal priming test). This is an issue which will be returned to in the next chapter.

In sum, the above studies indicate that adults, as well as children, are able to learn a) new meanings associated with novel word forms, b) new meanings for existing words, and c) new words as labels for existing meanings. This is the case both in explicit learning tasks where novel visual stimuli are overtly mapped to words, and via statistical learning of word-referent associations. There are also data suggesting that the learning of new meanings for existing words can be modulated by the semantic relationship between the existing and novel meanings, at least when the existing meaning is a single dominant one (Rodd et al., 2012). Moreover, explicit knowledge about new meanings, or novel-word meaning mappings, can also transfer to implicit effects in online word processing. The next question turned to is thus what impact this acquisition of meaning has on the learning of novel word forms.

2.3 Semantic impact on word learning

Having established that participants can learn both the form and meaning of novel words across a range of conditions, the next question is the degree to which the acquisition of the meaning of a new word impacts upon learning of the phonological form. This distinction between word form and meaning pertains to the ability to learn new word forms in the absence of meaning (for example, becoming familiar with the new phonological form *methanack*), versus learning a semantic association with this new phonological form (for example, that a *methanack* is a type of coffee maker). The critical question is how the provision of a semantic association impacts upon the recognition, retrieval and online processing of the new phonological form. Models of spoken word recognition, such as the Distributed Cohort Model (DCM; Gaskell and Marslen-Wilson, 1997) suggest a role for meaning in the recognition of existing words. As described in the previous chapter, in the DCM lexical representations are modelled as the activation of form and meaning across a distributed connectionist network. During the competitive process of word recognition, lexical activation emerges from the matching between the phonetic input of the speech signal being mapped to a phonological code, and the parallel activation of semantic codes (Marslen-Wilson, 1987; Zwitserlood, 1989). A recognition point in the speech input is reached when one lexical item is selected through the stabilisation of network activation, allowing the unique identification of a lexical item. Given this coupling between form and meaning representations in known word recognition, it is therefore important to address the consequence of meaning on acquiring new words in the first place.

2.3.1 Semantic impact on measures of word identification and recognition

An early investigation into the semantic influence on the perception of novel words came from Whittlesea and Cantwell (1987). They focused on the identification of letters in written words, which are generally easier to identify in existing words than nonwords (the word superiority effect), to test the effect of meaning on the perception of trained novel words. In the meaning condition participants learnt novel written words for concepts with no familiar English word (e.g. a RAVIT is a ‘group of butterflies’). In the test phase participants were briefly presented (for 20ms) with four types of stimuli, followed by a pattern mask. The four types of stimuli were trained meaningful novel words, untrained novel words, existing words and single letters. After the offset of each stimulus, a marker appeared at one of the letter locations, and participants were required to report the identity of the letter which had been in that location. The probability of identifying letters correctly did not significantly differ for the trained meaningful items and known words, but the probability of identification for these items was significantly higher than for untrained novel words and single letters. The authors then tested whether this advantage was due to meaning per se, as it could have emerged simply from repetition of the novel words during training. They again trained novel words with a meaning, but also included a meaningless condition in which novel words were repeated with the same number of exposures but no meaning (trained via a letter-comparison task). In the perceptual identification task the meaningful and known words again did not differ, but probability of a correct response was significantly higher than for the meaningless trained words and single letters. As the meaningless items had the same number of exposures during training, this suggested that meaning specifically facilitated the perceptual identification of the words. Whittlesea and Cantwell (1987) then tested whether the mechanism of the meaningful word advantage was due to greater perceptual integration of the whole written form during training compared to the meaningless condition, in which training focused on individual letters. The same meaningful and meaningless training on novel words was given as previously; however, the perceptual test was delayed until 24 hours after training, and participants' ability to recall the meanings explicitly was also tested. The same pattern as the previous results was observed, suggesting that the meaningful advantage persisted over this delay. Interestingly, there was no correlation between the number of meanings recalled after 24 hours and performance on the letter identification test. These data suggest that meaning can have a beneficial impact on the identification of novel written words both immediately after training and after 24 hours, suggesting that it may be helpful in generating a new word form representation (in concordance with the findings from Forster, 1985).

This work was extended by Rueckl and Dror (1994), who tested the effect of orthographic-semantic systematicity on the identification and recognition of novel written words. Participants learnt either novel words with similar endings which had semantically related meanings (e.g. *hurch, durch*, *kurch* each corresponding to an animal) or had semantically unrelated meanings (e.g. *hurch, durch*, *kurch* corresponding to shirt, dog, and table) over the course of five weeks. On a cued recall task after each training session participants initially showed higher accuracy for the systematic than the unsystematic novel words early in training, but by end of the fifth week performance was equivalent and at ceiling for both conditions. On a tachistoscopic identification task participants were more accurate for the systematic than unsystematic novel words, but this interacted with whether the word had been 'primed' by previous exposure in the cued recall task. Only the unprimed words showed an effect of orthographic-semantic systematicity, and it was the unsystematic novel words which were facilitated by being primed in the cued recall task. These data suggested that novel words characterised by a systematic orthography-semantic relationship were easier to learn and identify than novel words with unsystematic relationships, and thus aligned with the view that semantics can have a beneficial impact on word form learning.

These early findings of a beneficial effect of meaning on word identification, recognition and recall have been replicated by a range of studies using associative learning between novel spoken words and visual referents (e.g. Breitenstein et al., 2005; Takashima et al., 2014), and the semantic richness of implicitly learnt novel words

(Rabovsky, Sommer, & Abdel Rahman, 2012). Interestingly, however, it seems that this beneficial effect of semantics can be modulated by the training modality in which novel word-meaning associations are acquired. Balass, Nelson, and Perfetti (2010) trained participants on novel written words with a sentence explaining their meaning (orthography-meaning condition), on novel spoken words with an associated sentential meaning (phonology-meaning condition), and on novel words which were provided in both their written and spoken form but with no associated meaning (orthography-phonology condition). The test was a semantic-relatedness judgement task in which participants were presented with a word (which could be a learnt word, a known word, a filler word or an unfamiliar untrained existing word) followed by a meaning probe, which was a real word either semantically related or unrelated to the preceding word. Participants' task was to respond whether the two words were related or not. The behavioural data indicated no difference in speed and accuracy in the semantic-relatedness decision between the orthography-meaning and the phonology-meaning words, indicating participants had learnt the word meanings equally well in each condition. However, the P600 – an ERP recognition memory component considered to distinguish between recently presented and unpresented stimuli (i.e. an episodic effect) – was greater for the orthography-meaning words than the phonology-meaning and orthography-phonology words, but only for skilled readers. Less-skilled readers showed no P600 effect for either trained versus untrained words, or between the different training conditions. From these results the authors suggested that, despite equivalent learning and comprehension of the word meanings, learning a novel word meaning coupled with an orthographic representation had a greater impact on subsequent word recognition than learning it with a phonological representation. An alternative explanation is that the word meanings had a greater impact on orthographic word memory due to being trained and tested in the same modality (e.g. an orthographic form being trained with a written sentence meaning, and then tested on written word pairs) and the phonological forms required additional time or training to transfer to online recognition effects in the visual modality for the test (cf. Johnston et al., 2004).

There is also evidence to suggest that exposure to a written versus pictorial meaning can affect novel word memory differently depending on participants' perception of task difficulty. Carpenter and Olson (2012) tested this in a series of experiments by training participants on novel Swahili words with either a picture relating to their meaning (e.g. *kelb* paired with a picture of a dog), or an English translation of their meaning (e.g. *kelb* – dog). The test of learning was a cued recall task in which participants were presented with the definitions or pictures, and asked to recall the Swahili word. There was no difference in cued recall accuracy between the words learnt with a picture or with a translation, despite better free recall of the pictures than the translations from the training task. However, a picture advantage emerged when the cued recall test was repeated to provide additional retrieval practice, as participants' overconfidence judgements for the ability to recall the Swahili words from both pictures and definitions decreased. Participants were then explicitly instructed to avoid an overconfidence bias in learning Swahili words, and here there was a learning advantage for the picture-associated relative to the English translation words for participants warned about the overconfidence bias. These data extend the evidence that meaning can facilitate novel word learning by indicating that the type of meaning that is beneficial may be affected by how participants approach the task.

2.3.2 Semantic impact on online measures of word processing

The above data suggest that semantic exposure can have a beneficial effect on word identification, recognition and recall (Forster, 1985; Whittlesea & Cantwell, 1987), and that the magnitude and nature of this benefit can be modulated by orthographic-semantic systematicity (Rueckl & Dror, 1994), the acquisition of meaning with written versus spoken words (Balass et al., 2010), and the way in which different types of meaning are treated (Carpenter & Olson, 2012). Interestingly, however, this beneficial effect of semantics on explicit measures of word learning does not always translate to measures of online lexical processing.

The absence of a semantic benefit was observed by Sandak et al. (2004) in the case of speeded naming, whereby participants were trained on novel written words via an orthographic (letter detection), phonological (rhyme judgement) or semantic (picture-association learning) task. The effect of training condition on the reading aloud of the newly-learnt words was then tested in a naming task immediately after training. Faster naming latencies were found for words trained phonologically and semantically than for those trained with a focus on orthographic features, but there was no advantage for the semantic over the phonological training. However, fMRI data from the naming task suggested that different processes drove the equivalent performance for the phonologically and semantically trained novel words. It was phonological training which resulted in the most efficient neural processing during the naming task, indexed by the most reduced activation of the left OT region. The authors argued that even if there was some form of implicit phonological processing during the semantic learning condition, this was not sufficient to increase neural efficiency during the naming task. Because participants were given qualitatively different learning tasks for phonological (rhyme judgement) and semantic (picture-association learning) training conditions, each could have been equally successful but with different strategies for online lexical processing of the words during the naming task.

Similar findings were obtained by Gronholm, Rinne, Vorobyev, and Laine (2007) in a PET study comparing object naming performance in adults with and without mild cognitive impairment (MCI). Both groups of participants learnt novel names coupled with pictures of novel objects over a four-day period. Half of the object names were also accompanied by a definition for additional semantic support. In the object naming test it was observed that the control group learnt more names without semantic support, whereas the MCI participants learnt the name of the same number of object names correctly from both conditions. Interestingly, however, when the semantic versus no semantic support conditions were contrasted in the MCI group, there was activation in a visual processing area (BA 18) associated with naming familiar objects; the authors interpreted this as the semantic support potentially contributing to more vivid visual associations for those objects. These findings converge with Sandak et al. (2004) to suggest that despite equivalent behavioural performance in online naming tasks for novel words with different levels of semantic training, greater semantic training may support performance through different mechanisms.

Hultén, Vihla, Laine, and Salmelin (2009) obtained similar findings to Sandak et al. (2004), in a study where participants were trained on an unfamiliar picture associated with a novel name, a semantic definition, or both a name and semantic definition. The key behavioural test was naming latencies of the newly-learnt pictures. Interestingly, picturing naming performance was equivalent for novel names learnt in isolation and novel names learnt with an associated definition. This again suggested that semantic exposure does not necessarily benefit online processing immediately after learning (see also Cornelissen et al., 2004, and Whiting, Chenery, Chalk, Darnell, & Copland, 2007, for similar results).

A similar finding was obtained in 7-year-old children by measuring reading aloud (McKague, Pratt, & Johnston, 2001). The children learnt new words either with or without a semantic context. In the semantic condition, meaning was provided by a story in which each new word was presented several times in the text, along with corresponding pictures; in the non-semantic condition the novel words were learnt from a list. In a subsequent test of reading the novel words aloud, there was a training advantage whereby trained novel words were read more accurately than untrained words, but this effect was not modulated by whether the training was semantic or not. Whilst the main question addressed by McKague et al. (2001) was whether phonological training could lead to the development of orthographic codes, these findings indicate no semantic benefit on this process. It is possible that the novel words may not have been complex enough to benefit from semantic information: there is some evidence from models of reading that semantic information can bolster the processing of more orthographically complex words (Strain, Patterson, & Seidenberg, 1996). At any rate, these data suggest that a semantic benefit is not observed for the crossmodal transfer of newly-learnt words and their impact on reading aloud performance (see also Johnston et al., 2004).

2.4 Summary

From the above review it is evident that adults can readily acquire knowledge about the forms and meanings of new words (e.g. Breitenstein & Knecht, 2002; Church & Schacter, 1994; Forster, 1985; Gupta, 2003; Saffran et al., 1996; Salasoo et al., 1985). However, the influence of semantic exposure on the acquisition of new written or spoken words is mixed. Whilst there is a beneficial effect in most cases for identification, recognition and recall (e.g. Forster, 1985; Rueckl & Dror, 1994), online measures of lexical processing such as naming and reading aloud do not tend to show this semantic benefit (Gronholm et al., 2007; Hultén et al., 2009; Sandak et al., 2004). In particular, increased neural efficiency of phonological over semantic learning during naming (Hultén et al., 2009) may seem in conflict with the benefit of semantic training on explicit measures of word learning that require recall or recognition of the trained word form. Moreover, the lack of semantic benefit across all measures of word learning is surprising (e.g. as stated by Gronholm et al., 2007), in light of the levels of processing theory of learning and memory from Craik and Tulving (1975), suggesting that greater processing depth for information will lead to subsequent gains in memory for that information at later test.

One possible explanation for the lack of consistent semantic benefit is that semantic learning helps to establish representations supported by more distributed memory systems, which aid word recognition and recall but may not transfer to tasks with a more substantial phonological output component, such as naming. Evidence for this hypothesis comes from neuroimaging studies finding a wider range of cortical networks involved in the processing and retrieval of new words learnt with semantic information (e.g. Sandak et al., 2004; Takashima et al., 2014) and observing greater activation in visual association areas for semantic learning relative to training with less semantic support (Gronholm et al., 2007). One possibility is thus that this range of networks may aid retrieval for words supported by semantic information, but that this retrieval advantage may not translate to online lexical processing in the case of naming tasks, which may necessarily involve a more phonologically-driven process.

Another possibility is that the non-semantic conditions are not genuinely non-semantic, but that participants to an extent generate their own implicit meanings for novel words. Self-generation of meaning was observed by Davis et al. (2009), in which participants were trained on novel spoken words in isolation (with no meaning) but nonetheless responded with self-generated meanings for the words in a subsequent meanings-rating task (a similar finding was obtained by Dumay et al., 2004). This self-generation of meaning even for novel words learnt in isolation could potentially obscure any benefit of the semantic training conditions. However, it is not clear how (or why) this effect would differ between explicit recognition and implicit measures of online processing. It is also uncertain whether the self-generation of meaning is experimentally generated (i.e. because participants are in an artificially pared-down word learning context) or a meaningful element of how novel word acquisition operates in everyday settings.

Finally, it is possible that semantic exposure does have an effect on both explicit and implicit measures of word learning, but more time is required for the latter to emerge. One suggestion from the domain of visual learning is that implicit knowledge is gained immediately, but only after a period of 24 hours does explicit knowledge emerge (Fischer, Drosopoulos, Tsen, & Born, 2006); conversely, the opposite dissociation has been observed in the word learning literature (Davis & Gaskell, 2009, for review). It is possible that the process of offline consolidation could facilitate transfer between explicit and implicit word learning systems (e.g. Davis et al., 2009; Takashima et al., 2009) and subsequently contribute to delayed semantic gains in online lexical processing. The following chapter thus addresses the impact of offline memory consolidation and semantic exposure on novel word learning.

Chapter 3: Memory consolidation and word learning

3.1 Introduction

Long term memory capacity is constrained by the fixed size of the adult cortex, and continued memory formation throughout the lifespan therefore requires the ongoing updating and reorganisation of existing representations (Walker, 2005). Memory consolidation is the process which stabilises new memories and enables their flexible incorporation with existing representations. The term *consolidation* was first used by Müller and Pilzecker (1900; reported in Lechner, Squire, & Byrne, 1999) in relation to the time required for new memories to become 'fixed'. Current usage of the term *consolidation* encapsulates the range of synaptic and systems-level processes underpinning the long-term stabilization and integration of new memories in the days, weeks and months following encoding. The effects of consolidation manifest behaviourally in terms of protection against forgetting, enhanced access to new memories, and promoting the generalisation of new skills and knowledge (e.g. Diekelmann et al., 2013; Frankland & Bontempi, 2005; Rasch & Born, 2008, 2013; Walker, 2005). Over the last decade there has been significant interest in the related possibility that memory consolidation may be involved in some aspects of word learning (Davis & Gaskell, 2009, for review). Of particular interest for this thesis is the proposal that memory consolidation may be required for newly-learnt phonological representations to engage in competition with existing lexical representations, a process referred to as *lexicalization* (Chapter 1; Gaskell & Dumay, 2003). The below review will thus provide an overview of memory consolidation in general before discussing its specific role in word learning[4].

3.2 Theoretical accounts of memory consolidation

Proposals for the mechanisms of memory consolidation are tied to the *stability-plasticity* problem: the means by which a memory system can retain old memories

[4]It is worth noting that there are two broad types of memory consolidation: *system consolidation* and *synaptic consolidation*. System consolidation refers to the reorganization of the neural systems supporting memory, for both declarative (e.g. Gais, Lucas, & Born, 2006) and non-declarative (e.g. Walker, 2005) memory. System consolidation tends to occur over a more gradual time-course than synaptic consolidation, which concerns the growth and restructuring of synaptic connections in the hours following learning (Dudai, 2004; Hebb, 1949). A full review of synaptic consolidation is beyond the scope of this chapter, and the focus here is thus on the mechanisms, theory and evidence pertaining to system consolidation.

whilst flexibly incorporating new ones (Carpenter & Grossberg, 1987; French, 1999; McCloskey & Cohen, 1989). An early solution to this problem was proposed by Marr (1971) with the suggestion that the learning of new memories and protection of existing memories could be mapped onto distinct brain structures. Marr (1971) proposed that the archicortex (a component of the limbic system which includes the hippocampus) contained a 'simple memory' system with the capacity to learn new information and retain it over the short-term, with a transfer of information from this simple memory system to the neocortex during sleep (Marr, 1970). Marr (1970) further proposed that the stabilisation of new memories was governed by the formation of new 'classificatory units' in the neocortex to represent similar information and experiences.

Indeed, early observations of temporally-graded retrograde amnesia (e.g. Ribot, 1882; Scovile & Milner, 1957; Squire & Alvarez, 1995) supported the presence of distinct systems to meet the demands of both acquiring and retaining memories. The critical finding was that human medial temporal lobe damage (including the hippocampus) produced greater memory loss for recently-acquired memories compared to remote memories. This temporal gradient of memory loss suggested that the hippocampus had only a time-limited role in memory storage and retrieval (although note that the forms of memory which the hippocampus has a time-limited role in are debated; Frankland & Bontempi, 2005), and thus that recent memories stored in the hippocampus were not yet transferred to the cortex for long-term representation.

Theoretical accounts of memory consolidation stem from the above proposal of twin memory systems. In the standard consolidation model (Squire & Alvarez, 1995) the encoding of new memories is initially supported by the hippocampus and distributed cortical regions (whereby the particular cortical regions involved will depend on the type and content of the new memory). The reactivation of the hippocampal memory subsequently reinstates the distributed cortical memory, such that the connections between these distributed representations are strengthened. Gradual strengthening of these intra-cortical connections allows the representation of the new memory independently from the hippocampus, and the reorganisation of cortical networks to incorporate the new memory (Figure 5). The reactivation of the hippocampal memory is thus the central mechanism enabling consolidation, and can occur *online* (during a particular task) or *offline* (during sleep or restful wake). This thesis is primarily concerned with offline consolidation. Evidence for a beneficial effect of sleep during offline consolidation in particular comes indirectly from reports of an advantage for sleep on memory, relative to an equivalent period of wakefulness (e.g. Karni, Tanne, Rubenstein, Askenasy, & Sagi, 1994; Korman et al., 2007; Ellenbogen, Hu, Payne, Titone, & Walker, 2007). More direct evidence is derived from studies reporting an association between specific aspects of sleep architecture and memory gains (e.g. Karni et al., 1994; Tamminen, Payne, Stickgold, Wamsley, & Gaskell, 2010; Tamminen, Lambon Ralph, & Lewis, 2013). The standard consolidation model thus posits a decay in the hippocampal representation of new memories over time, in parallel with the strengthening and reorganisation of distributed cortical connections for long-term representation, whereby the shift from a hippocampal to neocortical representation is enabled by hippocampal reactivation.

A highly influential account of memory consolidation stemming from the standard consolidation model is the Complementary Learning Systems (CLS) model (McClelland et al., 1995). The CLS model is a dual-systems account of memory which specifically proposes that the hippocampus is a fast learning system, whilst the neocortex is a slower learning system. Critically, in the CLS model neocortical learning is

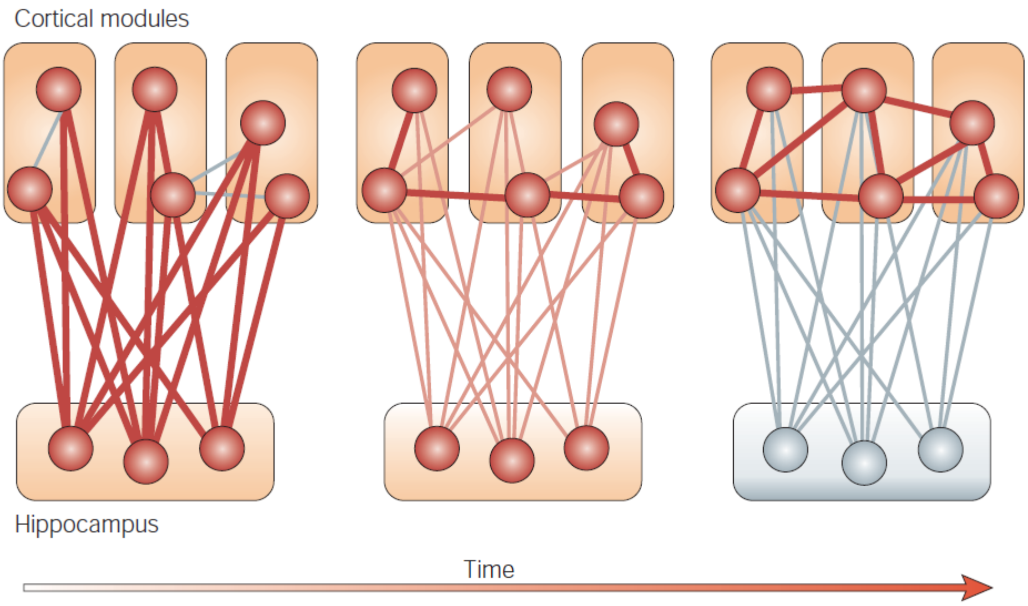

Figure 5. A schematic of the standard consolidation model.
The leftmost panel depicts the representation of recently-acquired memories, in which strong hippocampal-neocortical connections are present, with weak intra-cortical links. In hippocampal reactivation during offline consolidation, the hippocampal-neocortical links are thus central to the *reinstatement* of the network of cortical activations. It is often during offline consolidation that new cortical memories are strengthened and reorganised via this reinstatement. The ongoing strengthening of cortical connections during offline consolidation then promotes a gradual decrease in the strength of hippocampal links (middle panel), before the intra-cortical links are sufficiently stable and reorganised for the consolidated memory to be retrieved independently from the hippocampus (right panel). Figure from Franklin and Bontempi (2005).

slow to avoid catastrophic interference, in which the learning of new neocortical mappings eliminates or damages existing knowledge (originally conceptualised as mappings between input and output representations in distributed connectionist models; French, 1999; McCloskey & Cohen, 1989). The CLS model therefore predicts a gradual transfer process between the hippocampal and neocortical systems, whereby the consolidation interval is governed by the rate of hippocampal decay, and the rate of neocortical integration of new hippocampal traces. Interestingly, it follows that neocortical transfer may also proceed at a rate influenced by the capacity of new memories to interfere with existing knowledge, whereby new memories with a greater likelihood of interfering will undergo a more gradual consolidation time-course (Takashima et al., 2009; Tamminen et al., 2013; Tse et al., 2007; van Kesteren, Fernández, Norris, & Hermans, 2010). Consistent with this suggestion, McClelland (2013) proposed a recent modification to the CLS model whereby neocortical learning is conceptualised as *prior-knowledge dependent* rather than 'slow'. The core principles of the CLS model are thus consistent with the standard consolidation model, in terms of distinct learning systems with different learning rates, but the CLS model critically suggests that the rate of neocortical learning is contingent on avoiding catastrophic interference.

An alternative to the standard consolidation model is the Multiple Trace Theory (MTT; Nadel & Moscovitch, 1997). MTT stemmed from Nadel and Moscovitch's observation that retrograde amnesia was not necessarily temporally graded in the case of autobiographical (or episodic) declarative memory, and that the recall of detailed autobiographical memory could engage the hippocampus. Accordingly, MTT proposes that context-rich episodic memories specifically are supported by multiple memory traces which are established in the hippocampus, and links between the neocortex and these hippocampal memory traces remain indefinitely. Importantly, MTT also incorporates the reactivation of newly-learnt hippocampal memories. As with the standard consolidation model, this reactivation enables the reorganisation of existing memory traces for the long-term representation of new memories. However, whilst the standard consolidation model proposes only neocortical reorganisation, the MTT proposes that reactivation should also generate new hippocampal memory traces in the case of context-rich episodic memory. The indefinite hippocampal involvement in memory is the key point differentiating MTT from the standard consolidation model.

Whilst the standard consolidation model appears to be more well-established in the literature as a whole (see Dudai, 2004, for review), it is important to note that the standard consolidation model is limited by a) a varying consolidation time-course in relation to the measurement used, and b) a lack of clarity concerning the neurobiological reasons for the division of initial and long-term memory formation between the hippocampus and neocortex, respectively (Frankland & Bontempi, 2005). The central tenet of memory consolidation as a time-dependent shift in the systems supporting memory nonetheless generates testable predictions regarding a behavioural change over consolidation, and a qualitative shift in the neural systems supporting memory. We can now turn to the word learning literature regarding these predictions.

3.3 Evidence for memory consolidation in word learning

3.3.1 Complementary learning systems

The application of memory consolidation models to word learning can be considered within the Complementary Learning System framework, as proposed by Davis and Gaskell (2009). The CLS account of word learning draws on the features proposed by McClelland et al. (1995) of dual systems with a fast and slow rate of learning, and a gradual transfer process between them. Two key predictions can be generated from this account: i) immediate access to some aspects of word knowledge, with slower access to other aspects of word knowledge, and ii) a shift in the neural systems supporting word retrieval over consolidation. With respect to the first prediction, a central line of evidence in the word learning literature is of good immediate declarative memory for new words (as reviewed in Chapter 2), but a slower consolidation process for new words to influence the processing of existing words (e.g. Dumay et al., 2004; Dumay & Gaskell, 2007, 2012; Gaskell & Dumay, 2003). This slower integration of newly-learnt word forms with existing words is the process of *lexicalization* (Chapter 1). The dissociation between immediate good recognition of novel words followed by a delay for their integration suggests distinct rates of learning, at least for these aspects of word knowledge. Furthermore, the complementary time-course of a decay in explicit recall as lexical engagement increases (e.g. Tamminen & Gaskell, 2013) further supports a partition between two learning systems.

With regards to the second prediction, Breitenstein et al. (2005) investigated the role of the hippocampus in the initial encoding of novel words associated with picture objects. Better vocabulary learning in the picture-associated condition was related to the magnitude of hippocampal activity during learning. The learning and representation of new knowledge by the hippocampus, and medial temporal lobe more generally, has been substantiated by more recent neuroimaging studies implicating these structures in word learning (e.g. Davis et al., 2009; Flegal, Marín-Gutiérrez, Ragland, & Ranganath, 2014; Takashima et al., 2014) with a reduced hippocampal activation for the retrieval of remote compared to recent memories (e.g. Gais et al., 2007; Takashima et al., 2006). Evidence for the dual hippocampal-neocortical learning mechanism in word learning specifically was tested by Davis et al. (2009). A design was used in which one set of novel words was trained on Day 1, with another set of words trained on Day 2, and both sets of words were tested on Day 2. The Day 1 set thus had the opportunity for offline consolidation prior to testing, whilst the Day 2 set was unconsolidated. A contrast between unconsolidated novel words and untrained novel words with existing words showed an elevated response to both groups of novel words compared with existing words in a bilateral region of the superior temporal gyrus, in addition to an increased response in the bilateral motor cortex, supplementary motor areas, and cerebellum. The same contrast between consolidated novel words and existing words did not yield any significant voxels. These neuroimaging data suggested that unconsolidated words had distinct neural representations relative to consolidated words, which were closer to the neocortical representation of existing words. These findings are consistent with the CLS account in terms of qualitatively distinct neural systems representing unconsolidated and consolidated new words.

A critical cornerstone for the role of memory consolidation in word learning is evidence that sleep plays a role in the integration of new and existing linguistic knowledge. Marr (1970, 1971) first proposed that sleep may provide an optimal, interference-free state enabling the necessary stabilisation of new memories and reorganisation of cortical networks (McClelland et al., 1995; Squire & Alvarez, 1995). Recent reports have further suggested that hippocampal reactivation, a key mechanism of memory consolidation, may be promoted by sleep (Fuentemilla et al., 2013). The first suggestion that sleep may benefit lexical integration specifically came from Dumay and Gaskell (2007). Dumay and Gaskell (2007) built on earlier findings in which Gaskell and Dumay (2003) observed that an inhibitory effect of new words on reaction times to existing words did not emerge immediately, but only after a 1 week delay between learning and test. Dumay and Gaskell (2007) thus asked whether the passage of time was sufficient to promote lexicalization, or whether sleep was a necessary state. Participants were trained on the phonological forms of new spoken words in either the

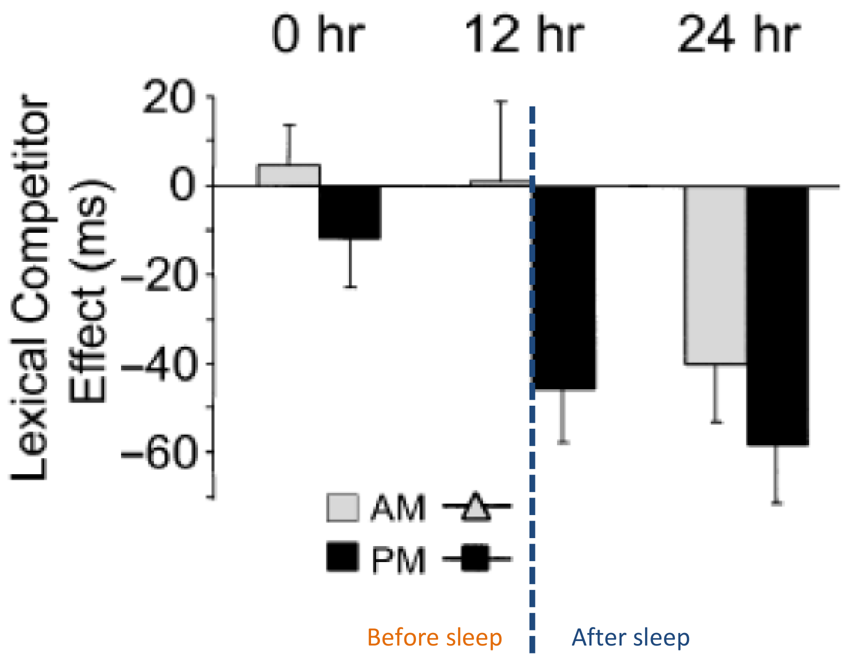

Figure 6. Lexical competition effects before and after sleep.
The lexical competition effect is the difference between the processing time of existing words for which a new competitor has been acquired, and control words for which no new competitor was trained. The slowing of responses to existing words *with* a new competitor relative to those without thus indicates that the new words have entered into lexical competition, by slowing responses to existing words. In this figure a more negative lexical competition effect indexes slower responses to words with a new competitor. The group trained in the morning is the 'AM' group, and the evening group is the 'PM' group. The dotted vertical line shows the time at which participants slept, indicating that lexical competition effects only emerged after sleep (at 12 hours in the PM group, and at 24 hours in the AM group). Figure adapted from Dumay and Gaskell (2007).

morning or evening, and were tested immediately, after 12 hours, and after 24 hours. The critical comparison was between the immediate and 12 hour test: for the participants trained in the evening, the 12 hour period contained a night of sleep, whilst for the participants trained in the morning this was a 12 hour period of wakefulness. An inhibitory effect of the newly-trained words on existing words was not observed immediately. However, after 12 hours an inhibitory effect on responses to existing words was present in the evening group only, who had slept between the training and 12-hour test. There was no inhibitory effect for the morning participants at the 12-hour test, but only at the 24-hour test (and thus following a period of sleep; Figure 6). These findings provided strong evidence to suggest that the lexicalization of new spoken words required sleep, an effect which has also been observed in children (Henderson, Weighall, Brown, & Gaskell, 2012).

Tamminen et al. (2010) further observed that distinct aspects of the neural architecture of sleep were correlated with overnight performance gains following learning. The degree to which newly-learnt words inhibited responses to existing words after sleep showed a positive correlation with sleep spindles recorded during the previous night of sleep. Further, the extent of declarative memory improvement after sleep (measured by an increase in recognition memory speed) was positively correlated with time spent in slow-wave-sleep. The data of Dumay and Gaskell (2007) and Tamminen et al. (2010) thus support a causal role of sleep in the lexical integration of new words. Tamminen et al.'s (2010) data further suggest that specific aspects of sleep architecture may separately facilitate lexical integration and the strengthening of declarative memory. Taken together, the evidence reviewed in this section points to the alignment between the temporal profile of adult word learning and predictions generated by both systems-level accounts of memory consolidation, and the CLS account of word learning specifically.

3.3.2 Limitations of the complementary learning systems account

One current limitation on the CLS model with respect to word learning (and memory consolidation in general) is that relatively little is known about the degree to which newly-acquired words remain dependent on the hippocampus over the longer-term (cf. Nadel & Moscovitch, 1997). The neuroimaging data of Davis et al. (2009) indicated a distinction between the representations of consolidated relative to unconsolidated words, in terms of increased neocortical representation for the former. However, such data are not directly informative about what representation the hippocampus retains. Notably, there is some evidence that hippocampal activity after learning drops to a pre-learning baseline level several months after learning (Takashima et al., 2006), which may suggest that the full disengagement of the hippocampus from representing newly-learnt knowledge is on a timescale of several months, rather than the 24 hours tested in the neuroimaging studies of lexical consolidation. There are also data from medial temporal lobe amnesiacs suggesting that a degree of declarative word learning can occur through neocortical mechanisms via 'fast mapping' (Sharon, Moscovitch, & Gilboa, 2011), although it should be noted these data are contentious and their replication remains unclear (Greve, Cooper, & Henson, 2014; Smith, Urgolites, Hopkins, & Squire, 2014).

A second apparent contradiction to the CLS account comes from reports in the adult language learning literature. One line of evidence concerns ERP data suggesting that rapid changes in neocortical responses can occur during the learning of novel word forms (e.g. Shtyrov et al., 2010), and in particular the finding that the rapid integration of new word with existing word meanings can be indexed by a modulation of the N400 ERP response, suggesting semantic integration (e.g. Borovksy, Kutas, & Elman, 2010; Mestres-Missé, Rodriguez-Fornells, & Münte, 2007). However, changes in electrophysiological responses may reflect the processes involved in accessing new word knowledge, which is not stored neocortically per se. Moreoever, tasks observing the co-activation of novel and existing word meanings (e.g. Borovsky et al., 2010; Mestres-Missé et al., 2007) critically do not measure the impact of new word meanings on existing word meanings (as in e.g. Tamminen & Gaskell, 2013). Accordingly, it is possible that the rapid generation of cortical responses to novel items, although similar in magnitude to responses evoked by existing items, reflect a more episodic form of learning. A further line of evidence inconsistent with the CLS account relates to the immediate generalisation of new spelling-sound mappings to untrained words (Taylor, Plunkett, & Nation, 2011). However, such generalisation may be enabled by the provision of unlimited time to respond, and thus the retrieval of detailed, context-dependent memory traces. Indeed, generalisation has emerged only after consolidation in a speeded shadowing task (Tamminen et al., 2012), suggesting that the generation of context-independent representations – those which support fast, automatic generalisation in a speeded task – may require consolidation to emerge.

3.3.3 Summary

On balance, the above evidence is consistent with a word learning system which capitalizes on general memory consolidation mechanisms. This argument is supported by two lines of evidence. Firstly, whilst access to explicit knowledge about new word forms and meanings is fast and immediately available (as reviewed in Chapter 2), the integration of new and existing words more gradual (e.g. Dumay et al., 2004; Dumay & Gaskell, 2007, 2012; Gaskell & Dumay, 2003). The initial encoding of novel words appears to be mediated by the hippocampus (e.g. Breitenstein et al., 2005), the involvement of which may decay over six months following learning (Takashima et al., 2006). Further, a qualitative shift in the neural representation of new words is observed following 24 hours of consolidation (Davis et al., 2009; Takashima et al., 2014). Finally, it appears that sleep may play a central role in lexicalization (Dumay & Gaskell, 2007;

Henderson et al., 2012; Tamminen et al., 2010). These findings are concurrent with the CLS account of word learning (Davis & Gaskell, 2009), proposing that word learning is mediated by a fast hippocampal system and slower neocortical learning system, with a time-dependent transfer process between the two. This review now considers a closely related body of evidence in more detail: the lexical integration of new and existing word knowledge.

3.4 The integration of new and existing word knowledge

3.4.1 Lexical competition between new and existing words

As discussed in Chapter 1, lexical selection is a competitive process in models of spoken word recognition, whereby multiple lexical entries matching the speech signal will be activated in parallel and mutually inhibit each other until only one lexical candidate is recognised as the best fit for the speech input (e.g. the DCM, Gaskell &

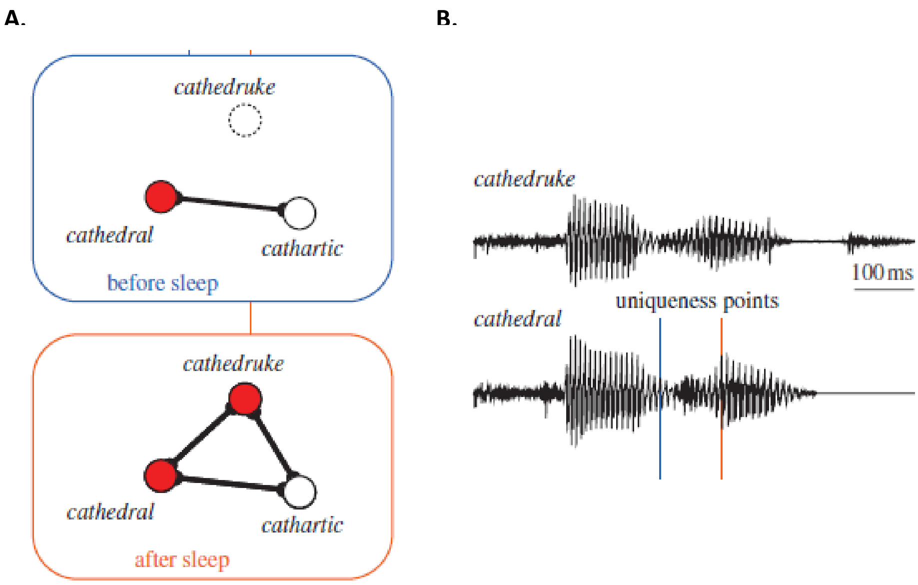

Figure 7. Lexical competition and its effect on spoken word recognition.

A) The lexical organisation of *cathedral* and *cathedruke*, before (top) and after (bottom) offline consolidation. Before consolidation the strongest competitor for *cathedral* is *cathartic.* The uniqueness point of *cathedral* before consolidation is shown in B) by the blue line. Following offline consolidation, the formation of new inhibitory links between the newly-learnt word *cathedruke* and its phonological neighbours mean the uniqueness point of *cathedral* is now later, as shown in B) by the orange line, due to more of the speech signal being required to rule out *cathedruke* as a possible candidate. The shift in the uniqueness point of existing words from the acquisition of a new competitor thus slows down reaction times, and this slowing of reaction times is used as an index of new words entering into lexical competition. Figure adapted from Davis and Gaskell (2009).

Marslen-Wilson, 1997; TRACE, McClelland & Elman, (1986). The evidence for competition during spoken word recognition is substantial (e.g. Allopenna et al., 1998; Gaskell & Marslen-Wilson, 2002; Norris, McQueen, & Cutler, 1995; Zwitserlood, 1989). The impact of new words on the recognition of existing words has thus become established as a fundamental measure of whether a novel word is able to affect the online processing of existing phonologically neighbouring words, and thus behaves as part of the mental lexicon (e.g. Gaskell & Dumay, 2003). This mechanism is depicted in Figure 7. The key question about this process of lexical integration, or lexicalization, is thus what is required for it to be successful.

Chapter 1 argued for the distinction between the learning of new phonological representations, and the engagement of these representations in *lexical competition* with existing words. Strikingly, whilst access to new phonological representations after learning is immediate, the engagement of these new representations in competition often requires a period of offline memory consolidation to emerge (e.g. Gaskell & Dumay, 2003; Dumay & Gaskell, 2007). As such, the cognitive processes involved in the entry of new words into lexical competition provide a particularly interesting window onto memory consolidation more broadly. The following section sets out the conditions under which new words can come to engage with existing words, and what factors are currently understood to influence this process.

Gaskell and Dumay (2003) first proposed lexical competition between new words and existing words as a measure of lexical integration, and tested the time-course of the emergence of lexical competition in a series of three experiments. Participants learnt novel spoken words in a phoneme monitoring task, in which they listened for the presence or absence of a target phoneme in the novel words. The novel words were highly overlapping phonological neighbours of existing words (e.g. *cathedruke*, neighbouring with the existing word *cathedral*), which, if entering into lexical competition, should slow down responses to existing overlapping neighbours due to a later uniqueness point in the existing words (as depicted in Figure 7). Following training, a lexical decision task was used to test the response latencies to the existing base words which had a high degree of phonological overlap with the novel trained words (e.g. *cathedral*). A two-alternative forced-choice task also tested explicit recognition of the novel items compared to phonologically similar foils (e.g. *cathedruce*). When tested shortly after training, participants showed significantly above chance recognition performance on the 2AFC task (91% accuracy). However, the existing base words with a trained competitor were responded to significantly more quickly than the control base words with no newly-trained competitor, thus providing no evidence for lexicalization of the trained novel words immediately after learning.

In the second experiment, the same phoneme monitoring training was used, with the tests again of lexical decision and 2AFC recognition memory. However, participants were tested over a longer timescale, with a lexical decision test, 2AFC test and phoneme monitoring exposure on each of the five days following the first training phase. The 2AFC accuracy was above 90% on all days of testing, and increased over the days of testing. The lexical decision results also showed a main effect of day, in which slower response latencies for the base words with a newly-acquired competitor relative to the control base words emerged on Day 4, and persisted on Day 5 of testing. Importantly, these competitor effects did not emerge for base words of an initial-deviation trained subset of items (e.g. *yothedral*), suggesting that the competition effects were specific to cohort-competitors (the onset-matched final-deviation *cathedruke* items). Experiment three extended this finding by replacing the lexical decision task with a pause detection task (Mattys & Clark, 2002). To disentangle the effect of consolidation time from repeated exposure to the words contributing to slower response latencies in the lexical decision task on Day 4 in Experiment 2, participants were given 36 exposures to the novel words in the first phoneme monitoring training (thus equal to the first three days of exposure prior to the emergence of competition effects in Experiment 2). In Experiment 3 participants were tested immediately after learning the 18 novel words (Day 1) and after one week (Day 8). The base words which had a newly-acquired competitor were responded to more slowly than the control base words after one week, but not immediately after training. Experiments 2 and 3 thus suggested that novel words did not enter into lexical competition immediately, but critically required a period of offline consolidation to do so.

A complementary finding was obtained by Bowers, Davis, and Hanley (2005) in the visual domain. Akin to spoken word recognition, models of visual word identification incorporate lexical competition, whereby multiple orthographically overlapping word representations are active and mutually inhibitive until identification is achieved when a single item becomes sufficiently activated to inhibit the other competitors. Participants were trained on novel written words which differed from existing words by one letter (e.g. BANARA-BANANA). Importantly, the existing words were all words with no orthographic neighbours, allowing any potential competition effects from the acquisition of BANARA to be measured on the existing words, due to the neighbourhood size change from zero to one. Participants were trained by repeated reading and typing of the novel words, and the competition of these new words was tested on a semantic categorization task. Bowers et al. predicted that existing words with a newly-trained competitor (e.g. BANANA) should be categorized more slowly than words without a new competitor, due to an increase in lexical competition for the visual identification of BANANA. The semantic categorization task was performed immediately after training on Day 1, and again on Day 2, followed by an additional training session and semantic categorization task. The reaction times showed that a reliable slowing of responses to words with a newly-trained neighbour relative to words without a newly trained neighbour only occurred on Day 2, in both the initial categorisation task and after the additional training. These data again suggested that robust competition effects did not emerge immediately but required a period of at least a day.

The seminal findings of Gaskell and Dumay (2003) concerning a delay for the entry of new words into lexical competition have generated replications across a range of studies (Bakker, Takashima, van Hell, Janzen, & McQueen, 2014; Brown, Weighall, Henderson, & Gaskell, 2012; Davis et al., 2009; Dumay et al., 2004; Dumay & Gaskell, 2007, 2012; Henderson et al., 2012; Henderson, Weighall, Brown, & Gaskell, 2013; Henderson, Powell, Gaskell, & Norbury, 2014; Tamminen & Gaskell, 2008). An important question underpinning this lexicalization work is the extent to which the measured effects truly reflect the engagement of new words in lexical competition. Based on the fact that such competition effects have been obtained with novel words which have a high degree of phonological overlap with existing words (e.g. *cathedruke-cathedral*) it has been suggested that either the form variants of existing words or the episodic trace of the newly-learnt word are being consolidated, which subsequently slows responses to overlapping neighbours. With regards to the latter possibility, Qiao, Forster, and Witzel (2009) used masked priming to examine a prime lexicality effect for newly-acquired written words. The prime lexicality effect is an effect in which novel word primes facilitate responses to existing neighbour targets (due to partial activation of the existing word form). In contrast, known word primes inhibit responses to existing neighbour targets due to their status as competing lexical entries. A reduction in the facilitatory priming effect should therefore be seen for novel word primes which have developed new lexical representations. Participants were trained on pseudoword neighbours of existing words (e.g. BANARA-BANANA). These novel words did not lead to any reduction in the facilitatory priming effect on existing neighbours, despite slowing down semantic categorisation responses to the existing words. However, in a more recent study Qiao and Forster (2013) observed a prime lexicality effect following four training sessions over the course of one month. The findings of Qiao and Forster (2013) thus support the contention that novel words can establish lexical representations, but that more time may be required depending on the measure of lexicalization used, with respect to lack of a prime lexicality effect following one night of consolidation in Qiao et al. (2009).

Dumay and Gaskell (2012) further addressed whether post-sleep competition effects reflected lexical competition or the consolidation of episodic traces. Participants learnt embedded base word competitors (e.g. *lir*<u>*muck*</u>*toze*), which were less clearly related to existing words, and were tested immediately after learning and 24 hours later. Lexicalization was tested in a word spotting task which involved detecting an existing word in a nonsense sequence. It was predicted that if overnight consolidation involved the consolidation of episodic traces of novel words, rather than the engagement of new words in lexical competition, word-spotting should be faster at the 24 hour test due to the strengthening of these episodic traces. Conversely, if the new words had entered into lexical competition at the 24 hour test, word-spotting should latencies should be slower. In accordance with this prediction, word-spotting latencies were significantly slower after 24 hours of consolidation. These findings were consistent with the proposal that the slowing of responses to existing words after acquiring a new phonologically-overlapping word reflected the engagement of the new word in lexical competition.

3.4.2 The impact of training on the lexicalization time-course

The data discussed thus far align with the idea that lexical integration is a relatively slow process with respect to other aspects of word learning. These findings are consistent with CLS accounts (Davis & Gaskell, 2009; McClelland et al., 1995), in which the central feature is that the integration of new with existing information is a necessarily gradual process, to avoid loss or damage to existing knowledge (McCloskey & Cohen, 1989). Accordingly, sleep has been suggested to provide an optimal state for this gradual integration process (Dumay & Gaskell, 2007; Tamminen et al., 2010). One critical point about the data discussed so far, however, is that novel words were learnt almost exclusively through phoneme monitoring training. Whilst phoneme monitoring is a valuable tool for training new spoken words, it raises the question of whether a different training paradigm could navigate around the slow lexicalization time-course. Given that offline consolidation serves to avoid catastrophic interference, it follows that if learning or online consolidation during learning can avoid disrupting existing knowledge, lexical integration may be able to occur without sleep-based consolidation as a necessary pre-requisite. Intriguingly, recent reports have indeed begun to indicate that lexicalization can also occur during wake. An examination of these studies thus provides a window onto how the training regime can impact upon the lexicalization time-course.

The influence of the learning regime on lexicalization was addressed by Fernandes et al. (2009). Participants learnt novel words in an artificial language learning paradigm. The learning task consisted of participants hearing a speech stream and extracting the novel words via statistical learning of the segmentation cues in the stream. The segmentation cues for the novel word boundaries could be either congruent or incongruent. Notably, over the course of the speech segmentation task, participants were exposed to the novel words 189 times, which is a substantially higher number of exposures than the phoneme monitoring paradigms which have typically used 36 exposures. The test of lexical integration was a lexical decision task to existing neighbouring words; if the novel words had been integrated the responses to existing neighbours of those novel words should be slower than the control words with no new competitor. This was found to be the case immediately after learning, with base words of novel trained words with congruent cues having significantly slower response latencies compared to control words. This effect increased over one week after training, and the words with incongruent cues slowed down lexical decision responses to existing words after one week. These findings thus suggest that sleep-based consolidation is not a necessary condition for lexical integration to occur. It is possible that the gradual nature of statistical learning in the training paradigm could have allowed the novel words to be interleaved with existing ones online, thus reducing the need for consolidation before these novel words could enter into lexical competition.

Szmalec et al. (2012) extended the finding of Fernandes et al. (2009), by arguing that the properties of the training regime determine whether sleep is necessary for lexicalization. Szmalec et al. (2012) used a Hebbian paradigm (akin to the statistical learning task) to train participants on novel words. The tests used were both lexical decision and pause detection, and participants were tested immediately after learning, after 12 hours, and after 1 week. Half of the participants were trained in the evening and had their 12-hour test the following morning, and thus slept between the two; the other half of participants were trained in the morning and had their 12-hour test in the evening, and thus were awake between the two. Lexical decision and pause detection were used to examine an increase in lexical competition for existing words. Critically, lexical competition was not observed immediately, but was observed in *both* the sleep and wake groups after 12 hours. These findings imply that although lexical integration requires a consolidation period, it does not necessarily require sleep. This result contrasts with the findings of Dumay and Gaskell (2007) who found lexical competition in a pause detection task only after sleep. One possibility for this difference in findings is that the Hebbian learning task used by Szmalec et al. (2012) allowed the novel words to be learnt implicitly and thus reduced their potential for interference (a possibility suggested by Diekelmann et al., 2009), but the mechanism for this implicit versus explicit learning difference is not clear. Szmalec et al. (2012) argued that sleep-based consolidation is only necessary when there is either a weaker memory trace from training, or when participants are explicitly learning new words (as in the phoneme monitoring paradigm). In sum, the findings of both Fernandes et al. (2009) and Szmalec et al. (2012) suggest that when novel words are learnt via a statistical learning task, lexicalization can occur during wake.

Interestingly, however, Lindsay and Gaskell (2013) observed lexicalization during wake after training participants using a phoneme monitoring task. The key idea driving this study was that lexical integration may be possible without sleep if the training regime incorporated the activation of existing knowledge, by interleaving presentations of the novel words with their existing base words. They contrasted massed and spaced learning, where in massed learning and in spaced learning the existing base words (e.g. *cathedral*) were presented over the course of a day in between the different phoneme monitoring training phases. This presentation of the base words for testing meant that exposure to the novel words was interleaved with activation of the existing words. Lexical integration was observed by the end of the day on both the massed and spaced learning tasks, but only when the interleaving of existing words had been included over the course of the day. When there was no interleaving of existing words, lexical integration was observed only 24 hours later, after a night of sleep. The data of Lindsay and Gaskell (2013) support the idea that consolidation may play a role in interleaving new with existing knowledge, and that training incorporating this interleaving may therefore bypass the need for sleep-based consolidation. Notably, as with Szmalec et al.

(2012) lexical integration still required time, and did not occur immediately as in Fernandes et al. (2009).

The above findings thus provide intriguing evidence to suggest that sleep-based consolidation is not a necessary pre-condition for lexical integration, but may be selectively beneficial depending on the training regime, type of encoding, and test task used (see also Coutanche & Thompson-Schill, 2014, and Kapnoula, Packard, Gupta, & McMurray, 2015). This proposal raises the possibility that specific properties of learning could bypass the need for sleep-based consolidation by avoiding catastrophic interference: the gradual statistical learning of new words via speech segmentation (Fernandes et al., 2009), a Hebbian implicit learning task (Szmalec et al., 2012), and the interleaved activation of existing related knowledge alongside training (Lindsay & Gaskell, 2013).

3.4.3 Summary

The evidence reviewed above suggests that consolidation can facilitate the lexical integration of new phonological forms, whereby the measurement of lexical integration is based on changes in processing of existing lexical items. Interestingly, although sleep may be the optimal state for consolidation, more recent data suggest this is not inevitably the case, and that the nature and duration of consolidation required may also be dependent on the training regime and test task used (e.g. Fernandes et al., 2009; Lindsay & Gaskell, 2013; Szmalec et al., 2012). It is noteworthy that the consideration of lexicalization has so far focused almost exclusively on the acquisition of novel phonological forms in the absence of meaning, and their entry into competition with existing phonological forms. Fully functional lexical representations critically require meaning for use in everyday life. Lexical competition therefore reflects only one aspect of lexicalization, and it is important to emphasise that investigations of phonological form competition alone may therefore only capture one dimension of the 'natural' lexicalization process. A highly relevant question thus concerns both how and when new word meanings are integrated, and the impact of meaning on the lexicalization of novel word forms.

3.5 Semantic knowledge and the lexicalization of new words

3.5.1 Semantic integration

As with the lexicalization of new phonological forms, measured by their entry into lexical competition with existing words, novel word meanings appear to undergo a similar process of integration within existing semantic networks. A key diagnostic for semantic integration of new word meanings is semantic priming, whereby responses to a target word (e.g. *kitten*) should be faster if preceded by a semantically related word (e.g. *cat*) compared to an unrelated word (e.g. *insect*). Studies probing the integration of new with existing word meanings have thus primarily done so using semantic priming. In line with the CLS account (McClelland et al., 1995), the integration of new word meanings should require a period of offline consolidation to avoid catastrophic interference with existing semantic knowledge.

In an apparent contradiction to this prediction, some previous studies have reported instances of priming between novel word meanings and existing words and/or meanings. Breitenstein et al. (2007) investigated the impact of learning novel words associated with existing objects on the priming of responses to semantically related objects. Participants learnt associations between novel spoken words and existing object pictures over the course of five days. On the fifth day, a primed semantic classification task tested whether the newly-learnt name-object association could prime existing objects. A trained spoken word was presented as a prime followed by a target object, which was semantically related or unrelated to the object association learnt during training. Participants responded as to whether the target object was natural or man-made, and responses to the target object were facilitated when the preceding word had been associated with a semantically related object during training. Comparable studies testing implicit meaning acquisition through ERPs were conducted in the visual domain by Mestres-Missé et al. (2007) and Borovsky, Elman, and Kutas, (2012), in which novel words were learnt in semantically constraining sentence contexts. After training, N400 ERP responses (thought to be a measure of semantic expectancies) to target known words were reduced, when preceded by a novel word trained with a meaning which was related to the known word meaning. The findings of Breitenstein et al. (2007), Mestres-Missé et al. (2007), and Borovsky et al. (2012) thus suggested that novel words may come to prime semantically related existing words immediately after learning, which would suggest rapid integration into existing semantic networks.

However, an issue with this type of semantic priming is that such effects could also be attributed to *associative priming* or *mediated priming* (as noted by Tamminen & Gaskell, 2013). Associative priming can be particularly difficult to disentangle from semantic priming in sentence learning tasks such as those of Mestres-Missé et al. (2007) and Borovsky et al. (2012), because it can facilitate responses to words that are associated by co-occurrence (for example, occurring in the same sentence during training) rather than by semantic meaning. An alternative way to measure the integration of novel word meanings into existing semantic knowledge is to thus measure the *inhibition* of semantically related real words. Clay, Bowers, Davis, and Hanley (2007) did precisely this, using the picture-word interference (PWI) task. The PWI is a task in which picture naming is delayed by the concurrent presentation of semantically related distractor word. Clay et al. (2007) trained participants on combinations of visually presented novel words, pictures and written definitions; each novel word belonged to the category of clothing, fruit, or a vehicle. The test phase consisted of participants naming aloud drawings of familiar objects from the same semantic categories as the trained novel word pictures. Semantically related novel words only slowed down picture naming responses after one week, and not in the test session immediately after the training phase. These findings thus provided evidence for a role of consolidation in semantic learning, and specifically in the ability of the meanings of newly-learnt words to compete with the meanings of existing words.

Tamminen and Gaskell (2013) further argued that for novel words to show semantic integration they should prime semantically related existing words, as a measure of automatic spreading semantic activation (e.g. Collins & Loftus, 1975). Participants learnt novel written words with a meaning via sentences, and through repetition naming. Semantic integration was tested with a semantic priming task, in which the novel words were used as primes before a semantically related target word in a lexical decision task (e.g. where *feckton* was learnt to be “a type of cat” during training, in the subsequent primed lexical decision task the prime would be *feckton* and the target word *kitten*). After one week the novel words could robustly prime the semantically related existing words, both when the novel word primes were unmasked and masked, indexed by faster responses to known word targets with semantically related novel word primes relative to unrelated novel word primes. This therefore implies that the activation of semantically related known words by novel words was through automatic semantic activation, as the target and prime were not exposed together during training, rather than driven by response strategies or episodic memory. Interestingly, the explicit recall of the novel word meanings decreased in parallel with an increase in the semantic priming effect one week after training. This result is complementary with the CLS model, by suggesting that novel word meanings showed increasing semantic integration over the week as they were abstracted from explicit knowledge of these meanings.

To understand the sleep-based neural mechanisms of semantic integration, Tamminen et al. (2013) investigated the relationship between neural sleep architecture and the semantic integration of new word meanings. Semantic neighbourhood density was used to manipulate the ease of semantic integration of newly-learnt words. This was because when presented with a list of existing words to learn, words with sparser semantic neighbourhoods (e.g. fewer semantic neighbours) are typically recalled with greater accuracy (Nelson & Zhang, 2000; this has also been observed in pre-schoolers by Storkel & Adlof, 2009). Tamminen et al. (2013) thus suggested that newly-learnt items could suffer from a degree of interference from pre-existing semantic neighbours; the key question following this observation was whether this interference would influence the semantic integration of novel words and the associated sleep architecture. In separate training sessions, participants learnt one set of novel words which had meanings falling into sparse semantic neighbourhoods, and one set of novel words with meanings falling into dense semantic neighbourhoods. Following training polysomnography was recorded overnight. The effect of semantic density manifested in a reaction time advantage for the sparse over the dense neighbourhood words across tasks of reading aloud, synonym judgement, and animacy decision. Semantic neighbourhood density also modulated sleep architecture: sparse neighbourhood words showed a higher density of sleep spindles than dense neighbourhood words, with a trend of more slow-wave activity after learning the sparse compared to the dense neighbourhood words. Strikingly, these data suggested that sparse semantic neighbourhood words may have been more readily integrated into semantic networks.

This finding aligns with the interesting proposal that memory consolidation may be able to proceed more rapidly for newly-learnt information which has *less* impact on existing knowledge (McClelland, 2013). Consolidation has been found to be accelerated for information that is consistent with extant knowledge in terms of a pre-existing schema (Tse et al., 2007). An explanation thus suggested by Tamminen et al. (2013) was that sparse semantic neighbourhood words had a lower likelihood of inconsistent knowledge in their neighbourhood, and therefore showed faster integration and greater spindle and slow-wave oscillations the night after learning. Conversely, words from dense semantic neighbourhoods may require a slower neocortical learning rate due to a higher likelihood of inconsistent knowledge in pre-existing semantic networks. In relation to semantic effects on the lexicalization of novel words, this observation suggests from the outset that the lexicalization of semantically-associated novel words may be slower than that of meaningless novel words, due to the addition of a semantic association boosting the potential for interference. The following section thus addresses the impact of the acquisition of semantic information on lexicalization to ascertain whether this is the case.

3.5.2 Semantic effects on the lexicalization of novel words

The lexical integration literature indicates that the lexical system can readily integrate novel words with no trained meaning; it is thus clear that meaning is not necessary for lexicalization to occur. Interestingly, however, the literature relevant to the semantic integration of newly-learnt word meanings further suggests that although the ability of novel words to prime semantically related real words would appear very rapid from ERP studies, for novel words to enter into reliable behavioural semantic priming a longer time-course is required. Given the delay of both lexical and semantic integration, a central question is thus the extent to which semantic information can impact on the time-course with which new words enter into lexical competition with existing words. This theme contrasts to the semantic impact on word learning explored in Chapter 2, which pertained to the impact of semantic information on word recall, recognition and online processing immediately after training. However, as is evident from the review in this chapter, word learning is characterised by (at least) two distinct stages of memory formation: immediate explicit knowledge and access to new word forms, with a slower entry of new words into lexical competition (e.g. Dumay et al., 2004; Dumay & Gaskell, 2007, 2012; Gaskell & Dumay, 2003). These dissociable time-courses raise the question of how semantic information impacts upon each of these distinct stages. Chapter 2 (section 2.3) reviewed the semantic influence on the immediate learning of new words; the following section thus tackles impact of semantics on the slower lexicalization process of novel words.

This question has been addressed in the lexicalization literature, in which a key consideration has been whether the observed delay in lexical competition effects is due to the semantically impoverished learning environment. Dumay et al. (2004) trained participants on meaningful words via sentences (e.g. *"A cathedruke is a type of vegetable", "The cook used the cathedruke in the stew"*), and words with no meaningful definition via phoneme monitoring. They measured lexical integration by lexical decision response latencies to existing words (e.g. *cathedral*). No evidence of lexical integration was observed immediately and, intriguingly, after 24 hours of consolidation it was *only* the form-only words which slowed down lexical decision latencies. It was only after one week that the meaningful words also entered into lexical competition. Similar findings were obtained by Gaskell and Dumay (2003) in a picture-training version of their Experiment 1 (in which no lexicalization was observed for phonological forms trained in isolation), whereby semantic exposure also did not enable lexicalization.

A comparable finding was obtained in children by Henderson, Weighall, and Gaskell (2013) . Five to nine-year-olds learnt unfamiliar science words with a meaning (provided via pictures and definitions) or form-only training (via exposure to both the spoken and written form of the words). Both training groups showed a significant lexical competition effect on a pause detection task after 24 hours, indicating that the semantic manipulation did not affect the time-course of lexical competition, despite significantly greater free recall in the semantic than form-only condition. It is thus interesting to recognise that in the Henderson, Weighall, and Gaskell (2013) study the semantically-learnt words did show lexical competition after 24 hours of consolidation; this result contrasts with the adult literature, in which semantic exposure delayed lexical integration such that it only emerged after one week (Dumay et al., 2004).

Conversely, Leach and Samuel (2007) observed that associating spoken words with pictures during training enhanced perceptual learning immediately after training. Participants learnt novel words with an attached meaning, via a picture association and a short passage using the words in a semantic context, or with no meaning via phoneme monitoring alone. A /s/ or /sh/ sound was embedded in the novel words, and word knowledge was measured by the adjustment of existing phoneme categories according to the /s/ or /sh/ phoneme contained within the newly-learnt words. Only the semantically-learnt words shifted existing phoneme categories after exposure, suggesting they had been rapidly engaged at a sub-lexical level.

On balance, the above findings would suggest that the provision of semantic information may slow the lexicalization time-course in adults (Dumay et al., 2004) but not in children (Henderson, Weighall, & Gaskell 2013), whilst meaning may benefit the engagement of new words at the sub-lexical level (Leach & Samuel, 2007). However, for these studies there is an important limitation with respect to the findings being informative about the role of meaning in lexical integration. Firstly, Dumay et al. (2004) used categorically different learning tasks in the meaningful and non-meaningful conditions. It is conceivable that in the non-meaningful condition participants engaged in a more fine-grained processing of the phonological forms, due to learning them during phoneme monitoring. By contrast, learning forms embedded in sentences in the meaningful condition did not require the same degree of phonological processing. This difference in exposure could be one factor contributing to why *only* the non-meaningful words were lexicalized after 24 hours of consolidation, which may not be a complete reflection of the role of semantics in the lexicalization process. Leach and Samuel's (2007) study further used a test (phoneme category perception) that probed a sub-lexical rather than lexical level of representation. It has previously been suggested that access to phonological information about a new word may be immediate, and distinct from the slower entry of this word into lexical memory (Davis & Gaskell, 2009; Dumay & Gaskell, 2012; Snoeren, Gaskell, & Di Betta, 2009). Whilst Leach and Samuel's (2007) data are thus informative about a potential benefit for meaning in immediate access to a word's phonemic properties, they do not necessarily address the role meaning may play in the integration of a new word into lexical-level memory.

Takashima et al. (2014) further addressed this question by using a learning task in which participants learnt novel words via phoneme monitoring, whereby half of the novel words were also presented with a visual referent. After 24 hours it was again observed that the form-only words had entered into lexical competition, as measured by pause detection, whilst reaction times for the picture-associated novel words did not significantly differ from the control baseline. As with Henderson, Weighall, and Gaskell (2013), free recall was higher for the picture-associated than form-only novel words. The authors interpreted these findings within a CLS framework, suggesting that the form-only novel words had shown lexical competition after 24 hours because they could establish stronger links with existing phonological forms, whereas the picture-associated words also had a visual cue (the picture) to establish a new representation on, meaning the novel form-existing form links were weaker. This proposal was supported by a positive correlation between the form-only competition effect after 24 hours and functional connectivity strength between the auditory cortex and posterior middle temporal gyrus, suggesting that the link between existing and novel word forms aided lexical integration on Day 2. These data thus suggested that whilst the picture-associated words had an explicit memory benefit, the form-only words could more readily undergo a transfer to enter into lexical competition after 24 hours.

3.5.3 Summary

With respect to the question of how semantic information impacts upon the lexicalization time-course, the above data suggest that semantic exposure may act to delay the entry of new words into lexical competition in adults. From the literature on lexical integration reviewed in section 3.4, it is now well-established that newly-learnt novel words require a period of a day to enter into lexical competition (at least when acquired during a phoneme monitoring task) and semantic exposure does not speed up this process, but rather seems to delay it relative to new words learnt in isolation from any semantic information (Dumay et al., 2004; Takashima et al., 2014).

Why could this be the case? Recall from the semantic neighbourhood integration data of Tamminen et al. (2013) that words in sparse semantic neighbourhoods may have been more readily integrated with existing semantic knowledge, and one interpretation of this effect was that sparse neighbourhood words potentially had less likelihood of interfering with existing semantically related words and concepts than dense neighbourhood words. Following this, one possibility is that the lexical integration of new words learnt with a meaning is slower than for those without a meaning because the additional semantic information has a higher likelihood of interfering with existing representations, and these words thus have a slower rate of consolidation. Note also that when testing the integration of new word meanings via semantic priming, Tamminen and Gaskell (2013) observed semantic priming of new word meanings (implying semantic integration) one week after training, whereas the time-course of lexical integration is typically within one *day* after learning (for training via phoneme monitoring: Davis et al., 2009; Dumay & Gaskell, 2007; Dumay & Gaskell, 2012; Takashima et al., 2014). A second, related possibility is thus that when novel words are trained with a meaning, *both* forms of knowledge must be integrated into the neocortical store concurrently; if it is the case that semantic integration is slower than the lexical integration of phonological forms, it may then be the case that the lexical integration of phonological forms trained with a meaning is constrained by the requirement for more gradual semantic integration. In line with these considerations, it may therefore be the case that the lexical competition effects observed after one day for phonological forms trained without meaning reflect a faster consolidation process than that which occurs in everyday learning.

3.6 Conclusions and thesis outline

From the data discussed in this chapter and the preceding two introductory chapters it is clear that adults can readily acquire knowledge about new word forms (e.g. Church & Schacter, 1994; Forster, 1985; Saffran et al., 1996; Salasoo et al., 1985). In the case of written word learning early representations may be underspecified (Johnston et al., 2004; McCandliss et al., 1997), and in the case of spoken word learning additional training or time may be required for representations to become invariant to physical stimuli changes (Church & Schacter, 1994). In short, the acquisition of factual knowledge about a new word form is rapid but in some cases not as precisely specified as that of known words immediately after learning.

In contrast, the lexicalization of novel words such that they engage in competition with existing words may critically require time. Lexicalization is often linked to sleep, although this is not always a necessary prerequisite (Dumay & Gaskell, 2007; Dumay & Gaskell, 2012; Gaskell & Dumay, 2003; Tamminen et al., 2010; cf. Fernandes et al., 2009; Lindsay & Gaskell, 2013; Szmalec et al., 2012). There thus appears to be separable stages of word memory formation: immediate access to knowledge about a word form and its impact on phonological knowledge, and the slower integration of these new words with existing lexical knowledge. A large body of current data supporting these distinct time-courses of word learning can be explained by the mechanisms of systems memory consolidation, whereby new memories are initially supported by the hippocampus, before a time-dependent stabilisation and reorganization of these memories within distributed cortical networks (Squire & Alvarez, 1995; Davis & Gaskell, 2009; McClelland et al., 1995).

It is also evident that adults can readily learn the meanings of novel words (e.g. Breitenstein & Knecht, 2002; Gupta, 2003; Rodd et al., 2012). However, there again seems to be a delay for novel word meanings to interact with existing word meanings (Tamminen & Gaskell, 2013). In terms of the impact of meaning on novel word learning, there is a semantic benefit on explicit measures of word recognition and recall (e.g. Forster, 1985; Rueckl & Dror, 1994), but this advantage does not always translate to online measures of lexical processing (Gronholm et al., 2007; Hultén et al., 2009; Sandak et al., 2004). Most interestingly, there appears to be no semantic benefit on the lexical integration of novel words: conversely, meaning seems to actively delay the time-course of lexical integration (Dumay et al., 2004; Takashima et al., 2014; but cf. Henderson, Weighall, & Gaskell, 2013).

Overall, three striking points emerge from this review. First, it seems that semantic information has a multifaceted role in word learning. Second, and relevant to this first point, the acquisition of new words may reflect two distinct stages of learning and representation. Third, the lexicalization of new words draws on general principles of memory consolidation, but relatively little is known as to what constrains the lexicalization time-course. This thesis therefore addressed the overarching research question: how are new lexical representations acquired? This broad research question was divided into two main themes centred on the role of semantics in word learning, and the impact of offline memory consolidation on word learning. The first theme asked how the knowledge acquired during the learning of novel words impacted upon the earlier and later stages of word memory formation. The second theme concerned the aspects of initial encoding which influenced offline memory consolidation and lexicalization. These themes were investigated by manipulating the provision of semantic information during the acquisition of new words, and measuring different levels of word learning over consolidation.

The current thesis thus presents a systematic investigation of the above issues through four experiments. Based on both the multifaceted contribution of semantics to word learning and the distinct stages of learning and representation, Study 1 and Study 2 used event-related potentials to address related questions: Study 1 first asked whether semantic exposure has an impact on the online acquisition of new phonological forms, and Study 2 addressed whether an impact of semantic information on early phonological form representations transferred to the offline consolidation process. Study 3 followed a parallel line of investigation by firstly addressing whether a semantic influence on establishing new phonological form representations transferred to their lexical integration, and secondly examining the long-term consequences of semantic versus non-semantic learning for lexicalization. Finally, Study 4 asked whether the nature of novel word encoding constrained the lexicalization time-course.

Chapter 4: The impact of meaning on online phonological form learning

4.1 Introduction

The first challenge in acquiring a new spoken word concerns learning its phonological form. From the data reviewed in the previous chapters, it is evident that adults can quickly acquire knowledge about new word forms (e.g. Church & Schacter, 1994; Forster, 1985; Salasoo & Shiffrin, 1985), although these new forms can be underspecified (Church & Schacter, 1994; Johnston et al., 2004; McCandliss et al., 1997), suggesting that newly-learnt words may benefit from additional consolidation time or training. There is also a body of evidence suggesting that adults are able to rapidly acquire knowledge about word meanings (e.g. Breitenstein & Knecht, 2002; Gupta, 2003; Rodd et al., 2012). However, whilst learning new word meanings can be beneficial for the recognition, identification and explicit recall of newly-learnt phonological forms (e.g. Leach & Samuel, 2007; Rueckl & Dror, 1994; Whittlesea & Cantwell, 1987) semantic exposure can delay lexicalization relative to when newly-learnt words are acquired with no associated meaning (Dumay et al., 2004; Takashima et al., 2014; cf. Henderson, Weighall, & Gaskell, 2013). The immediate semantic advantage for the recognition and recall of novel words alongside a slower lexicalization time-course suggests that semantics may differentially impact the faster and slower aspects of word memory formation. As such, there is not presently a clear picture of the full time-course of a semantic influence on spoken word learning. This chapter therefore investigates the earliest stages of learning a new word by addressing whether semantic exposure affects the online acquisition of new phonological forms.

4.1.1 Form and meaning in spoken word recognition

Influential models of spoken word recognition propose an interaction between different sources of information during word recognition (as reviewed in detail in Chapter 1). In particular, the Distributed Cohort Model (DCM; Gaskell & Marslen-Wilson, 1997) posits that form and meaning are distributed in a single representational output layer, and accessed in parallel during word recognition[5]. At this output layer each lexical representation corresponds to a specific pattern of activation across the network, distributed across units activated by both phonological and semantic aspects of lexical knowledge. There are two key considerations regarding the DCM which suggest that meaning may facilitate spoken word recognition. Firstly, because a low level representation of the speech input is mapped onto both phonology and semantics in the distributed representational layer, this implies that connection weights in the network must have information about both types of mappings, suggesting phonology and semantics may be able to interact during the activation of the representational layer (as also noted by Tyler, Voice, & Moss, 2000, and Zhuang, Randall, Stamatakis, Marslen-Wilson, & Tyler, 2011). Secondly, the DCM predicts that nonwords will also activate the distributed representational layer, albeit less than words. It thus follows that in the learning of a novel word, a novel word with a semantic association may elicit a higher level of activation than one without a semantic association. Because the activation level of the network corresponds to word recognition, within the DCM this implies that a novel word with a meaning may elicit a stable pattern of activation (and thus be recognized) more quickly than a novel word without a meaning.

The influence of meaning on the phonological processing of known words was investigated by Tyler et al. (2000). Two tasks measuring word recognition speed, auditory lexical decision and repetition naming, were used to assess the impact of imageability on spoken word recognition latencies. Imageability is a semantic factor indexing the richness of a word's semantic features which can be perceived; for example, *chair* is a highly imageable word associated with sensory properties (e.g. feel, size, shape) whereas *hope* is low in imageability. Tyler et al. (2000) observed that high imageability words had faster auditory lexical decision and repetition naming reaction times than low imageability words, suggesting that high imageability facilitated the recognition process. Interestingly, however, this was the case only for words in *high* competition cohorts. Words in high competition cohorts had a large cohort size (measured by the number of words sharing onset CV or VCV with the stimulus word) and many cohort members with a higher frequency than the stimulus word, and thus a

[5] As discussed in Chapter 1, in the DCM the speech input is mapped onto a set of units representing phonetic features, followed by a layer of hidden units. The hidden units feedforward to a representational output layer, in which phonology and semantics are represented in parallel and accessed simultaneously. At this output layer each lexical representation corresponds to a specific pattern of activation across the network, distributed across units activated by both phonological and semantic aspects of lexical knowledge.

high level of phonological competition during recognition; the reverse was true for words in the small cohort group. Critically, the imageability effect being present only for the high competition cohort words suggested that when the process of recognition was more difficult, imageability could aid the discrimination process for known words. Strain et al. (1995) reported comparable findings in visual word recognition, with an imageability effect for low frequency exception words in a naming task. From these results Strain et al. (1995) proposed that when an orthography-to-phonology mapping was inefficient or error-prone semantics played a larger role in word naming (but cf. Monaghan & Ellis, 2002, for age-of-acquisition mediating this imageability effect). Taken together, the above evidence is consistent with the idea that semantic information may benefit the online recognition of known words as the discrimination process becomes more challenging.

Why should it be the case that semantic properties can facilitate the speed of spoken word recognition? An extensive literature suggests that spoken word recognition involves the parallel activation of multiple lexical candidates, with a continuous process of activation and competition between these candidates activated by the incoming speech signal, until activation settles on a single lexical item (Gaskell & Marslen-Wilson, 2002; Luce & Pisoni, 1998; McClelland & Elman, 1986; Norris, 1994). This simultaneous activation of multiple lexical candidates in a cohort has also been found to correspond to the activation of semantic correlates of the lexical candidates. Marslen-Wilson (1987) observed that the auditory presentation of the segment /kæpt/ (partially activating both /kæptın/ and /kæptıv/) sped up lexical decision reaction times to the visual presentation of *ship* and *guard*. These data implied that during the perception of the initial ambiguous /kæpt/ segment, semantic features of the potential candidate words were activated, and this semantic activation facilitated recognition of the semantically related target words (similar findings were also obtained by Zwitserlood, 1989). Similarly, Tyler and Moss (1997) examined the semantic priming of high and low imageability words in a patient with a generalised auditory processing deficit. Priming for both high and low imageability words was intact in the visual modality, but only high imageability words elicited priming in the auditory modality. Tyler and Moss (1997) thus suggested that the degraded auditory input for the words in the auditory modality was not sufficiently compensated for by semantic activation in the low imageability condition to elicit semantic priming effects.

Given this co-activation of the semantic properties of lexical candidates prior to word recognition, the facilitation of high-imageability words in Tyler et al. (2000) may have been due to increased activation levels of these words during the activation of multiple lexical candidates, which served to increase their discriminability from competitors in large cohorts. Greater numbers of semantic features are associated with increased activation in models of semantic processing (e.g. Collins & Loftus, 1975). In terms of the effect of this increased activation on lexical processing, Plaut and Shallice (1993) suggested that the representation of words over a larger number of semantic features (as is the case for high imageability words) generated stronger basins of attraction such that a network can settle into a stable state more rapidly; this stability could subsequently correspond to faster word recognition. Consistent with this proposal, increased or stable activation is incorporated in both interactive activation (e.g. TRACE, McClelland & Elman, 1896) and distributed (e.g. DCM, Gaskell & Marslen-Wilson, 1997) models as boosting evidence for a specific lexical candidate, and thus contributing to faster recognition latencies. Semantic properties may therefore facilitate the recognition process by increasing a lexical candidate's overall activation level, serving to decrease the time for recognition.

The mechanism of a phonological and semantic impact on lexical processing was investigated by Zhuang et al. (2011), by testing the joint contribution of phonology (via cohort size) and semantics (via imageability) to the neural processing of spoken words. The interaction between cohort size and imageability engaged the left posterior superior temporal gyrus (LpSTG), a region associated with phonological processing, and the middle temporal gyrus (MTG), a region involved in accessing meaning representations. In the LpSTG and MTG large-cohort words had a larger imageability effect, measured by the difference in activation between high and low imageability words, compared to small cohort words. Zhuang et al. (2011) interpreted this effect to suggest that word meanings were activated early in the recognition process and modulated LpSTG activity as a function of the word's phonological competitor environment. Specifically, in high competition environments where differentiation of a phonological form from its competitors is more challenging, the increased activation of words with many semantic features may aid their discrimination from other cohort members, suggested by the LpSTG/MTG interaction.

In sum, the above data are consistent with cognitive models of spoken word recognition positing a continuous interaction between phonology and semantics in the activation of multiple lexical candidates (Gaskell & Marslen-Wilson, 1997; Marslen-

Wilson, 1987), and models with an interactive architecture more generally (e.g. McClelland & Elman, 1986). Whilst these models do not make explicit predictions about a semantic facilitation on the recognition process, there is some empirical evidence to suggest that recognition is sensitive to the semantic features of words when discrimination between lexical candidates is more challenging.

4.1.2 Semantic effects in online measures of word learning

From the above observations the key question is whether semantic knowledge can also facilitate spoken word recognition during the acquisition of new words, or whether newly-learnt words must have an established lexical representation for semantics to facilitate their recognition. One possibility is that semantics could benefit recognition during learning, suggesting this interactive mechanism could operate during *both* the acquisition of new words and the processing of known words. Alternatively, a second possibility is that because a semantic benefit in the recognition of large-cohort words is critically related to the competition process and parallel activation of multiple lexical candidates, newly-learnt words may require established lexical representations, with inhibitory links to existing words, for semantic knowledge to impact upon the recognition process.

Indeed, evidence for semantic effects in measures of online processing for newly-learnt words is elusive. During the reading aloud of newly-learnt written words immediately after training, no difference has been observed between phonological and semantic training in terms of naming latencies (e.g. Hultén et al., 2009; McKague et al., 2001, in children; Sandak et al., 2004). Notably, however, this may be the case due to the nature of the word stimuli used. Hultén et al. (2009) used Finnish items with average phonological and orthographic neighbourhood sizes of 3.0-3.7, compared to a cohort size of >200 in Tyler et al. (2000). Sandak et al. (2004) likewise used novel words with neighbourhood densities ranging from 4-8. Based on the data of Tyler et al. (2000), in which word imageability facilitated recognition for high cohort words only, one possibility is thus that such facilitation was not present in these studies because discrimination between the to-be-learnt words was not sufficiently challenging for semantics to exert a beneficial effect[6]. Note, however, that naming tasks also include a substantial phonological output component and it may thus be the case that the absence of a semantic benefit relates to the recruitment of primarily phonological information to meet this task demand (as explained in Chapter 2, section 2.4).

Studies of novel word processing during and after learning have thus capitalized on the temporal precision of event-related potentials (ERPs) to measure when in processing the response evoked by novel words converges with that evoked by known words. A particular ERP component of interest has been the N400, a negative-going ERP component peaking approximately 400ms after stimulus onset. The N400 is often used to index the acquisition of new word meanings, whereby a more negative N400 potential is elicited by semantic incongruencies (Kutas & Federmeier, 2011, for review), and word recognition (e.g. Desroches, Newman, & Joanisse, 2009; O'Rourke & Holcomb, 2002). Mestres-Missé et al. (2007) investigated novel word meaning acquisition using the N400, by teaching participants novel written words in three semantically constraining sentence contexts. By the third sentence the N400 response evoked to sentence-final novel words was equivalent to that elicited by known words, an effect which the authors interpreted as indexing the rapid acquisition of novel word meanings. In a subsequent relatedness judgment task, participants made related/unrelated judgments to a real word target, which was semantically congruent or incongruent with a trained novel word prime. A reduction in N400 amplitude was observed for real word targets which were semantically congruent with the novel word primes, relative to targets which were semantically incongruent with the novel word primes and novel words for which no meaning had been acquired. No such reduction was observed for novel words trained in sentences with inconsistent meanings. The shift of novel word ERPs to converge with known word ERPs within a few exposures, and the subsequent sensitivity of the N400 to semantic attributes of the newly-learnt words, has been replicated for novel words acquired implicitly in story contexts and a range of sentence-context conditions (Balass, Nelson, & Perfetti, 2010; Batterink & Neville, 2011; Borovsky et al., 2010; Borovsky et al., 2012; Frishkoff, Perfetti, & Collins-Thompson, 2010; Perfetti, Wlotko, & Hart, 2005). Whilst these findings are primarily in the visual domain, the

[6] Note that cohort size in the Tyler et al. (2000) study was defined as the number of words sharing an onset CV or VCV with a stimulus. This cohort size measure is thus more extensive than the measure of a word's phonological/orthographic neighbourhood size, which are the number of words differing by one letter or phoneme to the item. Whilst the measures are not directly comparable the large numerical difference between the measures in each study nonetheless suggests that the novel words used in Hultén et al. (2009) and Sandak et al. (2004) were less challenging for discrimination compared to the existing words in Tyler et al. (2000).

convergence of novel and known-word ERPs has also been observed after limited exposure to spoken words (Shtyrov et al., 2010). Taken together, these findings suggest that novel and known word ERPs can rapidly converge and this convergence can provide a measure of novel word learning. A critical point, however, that these studies do not address the impact of semantic acquisition on earlier, form-based stages of word recognition (which is approximately 170ms after word onset in visual word recognition, indexed by the N170; Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; Ruz & Nobre, 2008; Yoncheva, Blau, Maurer, & McCandliss, 2010). Whether semantic training operates on the earlier stages of form acquisition is thus a question that remains relatively underexplored.

In relation to this question, a similar line of evidence concerns the sensitivity of ERPs to the temporal profile of spoken word recognition. A central point here concerns the presence of a *recognition point* in spoken words. The recognition point is the time after word onset at which a word can be recognized as an existing lexical item, or diverges from known items and is thus identified as a nonword. Experimental approaches to defining word recognition points vary, from taking the average point at which participants identify a word with 80% accuracy in a gating task (e.g. van Petten, Coulson, Rubin, Plante, & Parks, 1999), or identification from coarticulation/assimilation. Critically, the recognition point differs from the *uniqueness point*, which is the phoneme at which a spoken input matches only one lexical candidate, and is thus defined by recourse to the lexicon. To illustrate this distinction, compare the phonemes in *pen* (/pɛn/) and *pet* (/pɛt/). When comparing just these two words, the uniqueness point is at the onset of the final consonant. However, compare the articulation of /ɛ/ in each word; the different articulation suggests the recognition of *pen* versus *pet* can be made at the onset of the vowel, and thus prior to this uniqueness point (Marslen-Wilson, 1987). In this chapter, *recognition point* will henceforth be used to denote the time when the speech signal contains sufficient information for word recognition, without necessarily corresponding to the lexical uniqueness point.

Investigations of the time in word processing in which ERP components reach a peak amplitude, known as *peak latency*, have observed that the peak latency of the N400 is correlated with the recognition point in known words, whereby the N400 peaked on average 23ms later for words with late relative to early recognition points (Woodward, Owens, & Thompson, 1990; see also O'Rourke & Holcomb, 2002, and van Petten et al., 1999, for similar findings). Desroches et al. (2009) delineated the time-course of spoken word recognition more precisely by comparing ERP responses to visually presented real words, which were preceded by a nameable object picture. The picture-word name pairs were phonologically related in offset (e.g. cone-bone), onset (e.g. cone-comb) or phonologically unrelated (e.g. cone-fox). Words which were related in offset elicited a larger early phonological mismatch negativity (230-310ms following word onset) due to an early expectancy violation. In contrast, onset-related words elicited a larger late N400 response (410-600ms) due to a late expectancy violation. Desroches et al. (2009) interpreted these results in concordance with a dynamic model of spoken word recognition (e.g. TRACE; McClelland & Elman, 1986) incorporating both bottom-up phonological competition and top-down expectation from the lexical level. Taken together, these studies indicate that ERPs can capture the temporal profile of spoken word recognition, and provide a measure as to when novel and known words evoke similar responses during online processing.

4.1.3 Summary

In sum, the above data present an intriguing picture. Firstly, whilst a semantic benefit has been reported for the recognition of known words when discrimination is challenging (Tyler et al., 2000; Zhuang et al., 2011), there is no evidence of the same semantic benefit extending to the online processing of new words (e.g. Hultén et al., 2009; Sandak et al., 2004). This discrepancy may be associated with the phonological neighbourhood size of the items used, however, or the phonological output component of naming tasks. Second, the temporal precision of ERPs provides a valuable index of the online processes related to spoken word recognition (Desroches et al., 2009; O'Rourke & Holcomb, 2002; van Petten et al., 1999; Woodward et al., 1990). However, a large body of extant studies investigating the impact of semantic acquisition on novel word processing have done so using written words (e.g. Batterink & Neville, 2011; Borovsky et al., 2012; Mestres-Missé et al., 2007), and observed N400 effects in response to semantic judgment tasks. It therefore remains to be explored whether the provision of semantic information during learning may impact upon earlier stages of spoken word recognition during initial acquisition.

4.2 Study 1

The current study therefore asked whether the provision of semantic information would benefit spoken word recognition during the learning of new phonological forms. This question was motivated by the beneficial effect of semantics in challenging known word recognition, supported by considerations from models of spoken word recognition. Critically, however, as meaning may act to aid the resolution of lexical competition, it is theoretically interesting whether meaning impacts upon form-based processing before the formation of inhibitory connections between new phonological representations and existing words (as reviewed in Chapter 1 and Chapter 3). Study 1 therefore trained participants on new spoken words with and without a semantic referent, and capitalized on the temporal sensitivity of ERPs to measure the online recognition of these words during learning. The critical measure of learning was the convergence between novel-word and known-word ERP amplitudes at the average point of word recognition in the speech signal. It was predicted that if the provision of semantics facilitates the earlier stages of word recognition during learning, semantic-associated word ERPs should align with known word ERPs (cf. Balass et al., 2010; Batterink & Neville, 2011; Borovsky et al., 2012; Mestres-Missé et al., 2007; Shtyrov et al., 2010) earlier in learning than for non-semantic words. If, however, semantic exposure impacts only upon post-recognition processes, an effect of training condition should only be observed in a post-recognition N400 time window, with an equivalent time-course of convergence between novel and known-word ERP amplitudes in the earlier form-recognition time window.

4.2.1 Semantic learning paradigm

Addressing the contribution of semantic acquisition to spoken word recognition necessarily required a learning paradigm to contrast the acquisition of new words with and without semantic information, in a way that equated learning goals and information load across learning conditions. From an extensive literature of teaching participants new word meanings (of which an overview was presented in Chapter 2), a few key studies are particularly relevant to this issue. Cornelissen et al. (2004) and Whiting, Chenery, Chalk, Darnell, and Copland (2007) both trained participants on novel name-object pairs, with and without additional semantic information. Cornelissen et al. (2004) provided semantic information with a short definition of the object, whilst Whiting et al. (2007) provided semantic information with a description of the object's function. Interestingly, the retrieval of the object names in both studies was not benefited by semantic information, and in Whiting et al. (2007) picture names trained with definitions were disadvantaged relative to the picture names with no associated definition. Cornelissen et al. (2004) suggested that the semantic information was not sufficiently enriching to benefit picture-name memory, whilst Whiting et al. (2007) suggested that semantic information could be actively detrimental by reducing processing time for the name itself. These findings suggest that comparing semantic and non-semantic learning necessitates a similar information load in both conditions (a similar argument is made by Angwin, Phua, & Copland, 2014). Developing this idea, James and Gauthier (2004) trained participants on novel name-object pairs, in which the 'semantic' condition presented three adjectives alongside the novel name-object correspondences, whilst the non-semantic 'name' condition presented three proper names. These conditions were such that an equivalent amount of information was presented in both conditions, but meaningful attributes were acquired only in the 'semantic' condition. Again, however, no semantic benefit was present in the retrieval of the novel picture names. These findings raise a second useful property of semantic/non-semantic training comparisons: the equating of learning goals between conditions. Importantly, several reports have suggested that a focus on different levels of linguistic information can impact upon learning outcomes (Yoncheva et al., 2010; see also Ruz & Nobre, 2008, & Yoncheva, Maurer, Zevin, & McCandliss, 2014, for similar reports from known word processing) and the systems mediating the retrieval of new words (Gronholm et al., 2007; Laine & Salmelin, 2010; Takashima et al., 2014; Yoncheva et al., 2010). It follows that a comparable contrast of semantic and non-semantic word learning should recruit similar processes during training, with only the provision of semantic information differentiating the learning conditions.

These twin demands of i) an equivalent information load between semantic and non-semantic conditions, and ii) equivalent task goals motivated the development of a new learning paradigm in Study 1. Previous experimental work has focused on training participants on novel name-object mappings whereby a subset of these mappings are consistent, and thus learnable, and a subset of these mappings are inconsistent and thus unlearnable (Breitenstein & Knecht, 2002; Breitenstein et al., 2005; Dobel et al., 2009; Yu & Smith, 2012). The current study adopted a similar approach by teaching participants two categories of novel spoken words which were always accompanied by a visually presented picture. One category of novel words had a strong relationship with a visual referent across trials, and an associative link could thus be learnt between a novel word and visual referent; this is referred to as the *correlated* condition. The second category of novel words had no consistent relationship with a visual referent across trials, meaning no associative relationship could be learnt; this is referred to as the *uncorrelated* condition (Figure 8). This learning paradigm equated task goals across the

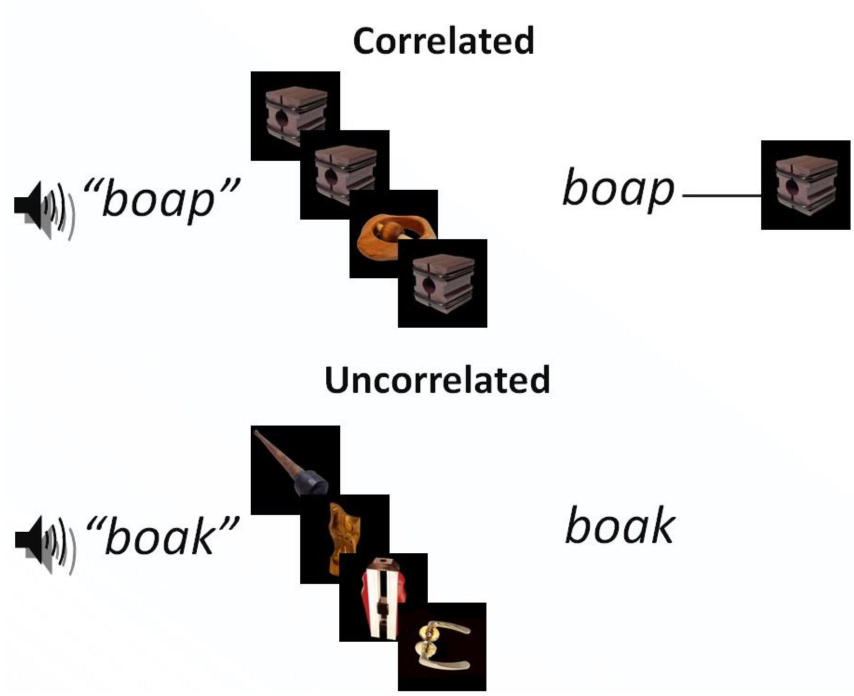

Figure 8. A schematic of the Correlated-Uncorrelated learning paradigm.
In the *correlated* condition a novel spoken word would be presented with a high co-occurrence with a visual referent across trials. In contrast, in the *uncorrelated* condition there would be no co-occurrence between a spoken word and a systematic visual referent across trials. At the end of learning participants could therefore acquire knowledge of a novel spoken word with an associated picture in the *correlated* condition, shown on the right-hand side of the figure, with equivalent knowledge of a spoken word form only with no associated picture in the *uncorrelated* condition.

two learning conditions, allowing the examination of the impact of semantic acquisition on phonological form learning, without categorical differences in information load or processing goals between the two novel word categories.

4.2.2 Using ERPs to measure spoken word learning

EEG records voltage change over the scalp over time. This voltage change is generated by excitatory postsynaptic potentials from pyramidal cell dendrites, which are oriented in parallel along the cortical sheet. The sum of these postsynaptic potentials over large numbers of cortical neurons with similar voltage fields, which are spatially aligned, is a dipole. Dipoles are charges that can be recorded by the electrodes placed over the scalp for EEG acquisition. As a dipole charge recorded at the scalp can therefore reflect the summed activity of 0.5 to 1 million neurons, the spatial orientation of dipoles is significantly smeared. This smearing is further increased by additional volume conduction and the scalp. The EEG signal thus measures the change of these dipole charges over *time*, at relative electrode positions on the scalp, with a millisecond temporal precision.

EEG data are averaged over all occurrences of a particular stimulus event of interest, such as the presentation of a word; this average is an event-related potential (ERP). Key to forming ERPs from raw EEG data is extracting the signal, a systematic evoked voltage in response to a given stimulus, from the electrical noise of non-stimulus-specific brain activity, muscular artefacts and environmental noise (i.e. background electricity from the stimulus presentation computer). After a series of pre-processing steps to maximize this signal-to-noise ratio in the EEG data, ERPs measure a *systematic* voltage change over time in response to a stimulus. It is for this reason that ERPs are an ideal measure to compare the temporal profile of novel and known spoken word processing. Critically, ERPs are informative about the *online* processing of a spoken word and it is this feature which differentiates them from reaction time measures, which are the output of a decision process rather than the aspects of processing leading up to it. Further, ERP responses to a stimulus can be measured in the absence of any specific task, providing a measure of stimulus processing without task demands. It is important to recognize that ERPs can therefore provide a bias-free, implicit measure of online spoken word processing rather than addressing the neural mechanisms of these effects per se.

Accordingly, one of the most interesting aspects of spoken word processing is its temporal profile. At word onset there is first an analysis of low-level acoustic features of pitch and intensity, common to all auditory stimuli (Rayner & Clifton, 2009, for review). Word and pseudoword stimuli subsequently begin to be treated differently to other classes of auditory stimuli, as the neural signal is processed in the core auditory and linguistic regions in the inferior frontal cortex (Pulvermüller, Shtyrov, & Ilmoniemi, 2003). When sufficient information is available in the auditory signal to identify the word an enhancement[7] of brain responses to known words compared to pseudowords emerges 50-80ms after this recognition point, as measured by MEG (MacGregor, Pulvermüller, van Casteren & Shtyrov, 2012; although see Pulvermüller & Shtyrov, 2006, for suggestions of a 100-200ms delay in lexicality effects for non-attended words). Recognition of the word form is followed by an analysis of higher-level attributes, such as lexical and category-level semantics (e.g. Ruz & Nobre, 2008). As explained previously, the term *recognition point* will be used in this chapter to denote the time at which sufficient information is present in the speech signal for an item to be recognized

[7] Note that the polarity of the difference between known and novel words depends on the ERP component being measured, along with the type of task used to measure processing.

in the context of a particular experimental task, and is thus distinct from the lexical uniqueness point.

The first ERP measure taken in the current study was thus the evoked voltage over the time window in the speech signal in which known and novel words could be recognized. The Methods section explains this *form-recognition* window in more detail. The second ERP measure was the evoked voltage over the *N400* time window, at 450-600ms following word onset, after recognition has taken place (Kutas & Federmeier, 2011, for review). The N400 is typically cited as index of the semantic analysis of a word (in sentence contexts or priming tasks, for example). However, the N400 can also be affected by repetition, typically with more positive N400 responses after repetition priming for familiar than unfamiliar items. One interpretation of this aspect of the N400 is thus as a measure of recognition memory (Rugg & Doyle, 1992). The N400 is further suggested to be related to the ease of recognition of a word, with more positive amplitudes for greater ease of word recognition (e.g. O'Rourke & Holcomb, 2002; van Petten et al., 1999). The current study thus examined the N400 as an exploratory index of post recognition processing for each novel word category relative to known words.

In sum, ERPs can provide a window into the online learning of new spoken words by delineating early (reflecting spoken word recognition processes) and late (reflecting post-recognition access) processing without requiring an overt response. Moreover, the use of known words as a baseline condition against which the learning of new spoken words is measured allows the observation of whether newly-learnt words are treated similarly to known words during the recognition process, and whether this is modulated by learning condition.

4.2.3 Methods

4.2.3.1 Participants

Twenty undergraduate and graduate students at Royal Holloway, University of London (mean age = 20.63 years, SD = 3.68 years, range 18-35; 14 females) took part in the study. All participants were right-handed, native English speakers. Handedness was assessed via self-report, and native language was verified from questions on language experience from the experimenter. The participants had either normal vision, or corrected-to-normal using glasses, and no known auditory, language or learning difficulties. All participants were paid for their participation. The study received ethical approval from the Psychology Department Ethics Committee at Royal Holloway.

Table 1. The stimulus set used in Study 1.

Known Words	Novel words (Set 1)	Novel words (Set 2)
bike /baɪk/	**bife** /baɪf/	chuke/ʃuk/
kite/kaɪt/	**kipe** /kaɪp/	daf /dæf/
loaf /loʊf/	**loak** /loʊk/	lup /lʌp/
pipe/paɪp/	**pite**/paɪt/	vate /veɪt/
knot /nɒt/	chufe/ʃuf/	*knop*/nɒp/
rake /reɪk/	dak /dæk/	*rafe*/reɪf/
roof /ruf/	lut /lʌt/	*ruke* /ruk/
soap /soʊp/	vape /veɪp/	*soat* /soʊt/

Note. The IPA transcription is shown beside each word. The table shows the relationship between the known words and two novel word conditions, in which the phonologically overlapping Known and Novel Set 1 words are shown in bold, and the phonologically overlapping Known and Novel Set 2 words are shown in italics. The remaining words are the phonologically overlapping novel-word pairs, of which one member of each pair was in each novel word condition. The critical point was that this relationship between each condition was the same for each participant, but the words in each novel word condition were counterbalanced between participants.

4.2.3.2 Materials and design

Word Stimuli. Twenty-four spoken words were presented during the experiment. Eight were known words and 16 were novel pseudowords, of which 8 were included in each of the correlated and uncorrelated novel word conditions (Table 1). All stimuli were monosyllabic, with a CVC phonological structure. Each known word had one onset phonologically overlapping novel pseudoword (e.g. *kite-kipe)*. The remaining eight pseudowords had an onset phonologically overlapping pair (e.g. *vape-vate*). All phonological pairs were thus onset competitors, which diverged at the final consonant. Half of the known word phonological pairs were allocated to the correlated-word condition and half were allocated to the uncorrelated-word condition. Of the eight pseudowords which were pairs with each other, one member of the pair was allocated to each novel word condition. There was thus an equal phonological relationship between each of the three conditions in terms of phonologically related pairs shared with the other two conditions, but with no phonologically overlapping pairs within conditions (Table 1). The onset phonological overlap between items was intended to promote learning based on precise phonemic attributes of the novel words, and to make discrimination between items sufficiently challenging (Tyler et al., 2000).

The novel words were systematically assigned to the correlated and uncorrelated conditions for each participant such that four novel words in each condition were always phonological pairs of the known words. The remaining four novel words were phonological pairs with four words in the other novel word condition. Half of the pairs consisted of contrasts of unvoiced consonants that varied on the place of articulation (/p/-/t/), and half the pairs differed in place and manner of articulation (/k/-/f/). The phonologically overlapping pairs were split between the novel word learning conditions such that each phonological contrast was present an equal number of times in both conditions.

The 8 known words were selected using the CELEX English Wordforms Lexicon (Baayen, Piepenbrock, & van Rijn, 1993) to choose words which were simple, imageable concrete nouns. The known words were approximately matched on phonological neighbourhood size, defined as the number of words that could be created by substituting a single phoneme in any position in the word (M = 20.25, SD = 4.33; range 13-26). The known words had an average CELEX log frequency of 1.04 occurrences per million (SD = 0.39; range 0.6-1.68). Data for all lexical variables was obtained from N-Watch (Davis, 2005). Phonologically overlapping novel words were generated from the 8 known words. Half of these novel words differed from the known words on the place of articulation contrast /t/-/p/ at the final consonant, and half on the place and manner of articulation contrast /k/-/f/ at the final consonant. The additional 8 novel words, which were phonologically overlapping pairs with each other, consisted of two pairs with a /t/-/p/ contrast and two pairs with a /k/-/f/ contrast. The final stimulus set thus consisted of 12 phonologically overlapping pairs, whereby half of these pairs differed on the /t/-/p/ contrast and half on the /k/-/f/ contrast. Independent t-tests verified no significant difference between the known and novel word groups on orthographic neighbourhood size, neighbourhood frequency mean, and the number of positions in the word where phonological neighbours could be generated (all ts < .6, ps > .5). Appendix 1 presents a table of these values.

The words were recorded in a soundproof booth, using CoolEdit with a monoaural (single-channel) recording at 22Hz. The words were spoken by a native English-speaking female with a Southern British English accent, and repeated several times to obtain tokens with the clearest phonological contrast between the overlapping pairs. The words were cut in CoolEdit for the onset of the speech signal to be at 0ms, and tokens were chosen such that the recognition point within each phonologically overlapping pair, whereby the recognition point was defined as vowel offset, were as closely matched in time as possible. The average recognition point across all 24 spoken words was at 275ms after word onset (SD = 57ms, range = 190-395). This recognition window in the speech signal would be the time window subsequently used for the ERP analyses. Appendix 2 presents a table of the auditory profile of each item.

Each of the 24 words were presented 28 times each throughout the experiment. Participants were exposed to each word once before the next round of exposures began. The words were presented via speakers on either side of the task computer, approximately 49cm from the participants' ears.

Visual Stimuli. The visual stimuli set consisted of 48 pictures in total: eight known objects which were prototypical referents of the known words, and forty novel objects which were photos of obscure real objects. The novel object pictures were obtained from a Google image search, and were checked to have no clear linguistic label in a small survey prior to the experiment (N = 6). The novel objects were selected to be matched both to each other and the known objects in terms of complexity, such that no single object was particularly eye-catching or memorable; Appendix 3 shows the 48 pictures used in the learning task. All objects were edited in Photoshop AS to match them on brightness and size, and were presented on a black background. Eight of the novel objects were randomly selected as referents to go with the correlated words for each participant; the remaining 32 novel objects were then foils (8 in the known word condition, 8 in the correlated condition, and 16 – 2 per exposure – in the uncorrelated condition). A different set of correlated-word referent pictures was thus selected for each participant, ensuring that no idiosyncratic differences between the visual stimuli could have consequences for learning across participants.

On each trial, two objects were presented on a computer monitor (depth 30.5cm, width 41cm, resolution 1280 x 1024px), at 2^{o} of a visual angle either side of a central fixation cross. Both stimuli subtended a visual angle of no more than 9^{o} from fixation to reduce participants making saccades at the onset of the objects.

Learning Paradigm Design. The experiment consisted of 672 trials in total (224 per condition over the full experiment). This included 28 exposures to each stimulus. Trials for the three conditions were interleaved, and participants were exposed to each item (i.e. each of the 24 words and 48 objects) once before the next round of exposures. Presentation order of the conditions was randomized within each exposure. Figure 9 presents a full trial layout.

In both the known and the correlated word condition, one picture would be a referent object and one would be a foil object. Participants' task was to use the left or right arrow key to select the correct referent object for the word, or respond with the down arrow key if they thought neither object was the referent for the word. Side of presentation (left or right) of the referent object was counterbalanced across trials, and the objects were flipped along their *x*-axis (i.e. mirrored) on half the trials to minimize attenuation effects.

In the known and correlated conditions the referent could be either present or absent. To maintain equal probability of referent presence or absence, the referent was present on 50% of the 28 trials for each word. Referent-present and referent-absent trials were mixed within each exposure, whereby half the words in the known and correlated condition would appear with their referent and half would appear with the referent for another word in that condition. On the referent-absent trials, the referents were only switched within-condition (to maintain exposure frequencies to each object across the three conditions, and prevent increasing task difficulty by a correlated word's

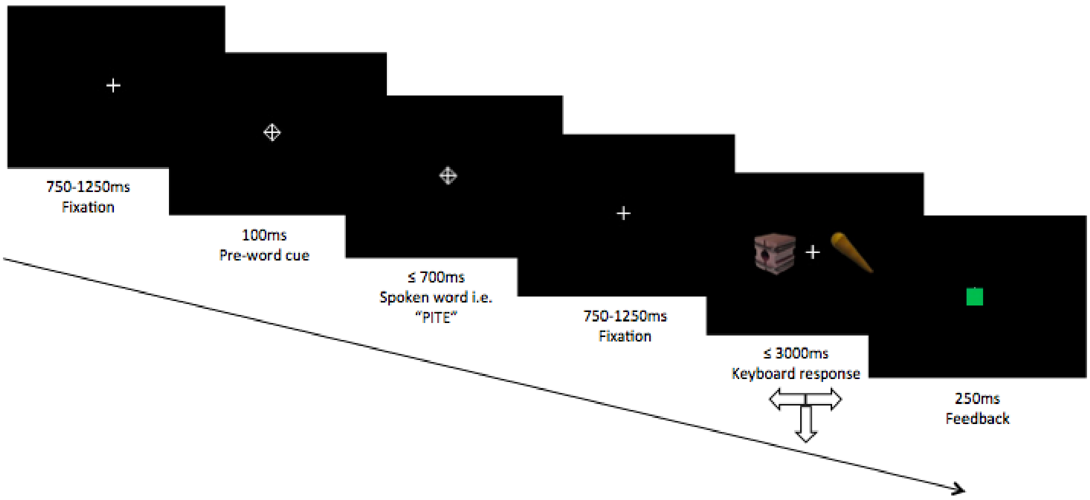

Figure 9. The layout of a single learning trial.
After responding participants received positive ('correct') feedback with a green square, or negative ('incorrect') feedback with a red square of the same size.

referent appearing with a phonologically overlapping uncorrelated word). Each word appeared with its referent object 14 times, and with each non-referent object from that condition twice (there were seven non-referent objects and thus 14 referent-absent exposures).

Whilst based on the correlation between words and referent objects participants should have been able to learn the referents in the correlated condition without feedback, feedback was given after each response for two reasons. The first was to engage participants in learning the word-referent associations, rather than learning passively from cross-trial correlations across exposures. The aim was that an active task would help participants to learn the novel words in a relatively low number of exposures (just 28 per word over a ~50 minute experiment). The second was to randomly distribute 33% positive and 66% negative feedback throughout the uncorrelated word trials, to prevent participants disengaging from the uncorrelated words. As there were no systematic referent objects for the uncorrelated words, it would formally be correct for participants to respond 'neither' on each trial. However, providing 'correct' feedback in these instances would lead to participants learning a stimulus-response association between each uncorrelated word and the 'neither' response. Rather, the objective of this condition was for participants to learn no association, either with a referent object or with a response. However, consistent negative feedback may have led to a reduced motivation to process the uncorrelated words, which would confound the ERP response. Random feedback was therefore provided, in which participants received 'correct' feedback on 1/3 of trials and 'incorrect' feedback on 2/3 of trials across the experiment, to enable the uncorrelated words to maintain a degree of relevance throughout the task but without any systematic association.

The foil assignment procedure consisted of the rotation of the foils through the words, with each foil only appearing with each word once during the experiment. There were three critical points to consider. The first was to ensure that for any given trial participants had been exposed to both the referent and foil object an equal number of times; secondly, after n exposures to a word, correct performance on exposure $n + 1$ should be driven by knowledge of the specific referent for that word. Specifically, this meant that participants should not respond based on learning the set of foil objects, and therefore knowing only that the foil was the incorrect object (rather than acquiring the mapping between the novel word and referent object). Similarly, participants should not be able to respond based on learning the 8 referent objects as a category of 'correct' objects for the correlated-word condition, and thus respond based on knowledge of these ‘correct’ objects rather than a one-to-one mapping between the correlated word and associated referent.

There were four points in the design to counteract these issues. Firstly, participants were exposed to every item once (each of the 24 words and 48 objects) before the next round of exposures began. Secondly, none of the foil objects were also referents; that is, the foil object set, F, was F = A – R, where A was all the 40 novel objects and R was the 8 referent objects, randomly selected from the novel object set for each participant. Third, one object from F was then pseudo-randomly assigned without replacement to each word, until all words were assigned a foil object (with two foil objects in the uncorrelated condition) and F was then reset with all 32 foil objects to be assigned on the next round of word exposures. The pseudo-random assignment was contingent on whether a given foil had previously appeared with a given word; if so, the foil was not assigned to that word again. This meant that there were no spurious word-foil correlations in the known and correlated-word conditions – that is, each foil object appeared with each word only once. Additionally, participants were never exposed to a foil object more than a referent because, within one rotation of the 24 words, each referent object and each foil object appeared only once.

Lastly, to ensure that participants responded based on specific knowledge about a words’ association with an object, rather than merely learning a ‘relevant’ category of referent objects (where responses lead to positive feedback, irrespective of the preceding word), referents were switched within the known and correlated word conditions. This meant that the object presented alongside the foil was still a ‘relevant’ object, but it was a referent for another word; participants therefore had to have learnt the specific one-to-one mapping between a word and referent to correctly respond ‘neither’ on referent-absent trials.

In sum, the foil object and referent object set were independent, and participants were exposed to each item n times before exposure n + 1, to ensure that previous exposure frequencies for each item were equal on any given trial and over the duration of the experiment. Uncorrelated word responses were followed by positive feedback randomly given at chance levels (1/3 of trials) across exposures, to maintain a level of processing motivation for the words throughout the experiment. In the known and correlated word conditions 50% of trials were referent-absent, to ensure participants chose a referent based on its association with a specific word, rather than merely learning it as part of a ‘relevant’ category of objects.

4.2.3.3 Procedure

Participants completed the task in a quiet booth, and the task was run in E-Prime 2.0. There was a self-paced break every 48 trials to help participants maintain focus on the task and correct any noisy electrodes. Participants were instructed that they would hear a word followed by two objects, and their task was to learn “which words go with which objects”. Instructions were kept deliberately ambiguous so as not to inform participants explicitly of a mutual exclusivity bias (i.e. that there was only one object for each word) or inform them that some words would not have a referent. All participants were debriefed regarding the purpose of the experiment after the task. Notably, informal discussion with participants indicated that on the whole they were unaware of two distinct novel word learning conditions. Participants were instructed to maintain fixation, especially at the onset of the two objects. The EEG set-up, experimental task and debriefing took approximately 1.5 hours in total per participant.

4.2.4 EEG Recording and Analysis

All EEG data were acquired using a 64-channel Biosemi ActiveTwo recording system, which used active electrodes (Biosemi, Amsterdam, the Netherlands), with a 10-20 cap setup. Data were recorded relative to a common average, at a 2048-Hz digitalisation rate (2048 samples of the EEG signal recorded per second, 417-Hz bandwidth). Oculomotor activity was recorded with four electrodes: one above and one below the left eye, and one at each of the outer canthi of the eyes. These vertical and horizontal electrode pairs recorded blinks and saccades, respectively. One electrode was placed on each mastoid bone as reference electrodes, to remove environmental noise from the EEG data after recording.

The EEG data were then down-sampled to 300Hz and re-referenced to the mastoid channels off-line. They were transformed with a 1Hz high-pass filter to remove any large jumps (from facial muscle contractions, for example) in the data. An independent components analysis (ICA) was conducted to remove oculomotor artefacts; this is explained in more detail below. Following the ICA, the EEG data were then segmented into epochs for the *known, correlated,* and *uncorrelated* word conditions over the four quartiles of the learning task (henceforth referred to as Blocks 1-4). The epoched EEG data were then baseline corrected to a 200ms pre-stimulus period.

Because the EEG signal undergoes gradual shifts over time, the zero level before stimulus onset may be different across channels (as shifts can occur due to muscle tension and 'drifts' from sweating over the scalp, for example). During baseline correction, the average signal over the 200ms pre-stimulus time period was computed across each recording channel and subtracted from all time points. Baseline correction is critical to ensure an observed effect is not already present in the signal before the stimuli were presented, which would suggest it was due to noise unrelated to the stimulus. Following baseline correction, a 30Hz low-pass filter then removed the frequency bands that did not contain the ERP signals of interest, manual artefact rejection of remaining trials with excessive noise, or oculomotor artefacts not removed by the ICA. To form ERPs the remaining segments were averaged according to word condition over each block. All data processing was performed using SPM8 (Wellcome Trust Centre for Neuroimaging, London).

4.2.4.1 Signal-to-noise ratio: Independent Components Analysis

In conventional EEG analyses, one of the final preprocessing stages is the rejection of segments of the data with oculomotor or other artefacts. Due to the high proportion of trial losses this can entail, especially in speeded (or excessively tiring) tasks in which participants may blink or move their eyes frequently, the signal-to-noise ratio can be significantly reduced by fewer trials in the final ERP average, thus making it noisier and less sensitive to subtle effects. It is consequently advantageous to remove the oculomotor components, without affecting the remainder of the EEG data, to reduce this trial loss. An ICA is therefore a useful tool to increase the signal-to-noise ratio in EEG data by removing blink and saccade components from each participants' dataset, allowing more trials to remain in the final averaged ERP (e.g. Shimi & Astle, 2013; Ungureanu, Bigan, Strungaru, & Lazarescu, 2004).

The ICA works by separating the continuous (un-epoched) EEG data into as many components as channels. The 64-channel system used for recording therefore means the ICA creates 64 separate components, or independent scalp maps (Ungureanu et al., 2004). Components are clustered by their topography and blink-time-locked (when using the ICA to identify oculomotor components) averages of activity. The key point is that individual channels do not necessarily correspond to components; rather, a component is a particular feature of EEG voltage distribution across the scalp that can be recorded across several channels at a point in time (such as alpha activity, which can be present across many channels at a time but nonetheless has a distinct scalp topography in certain tasks). The correlation of these 64 components with the eye channels (the vertical channels for blinks, VEOG, and horizontal channels for saccades, HEOG) is then plotted. The components highly correlated with each eye channel (with a correlation above 70%) can be visually examined to identify if their time-course and topographies correspond to blink and saccade components. These identified components are then selectively removed from the data, and the remaining independent components are projected back over the 64 channels. The ICA used tools from both Fieldtrip and EEGlab (Delorme & Makeig, 2004; Oostenveld, Fries, Maris, & Schoffelen, 2011).

An ICA approach to removing blink and saccade components from EEG data is particularly important in learning studies, given that the nature of the task can necessarily result in a small number of trials to examine representative stages of learning. When analysing data for a defined component, particularly one related to processing lower-level stimulus attributes (e.g. the N170 for orthographic analysis), the minimum number of trials per condition should be around 60 (Picton, Lins, & Scherg, 1995). Note, however, that this number must be that obtained *after* rejection of trials with excessive noise or oculomotor artefacts. Moreover, when looking for an ERP effect related to higher-level analyses of stimuli or related to more complex cognitive processes such as meaning acquisition, the effect inherently becomes more sensitive and variable than a lower-level perceptual effect. Subsequently, the source of noise stems from both fluctuations in the EEG signal and greater individual differences between participants, reducing the signal-to-noise ratio of the averaged potentials.

In the case of the current learning task, it required participants to be exposed to eight words per condition 28 times, yielding 224 separate trials per word category. Due to investigating learning over four blocks, there were only 56 trials per condition before artefact rejection. Any trial rejections could thus significantly decrease the signal-to-noise ratio, increasing the difficulty in observing a sensitive learning effect. The substantial reduction of trial losses by using an ICA to remove oculomotor components, and subsequently boosting the signal-to-noise ratio of the averaged ERPs, was therefore of particular importance due to both the nature of the learning study, and the examination of a learning effect reflecting higher-level processes.

4.2.4.2 Analysis Stage 1: Time Window Selection

To first examine the impact of the correlated-uncorrelated manipulation on the online processing of phonological forms during learning, a Condition (Known, Correlated, Uncorrelated) by Block (4 levels) repeated-measures ANOVA was conducted on voltages averaged over the 220-330ms time window following word onset. This time window was the mean recognition point across items with one standard deviation either side, rounded to the nearest 10ms (the mean time of vowel offset across items was 275ms, with one standard deviation of 57ms). Importantly, this approach of specifying the time window for analysis *a priori* based on the recognition point in the speech signal contrasts with existing ERP studies examining the temporal profile of known spoken word recognition. These studies have chosen time windows *a priori* based on ERP components of interest, such as the phonological mismatch negativity or N400 (e.g. Angwin et al., 2014; Desroches et al., 2009; Mestres-Missé et al., 2007; O'Rourke & Holcomb, 2002; van Petten et al., 1999). However, these studies either employed specific processing tasks to elicit ERPs of interest (Desroches et al., 2009) or varied the recognition point across items such that the peak latency within a time window could be mapped to the recognition point, with the prediction that later recognition points would lead to later peak latencies (O'Rourke & Holcomb, 2002; van Petten et al., 1999). Because the items in the current stimulus set were instead relatively closely matched on the timing of the recognition point, and were processed prior to picture onset with no explicit task demands, the recognition time window based on the speech signal was considered a more appropriate means to assess spoken word recognition.

Second, to test for a differentiation between the novel word conditions following the recognition point, voltages were averaged over the 450-600ms time window following word onset and again submitted to a Condition by Block repeated-measures ANOVA. This is the timeframe in which the N400 component is consistently observed (Kutas & Federmeier, 2011) and it was thus considered appropriate to choose this time window *a priori* for analysis. Because participants were not required to explicitly process the items for semantic attributes, the N400 analysis was instead treated as an exploratory analysis of the post-recognition processing of the correlated and uncorrelated novel words, in relation to the amplitude evoked by the known words.

4.2.4.3 Analysis Stage 2: Electrode Selection

To choose electrodes over which to average voltages for the form recognition analysis, paired t-tests were conducted across the 64 electrodes to identify those with a significant known word versus uncorrelated word voltage difference in Block 1, over the 220-330ms form recognition time window. This contrast yielded the following electrodes: Fp1, AF7, F3, F7, FT7, FC3, FPz, FP2, AF8, AF4, AFz, Fz, F6, and F8. Figure 10 shows a map of the electrode cap for reference to these electrodes. Voltages were pooled across these electrodes for spatial smoothing, and to increase the signal-to-noise ratio (following the procedure of Shtyrov et al., 2010).

The known versus uncorrelated contrast was used for electrode selection for two reasons. First, this contrast identified electrodes that simply picked up a difference between known and novel words at the beginning of the task. It thus followed that these electrodes could be used to examine an effect of *learning* across the task, in which the novel words could come to elicit amplitudes similar to the known words across these electrodes in the form-recognition time window. Second, because the contrast was

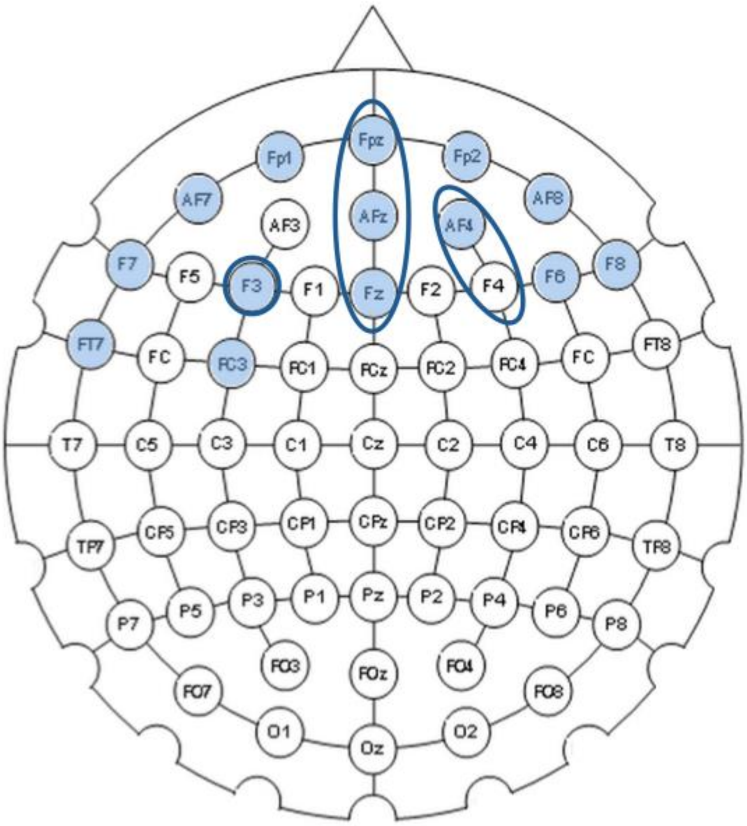

Figure 10. The electrode cap set-up.
The electrode set-up indicates the cluster of electrodes which picked up the known-uncorrelated word difference in Block 1. The electrodes which were used for the form-recognition window analysis (220-330ms) are filled-in in blue, and the electrodes used in the post-recognition (450-600ms) analysis are circled.

between known words and *uncorrelated* words specifically, the critical question pertained to whether the correlated word amplitudes showed the same *rate* of learning across these electrodes (indexed by convergence with the known word amplitudes). The design of the learning task equated the correlated and uncorrelated words for exposure frequency, and thus the central difference between them was the acquisition of a systematic semantic referent in the correlated-word condition. Therefore, if the acquisition of a semantic association in the correlated-word condition facilitated the recognition of their phonological forms, the rate of learning for the correlated words across these electrodes should emerge earlier in learning than for the uncorrelated words (a Condition x Block interaction). On the other hand, if semantic acquisition did not impact upon recognition, an equivalent rate of learning for both the correlated and uncorrelated words would be expected (a main effect of Block only).

The same rationale was used to select the electrodes in the post recognition time window. Paired t-tests across the 64 electrodes compared the known word versus uncorrelated word amplitudes across these electrodes in the first block of learning, at the 450-600ms time window. This contrast yielded six electrodes with a significant difference in known and correlated word amplitude: F3, FPz, AF4, F4, Fz, AFz (Figure 10). Voltages across these electrodes were again pooled for the main ANOVA.

It is important to recognize that electrode selection in previous studies of spoken word recognition, and word learning more generally, has frequently been based on either selecting electrodes of interest *a priori* based on the ERP component of interest (e.g. Alexandrov, Brocheva, Pulvermüller, & Shtyrov, 2011; O'Rourke & Holcomb, 2002; Shtyrov et al., 2010), selecting a range of electrodes at different spatial locations over the scalp and including electrode as a factor in the main ANOVA (e.g. Angwin et al., 2014; Desroches et al., 2009; Mestres-Missé et al., 2007; van Petten et al., 1999) or grouping electrodes into several clusters to be included as a factor in the main ANOVA (e.g. Perfetti et al., 2005). Whilst these approaches can prove valuable, they often require several assumptions about the distribution of an effect of interest. Because the current study indexed form recognition by mapping the ERP response to the recognition time window in the speech signal, rather than with a specified ERP component, selecting electrodes based on a data-driven contrast was considered more appropriate than an *a priori* selection of possible electrodes. Further, because the 450-600ms time window was chosen to explore post-recognition processing, without predicting a specific N400 effect in response to task demands, the same reasoning applied to electrode selection in this late time window.

4.2.4.4 Topographical analysis

Complementary to the above amplitude analyses, a topographical analysis was conducted to examine the relative distribution of neural generators underpinning the processing of each word category (known, correlated, uncorrelated) during learning. This topographical analysis is normalized by global field power and therefore insensitive to overall amplitude differences between conditions, but instead assesses if there is a differential *distribution* of relative activity between conditions (e.g. Astle, Nobre, & Scerif, 2009; Cristescu & Nobre, 2008). The first stage of the analysis involves the generation of topographical maps over the epoch (0-600ms, with 0ms corresponding to word onset) for each condition. This is a data-driven analysis run using Cartool software (Brunet, Murray, & Michel, 2011; Functional Brain Mapping Laboratory, Geneva, Switzerland), where topographical maps are generated from participants' group-averaged data. These topographical maps are then clustered together into a set of stable topographies which best explain the data over a particular period of the epoch in each word condition. The optimal number of clusters which best explained the data were defined by a cross-validation criterion (Pascual-Marqui, Michel, & Lehmann, 1995). This process of generating stable topographical clusters over the epoch for each condition is referred to as the *segmentation* process. These stable topographical clusters (also referred to as 'segmentation maps') represent periods of stable, non-overlapping electrical field patterns across the epoch. The epoch is thus segmented into time windows corresponding to the duration of each of these topographical clusters. A comparison of the topographical clusters generated by this segmentation process, and their duration across each condition, thus assessed i) whether the word conditions were processed by different distributions of neural generators, and ii) when in time this differentiation occurred. It is important to emphasise that this topographical analysis does not relate to the specific neural substrates or neural mechanisms of word processing, but simply identifies any time periods during word processing when *relatively* different distributions of electrical activity differentiate between the known, correlated and uncorrelated word conditions.

4.2.5 Results

4.2.5.1 Behavioural Results

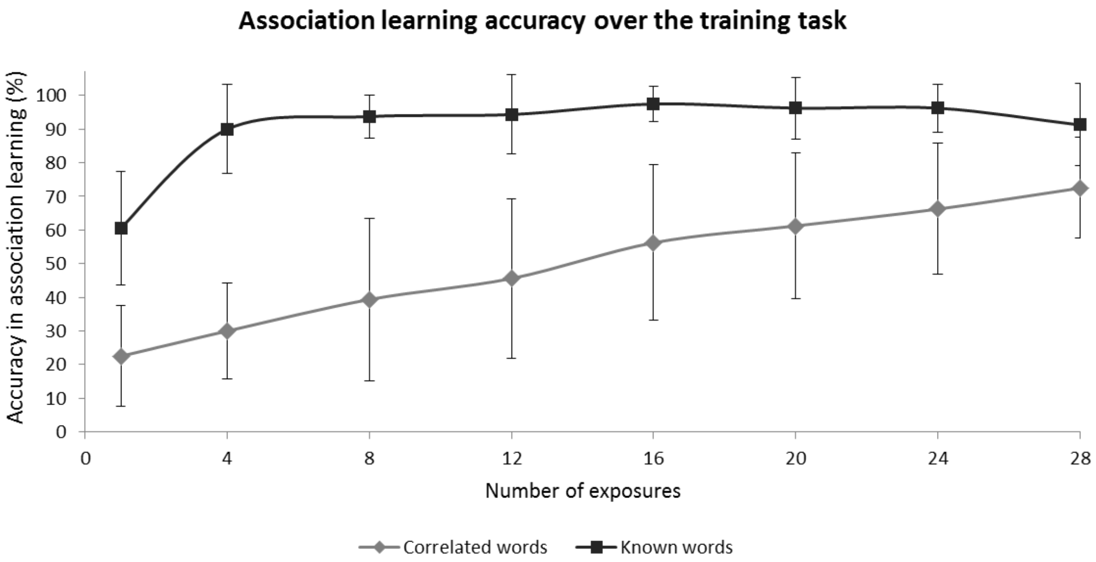

Figure 11. Association learning performance in the training task in Study 1.
Each data point shows the mean accuracy in choosing the associated picture across participants on that exposure, for the known and correlated words. The error bars show the standard deviation on each exposure

Accuracy. Analysis of the correlated-word percentage accuracy in each block of learning verified that participants learnt the correlated word associations, with an average accuracy of 65% at the end of training (SD = 15.19; Figure 11). A repeated-measures ANOVA with the factors of Condition (Known, Correlated) and Block (4 levels: Blocks 1-4) yielded a significant Condition x Block interaction, $F(3, 57) = 22.88$, $p < .001$. Paired t-tests verified that correlated word accuracy increased between the first and last block of learning (Block 1 vs. Block 4: $t(19) = -11.07$, $p < .001$). Accuracy for the correlated-word associations remained below that of known words in Block 4 (known words M = 94.82%, SD = 7.14; $t(19) = 10.61$, $p < .001$).

Reaction times. A Condition (Known, Correlated, Uncorrelated) by Block (Blocks 1-4) repeated-measures ANOVA on the reaction time data yielded a significant main effect of Condition, $F(2,38) = 75.63$, $p < .001$, which was qualified by a significant Condition x Block interaction, $F(6, 114) = 7.62$, $p <.001$. A repeated-measures ANOVA with the factor of Condition (3 levels) on each block separately, followed up by pairwise comparisons, verified that known words pictures were responded to significantly faster than correlated and uncorrelated words over each block (all Fs > 7, all ps < .01; known M = 549ms, SD = 59; correlated M = 636ms, SD = 77; uncorrelated M = 665ms, SD = 78). To then assess the correlated versus uncorrelated reaction time difference over the learning task, a Condition (Correlated, Uncorrelated) x Block (Blocks 1-4) ANOVA yielded a significant Condition x Block interaction, $F(3,57) = 9.90$, $p < .001$. Paired t-tests contrasting Correlated and Uncorrelated reaction times in each block showed no significant difference between the conditions in Blocks 1 and 2 (Block 1: $t(19) = -.22$, $p = .83$; Block 2: $t(19) = -1.76$, $p = .09$), but with a significant difference in Blocks 3 and 4, where correlated-word pictures were responded to significantly faster (Block 3: $t(19) = -4.26$, $p < .001$; Block 4: $t(19) = -3.92$, $p = .001$; correlated $M = 626$, $SD = 80$; uncorrelated $M = 675$, $SD = 79$). A repeated-measures ANOVA with the effect of Block on each novel word condition separately showed no significant main effect of block on either learning condition (correlateds: $F(3,57) = 1.49$, $p = .23$; uncorrelateds: $F(3,57) = 2.26$, $p = .091$).

4.2.5.2 ERP Results

The effect of semantic information on phonological form learning. Seventeen participants were included in the final ERP analyses; two were excluded for excessively noisy recordings, and one because the raw EEG data could not be converted due to a corrupted file. The form-learning analysis was conducted on the voltages averaged over the 220-330ms form-recognition time window, averaged over the 14 electrodes selected as described in section 4.2.4.3 above. These average voltages were submitted to a Condition (Known, Correlated, Uncorrelated) by Block (Blocks 1-4) repeated-measures ANOVA. This yielded a significant Condition x Block interaction, $F(6, 96) = 2.33$, $p < .05$. Follow-up ANOVAs with the factor of Condition on each block separately indicated that the effect of Condition was significant in Block 1 only, $F(2, 32) = 5.62$, $p < .05$. Paired t-tests within Block 1 indicated that uncorrelated word voltages were significantly more positive than both the known and correlated word voltages over the form- recognition time window (correlated vs. uncorrelated: $t(16) = 2.95$, $p = .01$; known vs. uncorrelated: $t(16) = 4.01$, $p = .001$). Conversely, there was no significant difference between the correlated and known word amplitudes, $t(16) = 0.33$, $p = .75$. There was no significant effect of Condition on the remaining three blocks (all $Fs < 2.35$, $ps > .1$). Figure 12 presents plots of these ERPs.

Post-recognition processing. The second amplitude analysis focused on the post-recognition N400 time window, 450-600ms following word onset. Voltages were averaged over the 450-600ms time window separately for each condition and pooled over the 6 electrodes selected as described in 4.2.4.3 above, and submitted to a Condition (Known, Correlated, Uncorrelated) by Block (Blocks 1-4) repeated-measures ANOVA. The Condition x Block interaction was significant $F(6, 96) = 2.22$, $p = < .05$. Follow-up ANOVAs examining the effect of condition on each block separately observed

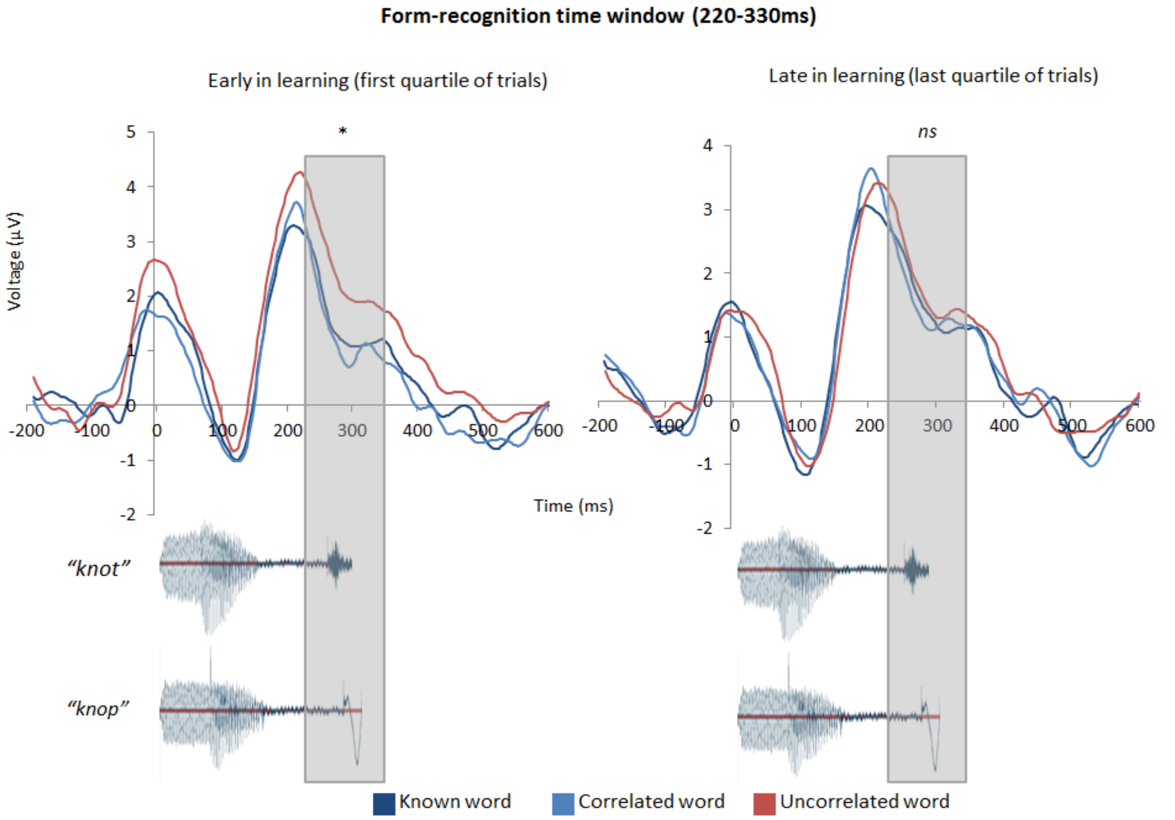

Figure 12. Form recognition ERP voltages locked to spoken word onset.

The ERPs are averaged over the electrodes used in the form-recognition analysis. The grey box shows the 220-330ms form recognition time window, derived from the average recognition point in the speech signal with one standard deviation either side, over which voltages were averaged in each condition for statistical analysis. The speech waveforms presented below the ERPs depict the unfolding of the spoken word against the ERP time-course, with sufficient information available in the speech signal for word recognition (i.e. differentiating *knot* and the novel word *knop*) in the 220-330ms time window.

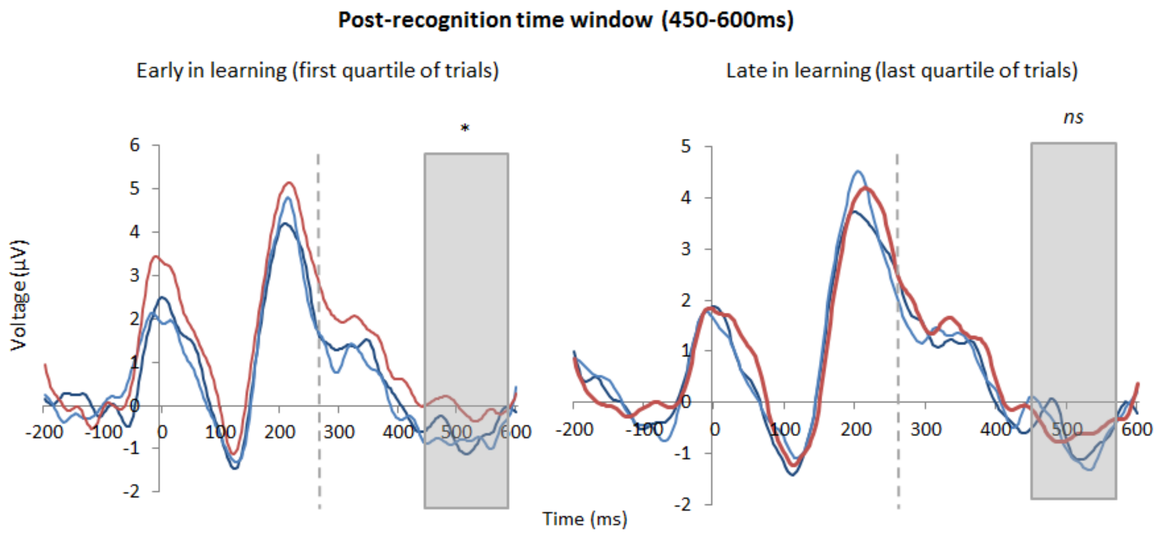

Figure 13. Post recognition ERP voltages locked to spoken word onset.

The ERPs are averaged over the electrodes used in the post-recognition analysis. The grey box shows the 450-600ms time window, and the dashed vertical line shows the average recognition point at 275ms. The same colour key is used here as in Figure 12.

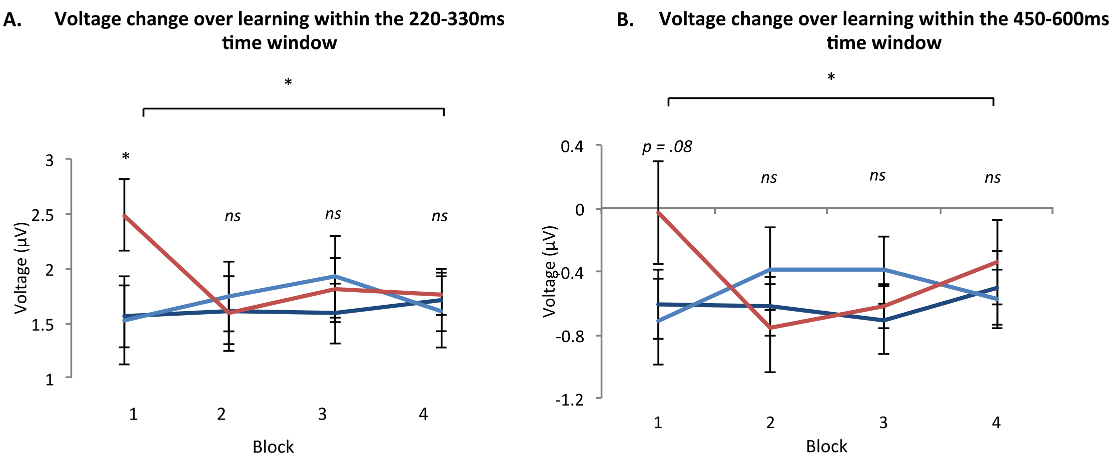

Figure 14. The average voltage in each block of the learning task.

The average voltage over A) the form recognition time window across blocks, and B) the post-recognition time window across Blocks 1-4 of the learning task, averaged over the electrodes selected for analysis. Note that each Block consists of 7 exposures to each word, with 28 exposures over the full experiment. Error bars show the standard error of the mean, and the same colour key is used here as in Figure 12.

a near-significant effect of condition on Block 1 only, $F(2,32) = 2.72$, $p = .08$. Paired t-tests on Block 1 then indicated that known words had a significantly more negative voltage than uncorrelated words, $t(16) = 2.17$, $p < .05$, and correlated words had a marginally significant trend towards a more negative voltage than uncorrelated words, $t(16) = 1.87$, $p = .08$. As with the form-recognition time window analysis, known and correlated words did not differ significantly from each other in Block 1, $t(16) = .035$, $p = .73$, and there were no significant effects of condition on the remaining three blocks (all $Fs < 1.2$, $ps > .3$). The N400 analysis thus mirrored the results of the form-recognition analysis, whereby known and correlated words were similar early in training and differed from the uncorrelated words, whilst all three conditions had evoked potentials of an equivalent magnitude from Block 2 onwards. Figure 13 presents the ERPs from this analysis, and Figure 14 presents the average ERP voltage over each block of the learning task in both the form-recognition and N400 analyses.

Topographical analysis. The topographical analysis was conducted using Cartool software (Brunet et al., 2011). The objective of this analysis was to verify if there was a difference in the relative topographical distribution of electrical activity for processing the known, correlated, and uncorrelated words within Block 1 and within Block 4. The group-level segmentation process, described in 4.2.4.4, was run between 0 and 600ms from word onset for each condition, within each block separately. In the segmentation process it was specified that each topographical map must be stable for at least 20ms in the group-averaged data to be included in a cluster. Maps with a spatial correlation of activity > 92% were merged into clusters. This segmentation process yielded a total of 12 clusters (six for Block 1 and six for Block 4), which explained 90% of the variance in the group-averaged data, and had cross-validation criterion of 191. The segmentation results are presented in Figure 15.

A within-participants fitting procedure then established if the topographical map which best explained the data across participants differed between the known, correlated, and uncorrelated word conditions (e.g. Astle et al., 2009; Cristescu & Nobre,

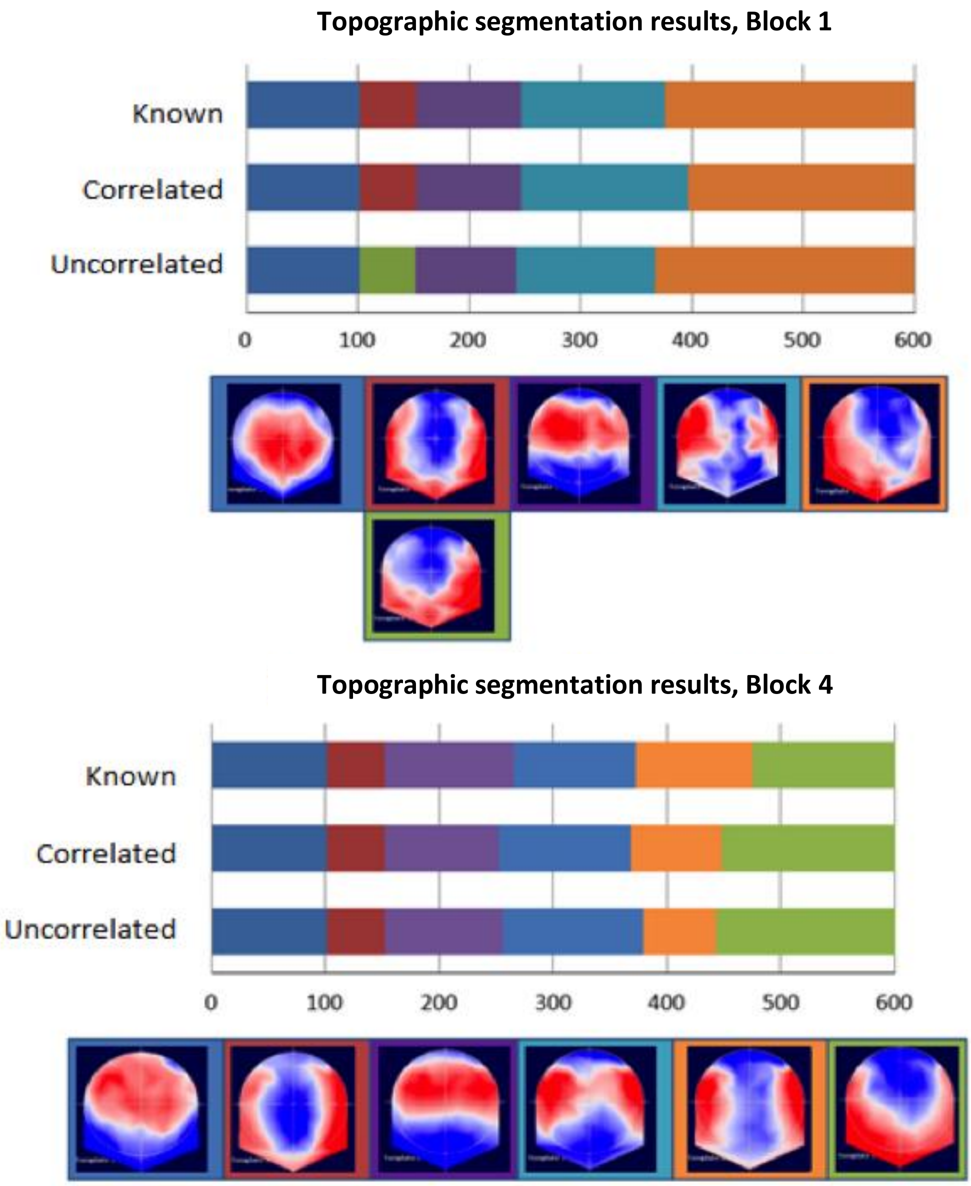

Figure 15. The results of the topographic segmentation procedure.

The *x*-axis shows the time from word onset, and each coloured bar corresponds to the same-coloured topographical map which explained the most variance in that condition. Each map represents a stable configuration of generators over the specified time window. The red map in Block 1 and Block 4 is the Map A referred to in the text, and the green map in Block 1 is Map B.

2008). This procedure used the average time of group-level map changes across the three conditions to examine the best fitting map within a given time window for each condition. The fit of each map was established by a competitive procedure in which one map was the best explanation of the data at each time point, for each individual participant. One time point corresponded to 1 millisecond within a time window. More time points for a given map within a time window, averaged across participants, would suggest that one map was a significantly better fit for the data in that time window. The segmentation process generated competing maps only for the 100-150ms time window in Block 1, and therefore the two maps in this time window were submitted to the fitting procedure. In Figure 15, these maps can be seen as the red map (Map A) and the green map (Map B), and Figure 16 presents results of the within-participants fitting procedure. The number of time points of the competing maps in each condition, averaged across participants, were submitted to a Condition (Known, Correlated, Uncorrelated) by Map (Map A versus Map B) repeated-measures ANOVA. This yielded a significant Condition x Map interaction, $F(2,32) = 5.60$, $p < .01$. Follow-up paired t-tests revealed that Map fit

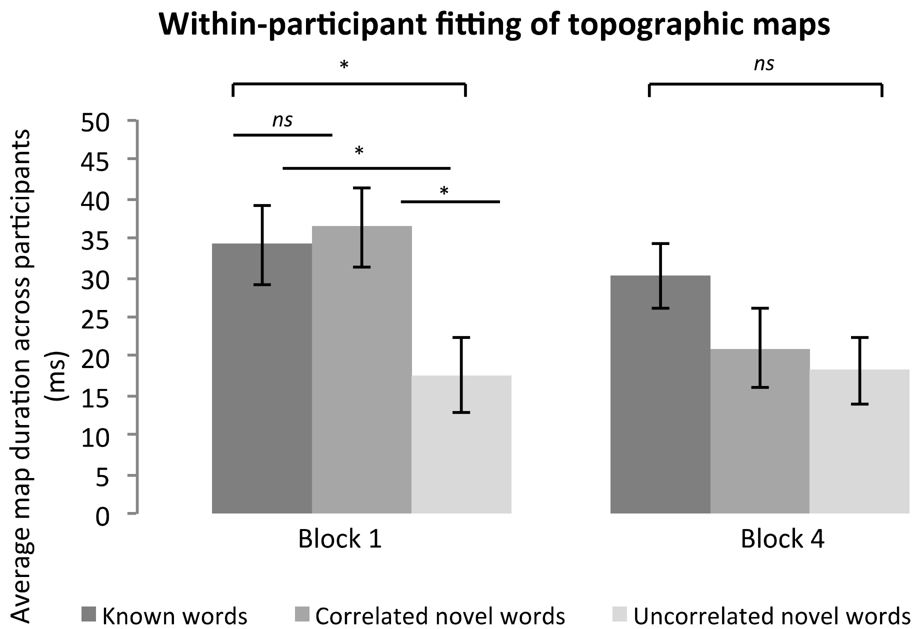

Figure 16. Within-participant fitting of topographic maps.
The average map duration across participants for Map A in Block 1 and Block 4 in the 100-150ms time window. The Block 1 results indicated that Map A did not differ in its duration between the Known and Correlated word conditions, but the map duration in both conditions significantly differed from the Uncorrelated words. Note that the fitting of Map B yields identical results (as the Map B duration is the 50ms time window duration minus the Map A duration, corresponding to the number of time points best explained by Map B over Map A). Error bars show the standard error of the mean.

did not significantly differ between the known and correlated words in Block 1 ($t(16) = .36$, $p = .72$) but significantly differed between known and uncorrelated words, $t(16) = -2.89$, $p = .01$, and between correlated and uncorrelated words, $t(16) = -3.01$, $p < .01$. The descriptive statistics indicated that Map A fit more time points than Map B for both the known and correlated words (known words: Map A duration = 34.12ms, SD = 21.04, Map B duration = 16.88ms, SD = 21.04[8]; correlated words: Map A duration = 36.41ms, SD = 21.12, Map B duration = 14.49ms, SD = 21.21). Conversely, Map B fit more time points than Map A in the uncorrelated word condition (Map A duration = 17.65ms, SD = 19.69; Map B = 33.35ms, SD = 19.69). These data thus suggested that Map A provided a better fit for known and correlated words in the 100-150ms time window, whilst Map B provided a better fit for the uncorrelated words. In the 100-150ms time window in Block 4, the Condition x Map interaction was marginal but did not reach significance, $F(2,32) = 2.64$, $p = .09$. There was thus no robust difference in the fit of the topographical maps in Block 4.

4.3 Discussion

Study 1 sought to address whether semantic exposure could influence the online acquisition of new phonological forms. This question was motivated by theoretical models of spoken word recognition which implicate a role of semantics in known spoken word recognition (Gaskell & Marslen-Wilson, 1997), and empirical data suggesting a facilitating effect of imageability on the recognition of known words in high competition cohorts (Tyler et al., 2000; Zhuang et al., 2011). However, there is a mixed role of semantics on online measures of processing in learning studies (cf. Hultén et al., 2009; Mestres-Missé et al., 2007; Sandak et al., 2004), despite clear benefits on word recognition, identification and recall (explained in detail in Chapter 2). These factors make it unclear whether meaning is also beneficial in the earlier recognition-based stages of processing during the initial acquisition of novel words, or only after a newly-learnt word is an established unit in the lexicon. To address this issue, a learning paradigm was employed in which participants were exposed to novel words that were either correlated or uncorrelated with a visual referent; participants therefore acquired knowledge of both a word form and a systematically-associated referent, or a word form only.

[8] Note that the standard deviations for the duration of both Map A and Map B are identical because the map durations are within a 50ms time window. The duration of Map A is thus 50ms minus the duration of Map B, and vice versa.

An increase in behavioural learning accuracy in the correlated word condition verified that participants learnt the associations over the course of the learning task. Analyses of ERP amplitudes within the form recognition time window suggested that in the first quartile of learning, uncorrelated words were treated significantly differently (with more positive evoked amplitudes) than both known and correlated words. Further, there was no significant difference between correlated and known words in this form-recognition time window. The post-recognition N400 analysis yielded a similar pattern, in which correlated and known words evoked similar amplitudes in the first block of learning, whilst uncorrelated word amplitudes did not converge with known words until the second block of learning. This differential rate of learning between the correlated and uncorrelated novel words was supported by topographical analyses. Within the first block of learning, qualitatively different distributions of activity processed the correlated and uncorrelated words in an early time window, and correlated words were treated as categorically similar to known words. At the end of learning, there were no topographical map differences between conditions over any time windows. One interpretation of these findings is thus that the provision of semantic information may facilitate the time-course of phonological form learning, indexed by a convergence of novel word ERP responses with known words.

4.3.1 The online acquisition of new phonological forms

These data suggest that an associated meaning may facilitate the rate of phonological form learning. Such a proposal is in agreement with the literature indicating a semantic facilitation on recall, identification and recognition measures of word learning (e.g. Breitenstein et al., 2005; Leach & Samuel, 2007; Forster, 1985). Strikingly, the correlated and known-word convergence within Block 1 was within the first seven exposures, suggesting markedly fast learning. Previous studies have similarly observed rapid learning of novel written words, measured by a convergence of novel with known word ERPs, after one or three exposures to novel words in constraining sentence contexts (Borovsky et al., 2012; Mestres-Missé et al., 2007). However, if meaning acquisition was sufficiently quick as to affect the ERP measure within the first few exposures to a word, it is also possible that the analysis of the learning data by averaging all trials over each quartile of the learning data was not sensitive to the earliest stages of learning, when the correlated words and uncorrelated words were viably identical, before correlated-word amplitudes converged with the known word amplitudes within Block 1. Rather than analysing by block, regression analyses of EEG data have provided sensitive measures of early psycholinguistic processes (Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006; Hauk, Pulvermüller, Ford, Marslen-Wilson, & Davis, 2009) and could thus be valuable in the analysis of such speeded learning.

Interestingly, of the two possibilities suggested in the introduction to this chapter – that semantics could benefit recognition during learning, suggesting an interactive mechanism between phonology and semantics could operate during *both* the acquisition of new words and processing of known words, or that newly-learnt words may need to engage in lexical competition for semantic knowledge to impact the recognition process – it seems that the former could be the case. One possibility is that as the correlated word associations were being acquired over the first few exposures, some features of this associative link with a referent were activated at the onset of each item (e.g. the ambiguous /paı/ onset in *pipe* or *pite*), which subsequently facilitated recognition of the correlated words at the recognition point where they could be identified (e.g. Marslen-Wilson, 1987; Zwitserlood, 1989), eliciting an ERP response akin to that of known words in the recognition time window. Whilst the uncorrelated words did not have this initial advantage, it is possible that seven exposures to their form in the first block were sufficient to also elicit a comparable ERP response to correlated and known words in the subsequent blocks.

4.3.2 Semantic information in spoken word recognition

This interpretation ties in with models of known spoken word recognition positing an interaction between form and meaning. For example, in the Distributed Cohort Model (Gaskell & Marslen-Wilson, 1997) nonwords can activate the distributed representational layer (via phonological input) but less so than words. One possibility is thus that the correlated words elicited relatively more phonological activation than uncorrelated words early in learning. A similar interpretation would come from the interactive architecture of TRACE (McClelland & Elman, 1986), in which feedforward and feedback connections between each level enable their interaction during the process of word recognition. This interactive architecture implies that if the model was extended to include a semantic layer, semantic information would feedback to the word form level and onto the phoneme level, thus implying that the recognition of a word's form could be affected by its meaning (the same point is made by Tyler et al., 2000).

However, it is critical to be clear that the data from Study 1 are not informative about lexical competition (this question will be returned to in Study 3). Because the cardinal feature of these models is the process of the competitive, parallel activation of multiple lexical candidates, and the novel words in Study 1 were unlikely to engage in this competitive process (due to the requirement of offline consolidation for lexical competition to emerge in most cases; as reviewed in Chapter 3), linking the semantic effect in Study 1 to models of spoken word recognition implies that a semantic-phonology interaction in recognition can operate without the requirement for words to engage in lexical competition. The current data are consistent with the idea of an interaction between semantics and phonological form learning during the earliest stages of acquisition, but do not speak to whether this interaction draws on the same mechanism as those recruited during known word recognition (e.g. Zhuang et al., 2011).

4.3.3 Limitations of the current study

The current study contains three critical limitations on interpreting the ERP data in terms of a semantic influence on form recognition during learning: the time-course of the recognition process, the temporal smearing of the recognition time window, and the measurement of word recognition. Firstly, the effect of word form learning was analysed over a time window with a standard deviation of 57ms; accompanied by the fact that neural indexes of spoken word recognition can take up to 80s post-recognition to emerge (MacGregor et al., 2012), the precise point at which word recognition could occur substantially varied on an item-by-item basis. In line with this limitation, it is notable that the temporal profile of spoken word recognition has also been measured using words with early and late recognition points, and comparing the delay in ERP peaks as a result of later recognition points (O'Rourke & Holcomb, 2002; van Petten et al., 1999; Woodward et al., 1990). For example, O'Rourke and Holcomb (2002) measured the peak latency of the N400 in response to words and pseudowords, and observed that the time-point of peak negativity was earlier for words than pseudowords. An alternative means of testing the impact of semantic acquisition on spoken word recognition during learning may thus be to use items with a precisely defined recognition point, and assess whether an earlier peak latency emerges sooner in learning for correlated relative to uncorrelated words.

Second, a related constraint concerns the auditory stimuli used. Given that half the words in the stimulus set were not minimal pairs, in the case of items containing the /k/-/f/ place and manner of articulation contrast (i.e. *chuke-chufe)*, recognition could have occurred prior to the defined form recognition time window during vowel duration or coarticulation before the disambiguating consonant. Similarly, as all items were different tokens, and were not cross-spliced prior to the recognition point (cf. Shtyrov et al., 2010) acoustic differences could have cued word identity before the defined recognition window. In concordance with this possibility, auditory priming studies have indicated that spoken word representations can contain substantial episodic detail (e.g. Church & Schacter, 1994; Goldinger, 1996; Schacter & Church, 1992). Similar processing benefits have been observed for recently-learnt words, the so-called *talker specificity effect* (e.g. Creel, Aslin, & Tanenhaus, 2008). The current data do not preclude the possibility that participants acquired detailed episodic representations of the tokens, and it is these which were accessed during the early stages of spoken word processing. It is thus possible that the observed ERP effects reflected access to acoustic memory traces (akin to repetition priming, albeit potentially faster for correlated words) as opposed to the process of word recognition. Critically, this issue of the temporally uncontrolled recognition point was strongly implicated by the topographical analysis. The topographical analysis yielded a difference in topographical maps between the known/correlated and uncorrelated words at 100-150ms after word onset in Block 1. Because the topographical analysis was not linked to any pre-defined time window, but identified periods of stable topographical maps from the onset of word processing, it implies that differentiation of the words could occur even earlier than the 220-330ms recognition window defined by the speech stimuli. Given that the same pattern of effects was present between both the amplitude and topographical analyses, it is possible both analyses tapped into a comparable process of correlated phonological form learning proceeding faster than uncorrelated learning, indexed by earlier correlated word similarity to known words in both amplitude and topography in the first block of learning. However, the identification of different time windows in each of these analyses discounts a strong interpretation of the observed effects being attributable solely to the process of spoken word recognition.

The final limitation to note concerns the nature of the ERP measurement. An *a priori* 'form recognition' time window was used to measure learning, but this did not correspond to an ERP component known to reliably index word recognition (such as the N170 potential in early orthographic processing; Bentin et al., 1999). An example of such a component in auditory processing is the mismatch negativity (the MMN), which is elicited in response to the recognition of a word as distinct from other items in a speech stream (e.g. Shtyrov et al., 2010). Whilst the time window was chosen to encapsulate the process of form recognition, there is nonetheless some ambiguity as whether it captures this process, especially due to the temporal variability of this time window as explained above. Further, the electrodes for analysis were chosen by contrasting known and uncorrelated word amplitudes over the time windows of interest in Block 1, and examining the subsequent effect of learning over these electrodes. Section 4.2.4.3 provides the rationale for this approach. Despite this, the contrast between known and uncorrelated words was one level of the main Condition by Block ANOVA. The presence of this selection contrast in the subsequent analysis meant that the stages of electrode selection and analysis were not entirely independent. The implication of this concerns whether the observed effects would have been obtained using an alternative method of electrode selection. This is an issue which the next chapter will address in turn.

The post recognition time window analyses suggested the same pattern of results as those earlier in word processing, albeit with only marginal significance for the correlated-uncorrelated word difference in Block 1. Analysing ERPs in this time window was intended as an exploratory approach to examine the relative difference between known, correlated and uncorrelated words following recognition. However, the polarity of the observed effect, whereby the known and correlated words evoked a larger negativity than the uncorrelated words, constrains the interpretation of this time window. One possibility is that this later ERP difference simply reflected a component driven by the earlier, and more robust, effect. An alternative interpretation is that the ERP in the N400 time window was reflecting a feature of phonological neighbourhood analysis following recognition: interestingly, more *negative* N400 potentials have been observed for words with larger neighbourhood sizes (Holcomb, Grainger, & O'Rourke, 2002, in the visual domain). Given that the known and correlated word amplitude in this time window was more negative than for the uncorrelated words in Block 1, this may reflect greater awareness of the phonological relationship between the correlated words and existing neighbours earlier in learning than for the uncorrelated words. However, the fact that only half of the novel words were highly overlapping neighbours of existing words could have contributed to the variability in this potential.

4.3.4 Chapter summary

Overall, whilst the data of Study 1 suggest that phonological form learning may be facilitated for novel words with an associated referent, the interpretation of these findings is constrained by the extent to which the ERPs were an accurate measurement of the recognition process. However, these data are nonetheless theoretically interesting in light of the impact of semantic exposure on later stages of the lexicalization process: in studies testing the lexical engagement of new phonological forms over consolidation, semantic exposure can delay the time-course of the entry of these new words into lexical competition (Dumay et al., 2004; Takashima et al., 2014). It is thus unclear whether any semantic advantage for phonological form learning after a single training session translates to offline consolidation. This question is of key importance in understanding the extent to which representations established early in the learning process constrain or enable subsequent lexicalization. Given that the Study 1 data suggest that semantic exposure may aid the process of acquiring phonological forms more quickly, this raises the question of whether semantic information may impact upon phonological form representations themselves, and how this influence is mediated by offline consolidation. It is this question to which this thesis now turns.

Chapter 5: Meaning and memory consolidation in phonological form learning

5.1 Introduction

The findings of Study 1 suggested that semantic exposure during learning could facilitate the online process of phonological form acquisition. This study indicated that novel words associated with a systematic semantic referent may be acquired more rapidly than words lacking this systematic semantic association. Following this, Study 2 aimed to investigate how offline consolidation affected any semantic benefit for learning new phonological form representations. Specifically, if novel words with a meaning show a benefit during encoding over novel words without such an association, do these semantically-associated words also express a discrimination benefit after a period of offline consolidation?

Two points motivate this question. The first relates to that raised in the previous chapter: models of spoken word recognition support the joint contribution of phonology and semantics to known word recognition (e.g. Gaskell & Marslen-Wilson, 1997; Zwitserlood, 1989), in terms of a semantic facilitation for words in high competition cohorts (Tyler et al., 2000; Zhuang et al., 2011) but the contribution of a similar mechanism to the acquisition process of new words is not well understood. The second point concerns the time-course of the semantic influence on word learning: despite the benefits often observed for semantic relative to non-semantic exposure on the identification, recall and recognition memory of new words after a single training session (e.g. Forster, 1985; Rodd et al., 2012; Rueckl & Dror, 1994) the emergence of lexical competition after one night of consolidation can be delayed for words learnt with a semantic referent (Dumay & Gaskell, 2004; Takashima et al., 2014; cf. Henderson, Weighall, & Gaskell, 2013). This chapter thus addresses the impact of semantic information on the learning of new phonological form representations, and the impact of offline consolidation on these representations.

5.1.1 Offline memory consolidation in word learning

It is now well established that offline consolidation, possibly related to sleep, can improve perceptual and motor abilities acquired during wake (e.g. Karni et al., 1994; Korman et al., 2007). The past decade has seen the emergence of a strong body of literature testing the related possibility that consolidation may play a critical role in some aspects of word learning. In a series of studies on the integration of novel spoken words into the mental lexicon, Gaskell and Dumay (2003) demonstrated that newly-learnt words (e.g. *cathedruke*) can come to compete with similar existing words (e.g. *cathedral*), but only if the initial learning phase was followed by a period of offline consolidation (see also Bowers, Davis, & Hanley, 2005 for an analogous study using visual presentation). Sleep appears to provide an optimal state for these consolidation processes (Dumay & Gaskell, 2007; Tamminen et al., 2010), but the integration of novel words into the mental lexicon is also possible during wakefulness under certain conditions (e.g. Fernandes et al., 2009; Lindsay & Gaskell, 2013; Szmalec et al., 2012). One interpretation of these effects is within the context of complementary learning systems (CLS) accounts (Davis & Gaskell, 2009; McClelland et al., 1995). As described in Chapter 3 (section 3.3), this account suggests that newly-learnt words are initially stored as distinct episodic representations, and that one function of consolidation may be to transfer these episodic representations to abstract lexical representations integrated with existing knowledge.

In addition to lexical integration processes, there is evidence to suggest consolidation is also important for the abstraction of newly-learnt information, in such a way that promotes linguistic generalisation. For example, Gómez, Bootzin, and Nadel (2006) found that infants who took a nap after a spoken learning task were able to extract an abstract rule relating elements in the training set that could be applied to untrained stimuli, in a manner that infants who failed to nap could not. Similarly, Tamminen et al. (2012) showed that adults who learnt a series of words with an internal morphological structure (e.g. teachnule, buildnule, sleepnule) could apply their knowledge of the element [-nule] to untrained stimuli, but only following a period of overnight consolidation.

In sum, whilst consolidation appears to be important in these higher-level aspects of word learning, it is unknown how it may impact on lower-level phonological form learning processes (e.g. Shtyrov et al., 2010). Importantly, a cardinal feature of learning a new phonological form is the development of a sufficiently well-specified phonological representation to allow discrimination from competitors and be sensitive to mispronunciations in a similar way to known words (e.g. White, Yee, Blumstein, & Morgan, 2013). Indeed, phonological specification of a new spoken word is an important early component of the full acquisition process. This has been suggested by studies observing a positive correlation between phonological short term memory (measured by nonword repetition) and word learning (e.g. Baddeley et al., 1998; Gathercole, 2006; Gupta, 2003; Page & Norris, 2009; Papagno & Vallar, 1992; see also Mueller, Friederici, & Männel, 2012), suggesting that short term phonological storage and word leaning is particularly important in children, but also supports word learning in adults. However, the link between the earlier process of phonological form learning and offline consolidation, which promotes the higher-level lexical integration and abstraction of these new phonological forms, is not well understood.

5.1.2 Semantic influence on word knowledge over consolidation

In contrast to the relatively consistent role of consolidation in lexical integration and abstraction, investigations of the influence of semantic information on novel word learning present a less clear picture. As discussed in Chapter 2, in studies testing explicit memory for newly-learnt whole words (e.g. Rueckl & Olds, 1993), the provision of meaning has been shown to be broadly advantageous. Associative learning between a word and visual referent (Breitenstein et al., 2005), semantic richness of implicitly learnt words (Rabovsky et al., 2012) and semantic relatedness of new word meanings (Rodd et al., 2012) also have a beneficial impact on measures of word recall and recognition memory. However, this beneficial effect of semantic information on explicit measures of word learning does not always translate to measures of online lexical processing such as speeded naming (e.g. Hultén et al., 2009; Sandak et al., 2004). The effect of semantics may thus depend on a range of task aspects, and the provision of semantic information does not promote a universal learning advantage.

Furthermore, the immediate benefit of semantic information on explicit measures of word learning is difficult to reconcile with the lexical integration literature (reviewed in Chapter 3, section 3.5.2). Dumay et al. (2004) trained participants on novel words (e.g. *cathedruke*) which were presented in either a meaningful sentential context or in isolation in a phoneme monitoring task. While novel words introduced in both conditions came to compete with existing words (suggesting lexical integration), those introduced in a sentential context required a longer period of consolidation to do so. Similarly, Takashima et al. (2014) trained participants on a set of novel spoken words, half of which were associated with a picture. They observed that only those trained without a picture engaged in lexical competition the subsequent day. Conversely, Henderson, Weighall, and Gaskell (2013) found that words trained in both semantic and non-semantic contexts yielded competition effects in children the day after learning. Similarly, whilst some studies have reported that the provision of semantic information is necessary to achieve generalisation in adult word learning paradigms (Merkx, Rastle, & Davis, 2011; Tamminen et al., 2012, both for morphological rule learning), others have reported generalisation effects even in the absence of semantic information (Taylor et al., 2011, in the case of artificial orthography learning).

In sum, the above data suggest that whilst the provision of semantic information has a strong influence on explicit memory for learnt words, the findings regarding higher-level word learning processes such as lexical integration and generalisation are less clear-cut. Although overnight consolidation has been established as an important factor in aspects of word learning including lexical integration (e.g. Gaskell & Dumay, 2003) and generalisation (e.g. Tamminen et al., 2012), it is not clearly established how consolidation might i) impact on lower-level phonological form representations, and ii) interact with semantic exposure from learning.

5.1.3 Paradigm for semantic association learning

In a similar way to Study 1, the question of a semantic benefit on phonological form learning in light of the mixed semantic effects in the literature raises the issue of how to manipulate the provision of semantic information. In a recent study in which the provision of semantic information was disadvantageous to lexical integration (Takashima et al., 2014), participants were required to learn novel words via phoneme monitoring, in which some were also presented with a visual referent. One possibility is that the semantic disadvantage in this study arose because learning two novel pieces of information (a new phonological form and a new meaning) was more cognitively demanding than learning just one novel piece of information. Takashima et al. further suggested that the additional picture referent for the picture-associated words could have increased the difficulty in making links between these word forms and existing, phonologically overlapping words, thus preventing their engagement in lexical competition. One possibility is therefore that when the amount of information and learning goals are equated, the acquisition of phonological representations may be supported by systematic semantic associations during training, due to associative links between forms and referents leading to a stronger memory trace (e.g. Leach & Samuel, 2007). A similar argument was used in Study 1 to support the use of a learning paradigm equating learning goals and information load across semantic and non-semantic learning conditions (section 4.2.1) and, based on the involvement of offline consolidation in the current study, remains relevant with respect to addressing methodological issues in the consolidation literature here. Thus, the current study employed the same learning paradigm as Study 1: in the *correlated* condition, there was a strong relationship between the novel words and their visual referent across trials, whereas in the *uncorrelated* condition, there was no relationship between the novel words and their visual referents across trials.

5.2 Study 2

Based on both the findings of Study 1, and the above data indicating a divergent effect of semantics on word recognition and lexical integration before and after offline consolidation, respectively, Study 2 investigated the impact of semantic information on phonological form representations and tested these representations both before and after consolidation.

Following on from the limitations of Study 1, Study 2 had four critical improvements. The first and primary issue with interpreting Study 1 was the temporally variable form recognition window used for analysis. This emerged both from the use of phonologically overlapping word pairs differing in place and manner of articulation, potentially providing coarticulation effects on the vowel which provided a cue to recognition before vowel offset (whereby the point of vowel offset was defined as the recognition point for the ERP analysis), and the use of different acoustic tokens, again potentially contributing to recognition prior to the pre-defined recognition point in the stimuli. Study 2 therefore used minimal pairs that diverged with a final place contrast (i.e. *vake, vape, vate*) were therefore used, and all stimuli were cross-spliced such as to be acoustically identical up to the uniqueness point. Because of this cross-splicing it was necessary to use a stimulus set consisting of minimal pairs that diverged with a final place contrast (i.e. *vake, vape, vate*). Unvoiced place contrasts (/p/, /t/, /k/) are superior to both voiced place contrasts and voicing contrasts for a defined recognition point, as information about word identity comes purely from the place of articulation of the consonant, without any differential coarticulation of the preceding vowel (which, in voicing contrasts, can lead to word recognition based on vowel duration, which is less clearly defined in time). The second methodological improvement of Study 2 was then to shift the trigger to the uniqueness point of each item in the stimulus set, allowing the ERPs to measure the processing of each item following a defined recognition point.

A third limitation in Study 1 was using this temporally variable time window to measure phonological form recognition, rather than a defined ERP component known to index a process of word recognition. Using a pre-defined time window was advantageous in providing a bias-free, *a priori* window for analysis of the ERPs; however, because of both the temporal variability of recognition and the potential delay between the recognition of the speech signal and this being reflected in the EEG (e.g. MacGregor et al., 2012), it was not possible to determine the precise stage of word recognition being measured. Conversely, using a defined ERP component has the benefit of being less ambiguous; the mismatch negativity (MMN) was thus used to index phonological form learning in Study 2. An overview of the MMN potential is given below in this section. Similarly, the final relevant limitation of Study 1 was the measurement of learning via no significant difference between known and novel words. Whilst this is not uncommon in ERP research (e.g. Borovsky et al., 2010, 2012; Mestres-Missé et al., 2007) a convergent measure indexing learning by the phonological discrimination of novel words from existing words would provide further support for phonological form learning, building on the measure used in Study 1. The MMN provides a measure of the phonological discrimination of a rare deviant word from a stream of filler words and thus also improves on this limitation of the previous study.

In the present study participants again learnt novel words with a high degree of phonological overlap with existing words, using the same correlated/uncorrelated training paradigm as Study 1. Following learning, the precision of newly-acquired phonological form representations was tested using the mismatch negativity potential (MMN) as an electrophysiological measure of auditory discrimination, both immediately after training (Day 1) and after 24 hours of consolidation (Day 2). Figure 17 presents a schematic of this design. The MMN has previously been shown to be a sensitive index of novel word learning and discrimination from known words, and critically is elicited in the absence of attention to the speech stream (and thus is not contaminated by specific processing goals). Shtyrov et al. (2010) used the evoked MMN as an index of novel word learning: a pseudoword was presented infrequently against a stream of known words, whereby the infrequent pseudoword differed by one phoneme from the known word (i.e. *pipe-pite*). By the end of a 14-minute exposure session the pseudoword elicited an MMN response, which Shtyrov et al. (2010) suggested was the result of rapidly forming a neural memory trace of the novel pseudowords. The MMN was elicited in response to a precise recognition point in the speech signal, at which the novel pseudoword could be discriminated from the known word stream, and it therefore measured the perceived phonological contrast between the novel pseudoword and known word. Using the MMN in a similar design in the test phase of Study 2 therefore allowed the investigation of whether systematic semantic information enhanced the acquisition of phonological form representations in the correlated-word condition, and the impact of consolidation on these new phonological representations.

Regarding the issue of the effect of semantic exposure on phonological form learning, it was predicted from the rationale and findings of Study 1 that the correlated words, with systematic picture associations, would show a benefit over the uncorrelated words. Regarding the impact of consolidation on phonological form representations, there were two possible outcomes. CLS accounts predict that consolidation can both strengthen access to new word representations, and promote their abstraction from episodic knowledge (Davis & Gaskell, 2009; McClelland et al., 1995). Enhanced access to new word representations has been observed in faster responses to the phonological features of new words (Snoeren et al., 2009) and gradually improving recognition and recall of new phonological forms over consolidation (Davis et al., 2009; Dumay & Gaskell, 2007; Dumay et al., 2004; Tamminen et al., 2010). Abstraction from episodic knowledge after consolidation has been observed for higher-level aspects of word learning such as semantic integration (Tamminen & Gaskell, 2013), morphological and grammatical rule learning (St Clair & Monaghan, 2008; Tamminen et al., 2012), and for

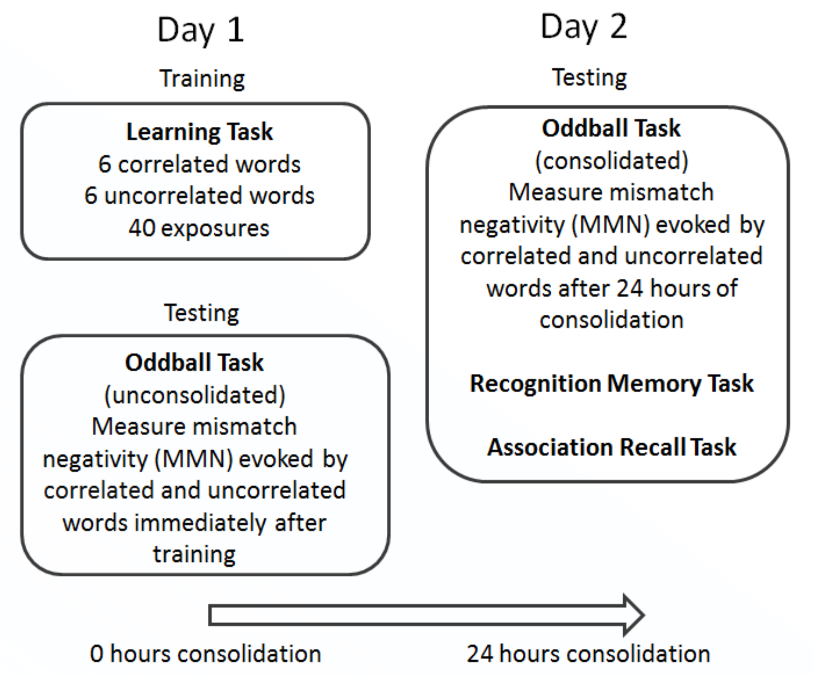

Figure 17. A schematic of the training and test design in Study 2.

Participants learnt correlated and uncorrelated novel words on Day 1, and were immediately tested on the auditory discrimination of these new words using the mismatch negativity (MMN) potential. Participants returned to the lab 24 hours later to repeat the MMN test, which was followed by behavioural tests of recognition memory and association memory.

non-linguistic statistical learning (Durrant, Taylor, Carney, & Lewis, 2011; Ellenbogen et al., 2007). However, it is not established whether abstraction may also operate on earlier phonological form learning processes which are a necessary pre-requisite. Hence, it was possible to observe either a strengthening of new phonological form representations, a shift in their dependence on episodic knowledge, or both.

5.2.1 Methods

5.2.1.1 Participants

Twenty-four right-handed native English speakers, verified in the same way as Study 1, completed the study (mean age = 21.5 years, S.D. = 2.59, range: 18-27; 15 females). The participants had no known auditory, language or learning difficulties. All participants were recruited from Royal Holloway and paid for their participation. The study received ethical approval from the Psychology Department Ethics Committee at Royal Holloway.

5.2.1.2 Materials and Design

Learning Task. The learning paradigm was the same as that used in in Study 1, with some minor changes. There were again three conditions in the learning task: the correlated condition, in which there was a strong association between the novel words and picture referents; the uncorrelated condition, in which there was no association between the novel words and picture referents; and the known word condition, which contained existing words and their corresponding referents. Participants were exposed to six monosyllabic spoken pseudowords in each learning condition (therefore twelve novel pseudowords in total) and six known words. The novel pseudowords were assigned to each learning condition as shown in Table 2. The pseudowords consisted of six minimal pairs drawn from a larger pool of items for each subject. Two of the pseudoword minimal pairs made up minimal triplets, which consisted of two pseudowords and one known word; these triplets were included to be later tested in the oddball task. Each item consisted of a consonant-vowel token taken from the naturally spoken known word recording (e.g. /kaɪ/, as in kite) cross-spliced onto a /t/, /p/ or /k/ voiceless stop consonant. These were taken from the onset of the final voiceless stop consonant in /kaɪt/, /paɪp/, and /baɪk/, respectively. This cross-splicing meant that each minimal set was identical until the final stop consonant (e.g. /kaɪt/ or /kaɪp/), with no

Table 2. An example stimulus set used in the learning task.

Correlated Words	Known Words	Uncorrelated Words
boap /boʊp/	**boat** /boʊt/	**boak** /boʊk/
kipe /kaɪp/	**kite** /kaɪt/	**kike** /kaɪk/
jep /dʒɛp/	**jet** /dʒɛt/	*clet* /klɛt/
vate /veɪt/	**stick** /stɪk/	**stit** /stɪt/
pite /paɪt/	**pipe** /paɪp/	*vape* /veɪp/
clep /klɛp/	**bike** /baɪk/	**bipe** /baɪp/

Note. The IPA transcription is shown beside each word. The middle column shows the known words (in bold). The column to the left shows the minimal pairs with these known words (in bold) that would be used in the correlated learning condition. The column to the right shows a similar list that would be used for the uncorrelated condition. In the subsequent MMN sessions only the minimal triplets would be used (the top two lines). However, to make the learning task sufficiently challenging extra known words were used which had a minimal pair (which could be allocated to either learning condition), and novel words which were minimal pairs with each other (these are shown in italics).

acoustic or coarticulatory differences before this disambiguation point (in the subsequent MMN sessions these points would be the trigger which the ERP waveforms were locked to). Each item could thus only be uniquely recognised at the final phoneme. All spoken stimuli were recorded and edited in Cool Edit 2000, and peak amplitude was equated across items. Inclusion of known words in the learning task equated prior exposure to both the pseudowords and known words which would later be presented in the oddball task. All pseudowords were counterbalanced between the correlated and uncorrelated learning conditions. Appendix 4 shows the full pool of stimuli, and Appendix 5 presents the auditory profile of the cross-spliced items.

On each learning trial the auditory presentation of a word was followed by two pictures. In the correlated-word condition one of these pictures was frequently a referent object, and the other picture was a non-referent foil object. In the uncorrelated-word condition both pictures were always non-referent foil objects. In the known word condition one picture was frequently the known-word referent (e.g. a picture of a kite), and the other picture was a non-referent foil object. The visual stimuli consisted of six known objects which were prototypical referents of the known words (presented in Appendix 6), and thirty novel objects which were obscure real objects from the Study 1 picture stimuli (Appendix 3). For each participant, six novel objects were randomly selected as referents for the six correlated words; the remaining twenty-four were non-associated foil objects, which were shown with a different word on each trial. After participants had been exposed to all eighteen words and thirty-six pictures, the foil pictures were reassigned to different words on the following round of trials. A different foil picture was thus presented with each word on each round of trials. One foil was presented beside the referent-category picture for correlated and known words, and two foils were presented with the uncorrelated words. There were 40 exposures to each word over the course of the learning task.

The six correlated pseudowords were thus frequently associated with the same novel object; the six uncorrelated pseudowords were presented without a consistent picture association. The participants' task was again to respond as to whether one of the two pictures was the referent for that word, or whether the referent was not present. In the known and correlated word conditions, the referent could either be present (2/3 trials) or absent (1/3 trials). On referent-absent trials, a different referent object from that condition was presented on every trial. This protocol ensured that accuracy for the correlated words emerged from learning a one-to-one mapping between a correlated pseudoword and referent, rather than simply a category of 'referent' objects; this is explained in more detail in the Methods section of Chapter 4. After responding, participants received feedback on whether they had selected the correct or incorrect referent. To maintain response motivation and attentiveness in the uncorrelated condition, positive feedback was randomly given at chance levels on each exposure. Because chance levels were considered 1/3 for this purpose (based on participants being able to respond 'left object', 'right object' or 'neither object' on each trial), this meant that 1/3 of uncorrelated-word responses were followed by positive feedback. This positive feedback was randomly interspersed with the 2/3 of negative feedback trials over the course of the experiment.

Test of phonological form learning. The MMN is an ERP measure most commonly evoked in passive oddball paradigms to a rare 'deviant' stimulus within a stream of 'standard' filler stimuli (Näätänen et al., 1997). The MMN is suggested to measure a memory trace evoked by the deviant (Pulvermüller & Shtyrov, 2006), or prediction error from the standard auditory stream (Winkler, 2007), and is highly sensitive to a range of lexical variables (Kujala, Tervaniemi, & Schröger, 2007; Shtyrov, Kimppa, Pulvermüller, & Kujala, 2011). This study followed the design of Shtyrov et al. (2010) by presenting novel word deviants against a background of known word standards. Critically, in this design the deviant stimulus must be detected as

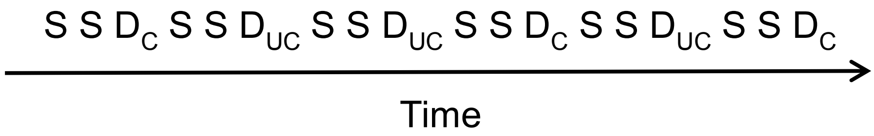

Figure 18. Schematic of stimulus presentation in the multi-feature oddball task.
S denotes the standard filler known word; D_C denotes the correlated word deviant, and D_{UC} denotes the uncorrelated word deviant. Figure adapted from Näätänen et al., 2004.

phonologically distinct from the standard to elicit an MMN (e.g. Shtyrov et al., 2010). It hence provides a pure measure of relative discrimination of newly-acquired spoken words at a neural level, eliminating confounds of task goals and explicit memory processes commonly evoked by behavioural testing.

In order to present both a newly-learnt correlated and uncorrelated pseudoword against a competitor environment of known words in the oddball task, a multi-feature oddball paradigm was used (Näätänen, Pakarinen, Rinne, & Takegata, 2004). This interspersed two repetitions of a known filler (i.e. boat) with a newly-learnt pseudoword deviant. The task started with fifteen presentations of the known token (e.g. boat) to habituate participants to the filler stimulus (Fisher, Grant, Smith, & Knott, 2011). There were then 900 trials in total, constituting 300 pseudoword exposures (150 correlated i.e. boap, 150 uncorrelated i.e. boak) and 600 known filler exposures (i.e. boat), with an 800ms SOA (Shtyrov et al., 2010). The pseudowords and fillers thus had a 1/3 and 2/3 presentation probability, respectively (Figure 18). A different minimal triplet was used in the oddball task on each day. Counterbalancing of the critical pseudowords between correlated and uncorrelated conditions and day of testing (Day 1/Day 2) meant that the same sounds were present in each novel pseudoword category, ensuring an evoked neural response therefore emerged from the learnt psycholinguistic properties of that word rather than salient acoustic properties.

Recognition Memory Task. On Day 2, participants engaged in a recognition memory test following the oddball task. The foil words diverged from the novel pseudowords at the final consonant, whereby items were voicing-contrast minimal pairs in all but one case (for /veɪk/, for which the voicing minimal pair was pronounced as /veɪg/, a real word). Examples of the recognition foils are given in Table 3.

Association Recall Task. After the oddball session and recognition memory task on Day 2, participants were tested on their memory of the word-picture associations learnt on Day 1. Participants responded using a sheet of paper with an array of thirty

Table 3. Example foil words used in the recognition memory task.

Correlated Words	Recognition Foils	Uncorrelated Words	Recognition Foils
boap	boab	boak	boag
kipe	kibe	kike	kige
jep	jeb	clet	cled
vate	vade	stit	stid
pite	pide	vape	vabe
clep	cleb	bipe	bibe

pictures from the learning task, six of which were referents for the correlated words and twenty-four of which were foil pictures. Appendix 7 presents an example of the association recall task.

5.2.1.3 Procedure

The learning task was run on Day 1 using E-Prime 2.0, with the spoken stimuli delivered via headphones. There were 40 exposures to all stimuli and 720 trials in total. Referent-present and referent-absent trials were randomised, and the order of items was randomised within each round of exposures. On each trial, participants first heard the spoken word followed by the presentation of two pictures. Instructions explained that the task required learning which words went with which objects. Participants responded using arrow keys based on whether the left, right or neither picture was the referent object.

The oddball task was run after the learning task on Day 1, and on Day 2 when participants returned to the laboratory after a 24 hour delay. Stimuli were presented through headphones whilst participants watched a silent video to detract attention from the auditory stream. A questionnaire about detailed events in the video at the end of each day yielded a mean accuracy of 81.22% (S.D. = 7.61) on Day 1 and 81.94% (S.D. = 7.93) on Day 2, verifying participants had been sufficiently engaged in the video.

In the recognition memory task on Day 2, participants heard each pseudoword and foil presented in isolation, and responded via keyboard to indicate whether that item was familiar or unfamiliar.

Finally, in the association recall task on Day 2, participants were presented with all twelve trained pseudowords via the headphones, and were instructed to write each word under its corresponding picture if they were confident the word went with that picture. The task was self-paced and participants made a key-press to advance to the next word. At the presentation of each word a number also appeared on the screen which participants were instructed to write beside the word on their response sheet. This ensured accuracy in coding responses in case of difficulties reading the handwritten responses, as the pseudoword forms were highly similar.

5.2.1.4 EEG Pre-processing and ERP formation:

The EEG data were acquired using a 64-channel Biosemi ActiveTwo system, using a 10-20 cap setup. Two additional electrodes were placed on the outer canthi of each eye, and two electrodes were placed above and below the right eye, to record saccadic and blink oculomotor artefacts, respectively. Two electrodes were placed on the right and left mastoid to re-reference the data offline, and the EEG was recorded using a 2000Hz sampling rate.

EEG data were down-sampled to 250Hz, and filtered with a 1Hz high-pass filter. An independent components analysis, which used tools from both Fieldtrip and EEGlab, removed oculomotor artefacts (Delorme & Makeig, 2004; Oostenveld et al., 2011; Shimi & Astle, 2013; Ungureanu et al., 2004); the ICA is explained in detail in section 4.2.4.1 of the previous chapter. To account for the different disambiguation points between the minimal pair triplets used on each day, the data were epoched such that the disambiguation point for each individual item occurred at exactly 0 ms in peri-stimulus time. Analyses were thus locked to the relative disambiguation point for each item, permitting a precise analysis of any MMN elicited as a function of psycholinguistic properties of the newly-learnt words. EEG data were then epoched from -600ms to 200ms (with ‘0’ the relative disambiguation point across items) and processed with a 30Hz low-pass filter. Epoched data were rebaselined to -50 to 0ms before the relative disambiguation point, to account for the shifting of the epoch point between items. Due to the varying disambiguation point across items, different relative word intensities preceded the disambiguation point; baselining the data immediately before disambiguation thus ensured these acoustic differences did not contribute to the MMN (Shtyrov et al., 2010). The removal of excessively noisy trials was then implemented using the Fieldtrip Visual Artefact Rejection tool (Oostenveld et al., 2011); this measured the overall variance in voltage within each trial, and trials with exceptionally high variance were removed. This process removed 3.52% of trials overall. Following this, the remaining trials were averaged to form an ERP for each condition over the oddball task on each Day.

5.2.1.5 Electrode and time window selection

The MMN is typically maximal over midline electrodes, and peaks approximately 120-200ms following the disambiguation point (Pulvermüller & Shtyrov, 2006). The midline electrodes which showed the most negative raw voltage in the grand-averaged topographies, Cz, CPz, Pz, POz, and Oz, were thus pooled together for spatial smoothing and to increase the signal-to-noise ratio, due to the relatively low number of trials per condition (Shtyrov et al., 2010). The mean amplitudes in a 50ms time-window from the first negative peak in the grand-averaged waveform across both days and pseudoword conditions (130-180ms) were analysed. To isolate the MMN from other components, a difference wave was computed by subtracting each participant's known standard voltage from their correlated and uncorrelated pseudoword voltage on each day (cf. Bishop & Hardiman, 2010). This difference wave measured the degree of critical pseudoword discrimination from the competitor environment of known words.

5.2.2 Results

5.2.2.1 Behavioural Data

Performance on the learning task indicated good knowledge of the correlated word associations by the end of the exposure session, with group-level accuracy averaged over the final ten exposures of the learning task at 74.38% (S.D. = 19.69). A repeated-measures ANOVA on percentage accuracy with the factors of Condition (Known, Correlated) and Block (Blocks 1-4) yielded a significant Condition x Block interaction, $F(3, 69) = 26.56$, $p < .001$. Paired t-tests verified that correlated word accuracy increased between the first and last block of learning (Block 1 vs. Block 4: $t(23) = -9.00$, $p < .001$). Accuracy for the correlated-word associations remained below that of known words in Block 4 ($t(23) = 9.87$, $p < .001$). Figure 19 presents the known word responses and the learning curve for the correlated words over the course of the experiment.

In the recognition memory test, conducted on Day 2, six participants did not respond for more than 50% of trials in one condition, meaning accuracy scores could not be computed for those individuals. Recognition memory accuracy scores for the remaining participants showed above-chance recognition of both correlated and

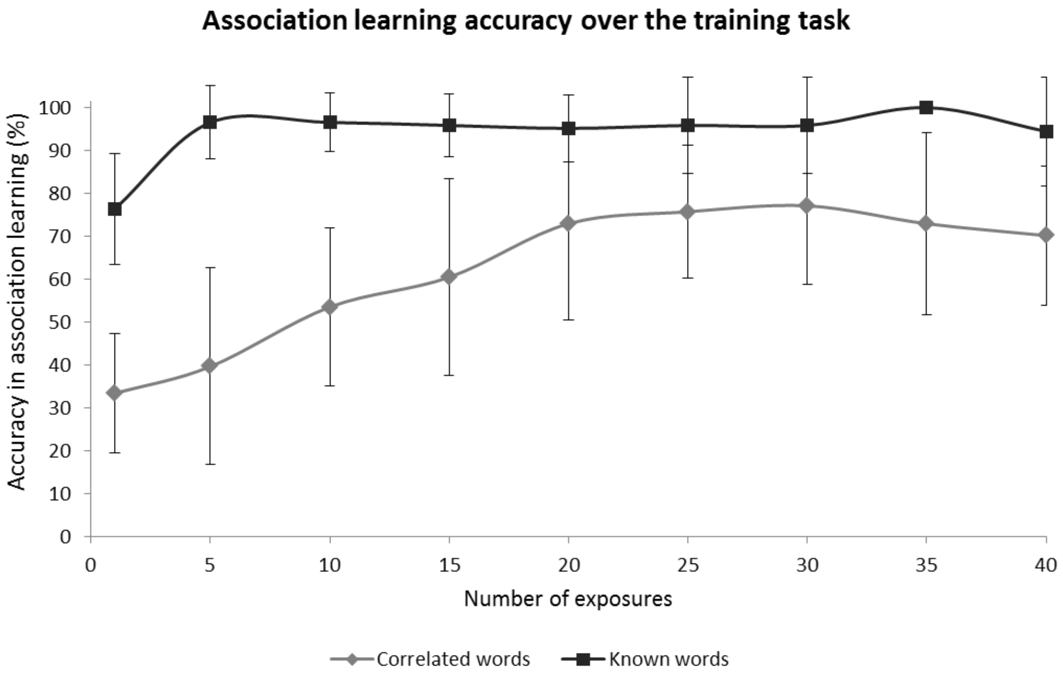

Figure 19. Association learning performance in the training task in Study 2.
Each data point shows the mean accuracy in choosing the associated picture across participants on that exposure. The error bars show the standard deviation on each exposure.

uncorrelated pseudowords (correlated: t(17) = 19.56, p < .001; uncorrelated: t(17) = 6.42, p < .001). A paired t-test on percentage accuracy found significantly higher recognition accuracy for correlated than uncorrelated words (t(17) = 2.84, p < .05; correlated M = 91.67%, SD = 9.04; uncorrelated M = 71.3%, SD = 14.07). There was no effect of condition on recognition memory reaction times, analysed for correct trials only (Correlated M = 489ms, SD = 183; Uncorrelated M = 450, SD = 174; t(17) = .81, p = .43).

The association recall test, conducted on Day 2 after the oddball and recognition memory test, was scored by the percentage of correlated words correctly assigned to their referent picture (out of the array of 30 pictures). Percentage accuracy showed that participants retained good knowledge of the word and picture associations on Day 2 (M = 64.58%, SD = 22.15). Errors were predominantly from ‘no object’ responses (not assigning correlated words to an object; 20.83%). Assigning a correlated word to an incorrect picture constituted 9.03% of errors, and labelling a picture with the uncorrelated minimal pair of its correlated label (e.g. labelling the *boap* correlated object as a *boak*) constituted 4.86% of errors.

5.2.2.2 ERP Data

In order to examine any quantitative consolidation-based changes in discrimination, the MMN difference wave elicited by correlated and uncorrelated deviants was averaged over all 150 exposures in the oddball task on each Day. It was reasoned that if there was a facilitatory effect of consolidation on phonological form learning there should be a greater evoked MMN magnitude on Day 2 for one (or both) of the newly-learnt pseudoword types. Although an online increase in a pseudoword MMN within a single session has been found previously in a comparable oddball task (Shtyrov et al., 2010), a consolidation-driven change in discrimination should yield an overall quantitative change in MMN magnitude from Day 1 to Day 2.

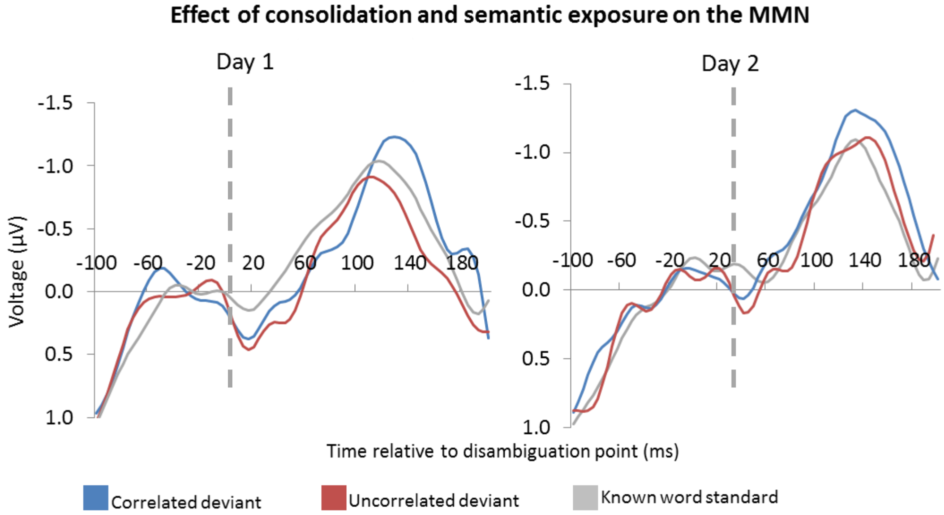

Figure 20. Effect of consolidation and semantic exposure on the MMN.
MMNs to the correlated, uncorrelated and known words on Day 1 and Day 2, averaged across electrodes Cz, CPz, Pz, POz and Oz. The vertical dashed line shows the relative disambiguation point across items.

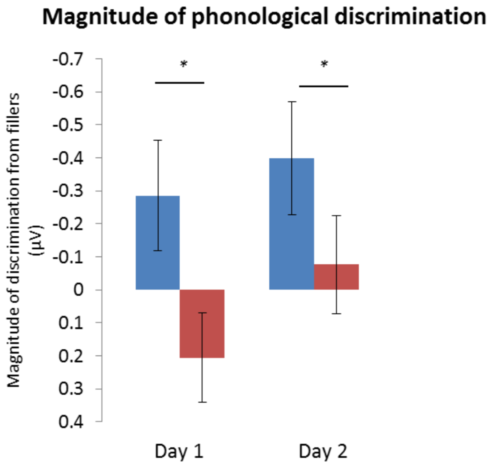

Figure 21. The magnitude of phonological discrimination.
The difference scores for each of the correlated and uncorrelated words from the known word standards, plotted for Day 1 and Day 2. The error bars show the standard error of the mean for a within-subjects design (Cousineau, 2005).

Effects of consolidation and semantic exposure on the MMN. In order to examine any consolidation-based changes in discrimination, the correlated and uncorrelated MMN difference wave on each Day was submitted to a Condition (Correlated vs. Uncorrelated) by Day (Day 1 vs. Day 2) repeated-measures ANOVA. This comparison yielded a significant main effect of Condition only, $F(1,23) = 14.02$, $p = .001$, with a significantly more negative correlated word MMN ($M = -.34$, $SD = .63$) than uncorrelated word MMN ($M = .06$, $SD = .55$; Figures 20 and 21) over both days. There was no main effect of Day and no interaction between Condition and Day (both Fs <1 and ps >0.4).

Relationship between the MMN and semantic association learning. The ERP analysis suggested enhanced phonological form discrimination for correlated words relative to uncorrelated words, and that this enhancement was equivalent on both days, indicating that consolidation did not strengthen access to the new phonological representations. However, CLS accounts also predict that a second function of consolidation may be the transformation of episodic representations to abstract lexical representations (e.g. Davis & Gaskell, 2009). From this prediction there are (at least) two possible sources of knowledge about newly-learnt phonological forms. One is episodic knowledge from recent learning, whilst the other is via a lexical store independent of episodic knowledge. Given this, a correlational analysis aimed to distinguish the

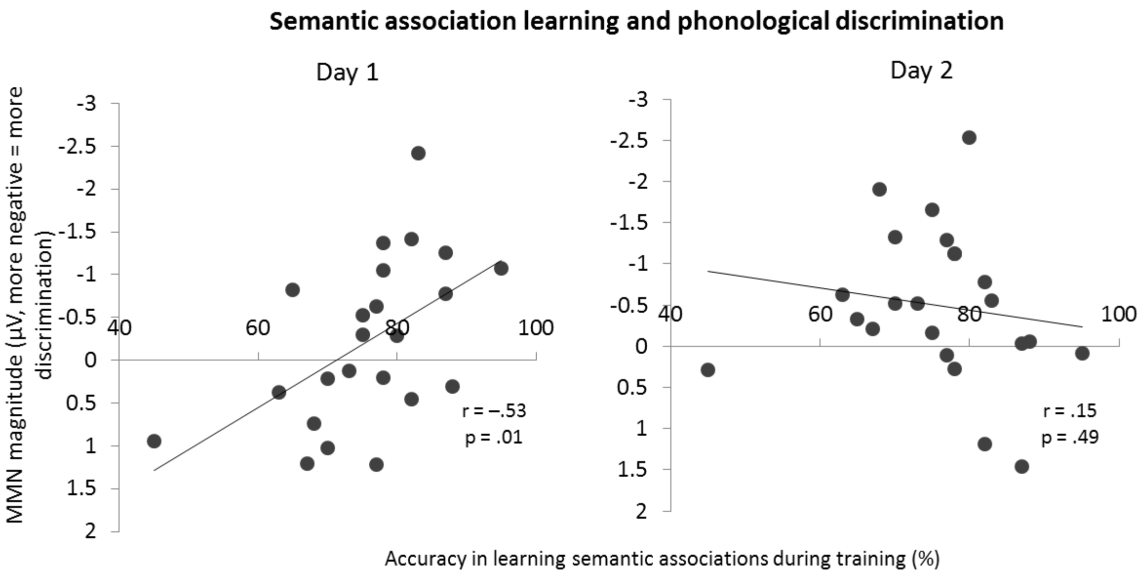

Figure 22. Relationship between the correlated-word MMN and semantic learning.
The relationship between the correlated-word MMN and semantic learning accuracy from the training task on Day 1 (before consolidation, left panel) and Day 2 (after consolidation, right panel). MMN magnitude is plotted on the y-axis and semantic learning accuracy is plotted on the *x*-axis. The polarity of the *y*-axis is reversed for ease of interpretation.

contribution of these two sources of knowledge to the MMN effects, to ascertain whether different types of knowledge underpinned the MMN on each day. This analysis thus investigated the extent to which the explicit learning of semantic associations on Day 1 underpinned the MMN for correlated words on Day 1 and Day 2. One participant was excluded from this analysis, due to having a learning score >2.5 standard deviations below the mean accuracy score. A bivariate correlation was run between each participant's accuracy score on the correlated word associations at the end of the learning task (averaged over the final 10 exposures) and the correlated word MMNs on Day 1. This analysis revealed a significant negative correlation between semantic learning accuracy and the correlated-word MMNs, $r(23) = -.53$, $p = .01$. This analysis indicated that as semantic learning accuracy improved, correlated-word discrimination improved, which was indexed by a more negative MMN voltage. A second correlation between semantic learning accuracy and the correlated-word MMN on Day 2 found no significant relationship, $r(23) = .15$, $p = .49$. Meng's Z-test (Meng, Rubin & Rosenthal, 1992) confirmed that the correlations differed significantly between Day 1 and Day 2 ($Z = 2.17$, $p < .05$). Figure 22 presents scatterplots of these correlations.

Recognition memory performance and the MMN. These correlational analyses suggested that in the correlated condition, phonological discrimination (indexed by the MMN) was initially tied to semantic learning accuracy, but following a period of offline consolidation there was no relationship between semantic learning and phonological discrimination. As supporting evidence for this analysis, a second set of correlational analyses tested for a relationship between recognition memory, an explicit measure of word knowledge, and the correlated and uncorrelated word MMN on Day 2.

The six participants for whom a recognition memory score could not be calculated were excluded from this analysis. A bivariate correlation was run between recognition memory accuracy for each condition on Day 2 and the correlated-word MMN and uncorrelated-word MMN on Day 2. This analysis yielded a significant negative correlation between the uncorrelated MMN and recognition accuracy, $r(18) = -.65$, $p < .01$, indicating that participants with relatively greater uncorrelated word discrimination (MMN) also had greater recognition accuracy. The correlated MMN on Day 2 showed no relationship with recognition accuracy, $r(18) = .04$, $p = .88$. It was then tested whether these correlations differed significantly using a Pearson-Filon test (Raghunathan, Rosenthal, & Rubin, 1996), which confirmed that the correlations differed significantly, $Z = 2.08$, $p < .05$. Figure 23 presents scatterplots of these correlations. The lack of

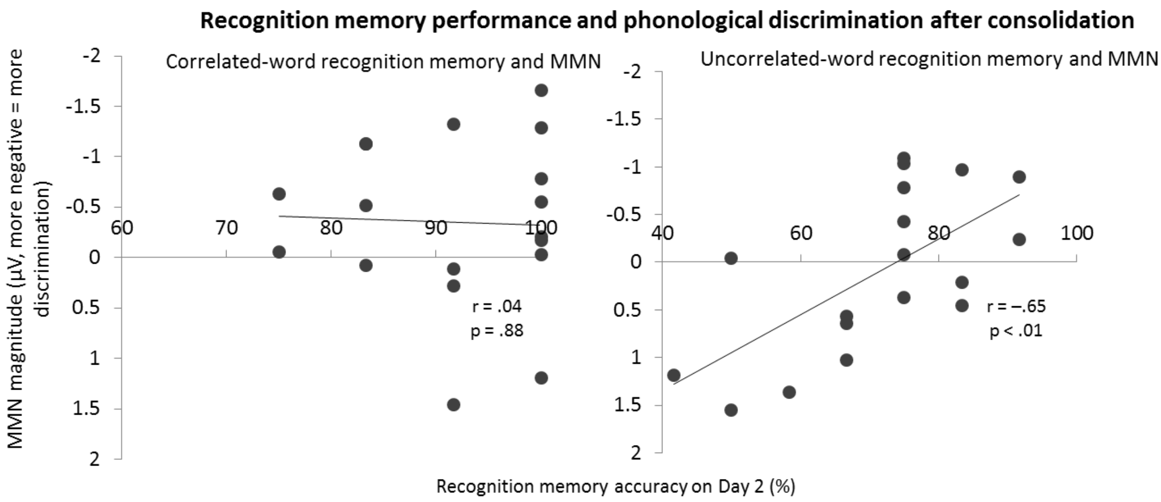

Figure 23. Relationship between the MMN and recognition memory on Day 2.
The relationship between recognition memory performance, measured on Day 2, and the MMN on Day 2 for correlated and uncorrelated words. MMN magnitude is plotted on the y-axis and recognition memory accuracy is plotted on the x-axis. The polarity of the y-axis is again reversed for ease of interpretation, where a more negative MMN corresponds to increased discrimination.

correlation between recognition memory and the MMN for correlated words on Day 2 in this second correlation analysis, in contrast to the uncorrelated words which were tied to explicit recognition on Day 2, mirrored the findings of the first correlation analysis.

5.3 Discussion

Study 2 aimed to establish whether the provision of systematic semantic information facilitated the learning of new phonological form representations, and the manner in which overnight consolidation impacted upon these representations. Participants learnt novel phonological forms accompanied by a novel visual referent, which was either systematically associated with the novel word (correlated condition) or differed on every trial (uncorrelated condition). Newly-acquired phonological representations were then tested using the MMN potential as an index of phonological form learning, building on the methodology of Study 1. The behavioural results showed successful learning of the correlated-word associations, and better recognition memory for correlated relative to uncorrelated words on Day 2. Additionally, performance on the association recall task suggested participants retained knowledge of the correlated-word associations on Day 2. ERP results showed a main effect of semantic condition only, with those words in the correlated condition yielding enhanced discrimination from known words. However, while discrimination performance did not change as a function of consolidation, correlational analyses suggested that it was underpinned by different sources of knowledge across the two days of testing. Explicit knowledge of the semantic associations in the learning task was reflected in discrimination of the correlated words on Day 1 but not on Day 2. This relative independence of the correlated words from episodic knowledge on Day 2 was corroborated by a second correlational analysis between the Day 2 MMNs and recognition memory accuracy, an explicit measure of word knowledge, and found a significant relationship for uncorrelated words only. There was thus no strengthened access to phonological representations by overnight consolidation, but the correlational analyses suggested that consolidation may assist in the abstraction of new phonological form representations associated with semantic information.

5.3.1 Phonological form learning and meaning

From the literature reviewed thus far previous conclusions regarding the role of semantic exposure on different aspects of word learning have been mixed (cf. Breitenstein et al., 2005; Dumay et al., 2004; Leach & Samuel, 2007). However, the current study suggests that the provision of systematic semantic information may confer a benefit for acquiring new phonological form representations, in concordance with the learning data from Study 1. This result also ties into models of spoken word recognition to suggest there may be a semantic influence on phonological representations not only during known word recognition (e.g. Gaskell & Marslen-Wilson, 1997; Tyler et al., 2000), but during the early stages of word acquisition. Previous models positing an interaction between phonology and semantics during learning have suggested that novel words characterised by systematic mappings between word forms and meanings are learnt with greater ease than novel words lacking this systematicity (Rueckl & Dror, 1994). The current study extends these findings by suggesting that novel words with a degree of systematicity (i.e. a semantic association) are not only learnt more readily than those without, but that this systematicity may impact upon phonological discrimination, rather than the word-level recall of new items.

However, it is important to recognise that the nature of such a semantic benefit as that observed here may be due, at least in part, to the task goals requiring the acquisition of meaning. As such, interactive connectionist frameworks positing an interaction between different levels of information (e.g. as in TRACE; McClelland & Elman, 1986) may benefit from considering the impact of learning goals on the outcome of the acquisition process. The learning task in the current and previous study emphasised associative learning, but it is equally plausible that an emphasis on phonological learning would minimise the recruitment of semantic information during training and consequently not afford such a semantic benefit (see e.g. Takashima et al., 2014; also cf. Forster, 1985; Yoncheva et al., 2010). The impact of learning goals on initial acquisition also has implications for the time-course of consolidation; for example, Szmalec et al. (2012) suggested that the implicit learning of new word forms via a repetition task led to more efficient lexical consolidation than the explicit learning of word forms (as in phoneme monitoring paradigms, e.g. Dumay & Gaskell, 2007). Learning goals are thus a central factor in evaluating the extent to which semantic information is recruited during training and its subsequent impact on consolidation.

Following this, another possibility is that rather than a semantic advantage, what was observed was a relative disadvantage of the uncorrelated words due to the noise created by the lack of a systematic referent in a task where the goal was to map a word form to an associated referent. Whilst this possibility cannot be ruled out, it is important to recognise that the uncorrelated words had significantly above chance behavioural recognition accuracy on Day 2, indicating that participants had a degree of familiarity with the uncorrelated-words, albeit less than the correlated-words. Further, varying the associative systematicity between the correlated and uncorrelated condition arguably provided a more realistic proxy of real-world learning than contrasting the correlated-word condition with a ‘form-only’ condition (for example, as in Takashima et al., 2014). In real-world situations, we are rarely exposed to a spoken word with no potential semantic meaning or goal to acquire one, and it is not uncommon to experience a word in different contexts across several exposures and thus struggle to extract a specific meaning, such as in the case of words with multiple meanings (e.g. bug). Finally, in experimental situations contrasting semantic and ‘form-only’ conditions (e.g. Dumay et al., 2004; Takashima et al., 2014) there is not only a difference in semantic content between the two conditions, but a categorical difference in learning goals, information load, and attentional demands. An interpretation is therefore that the current learning paradigm provides a contrast between associative semantic learning and an ambiguous learning situation where words could be treated as having either many potential referents or no referent, which is not unlike real-world word learning situations.

Despite this, the lack of an MMN for uncorrelated words on Day 2 could suggest the MMN was not adequately measuring phonological form learning. Similar to Shtyrov et al. (2010) there was an evoked MMN for the discrimination of the novel (correlated) words from existing words following a defined recognition point in the speech signal, whereby the MMN indexed the perceived phonological contrast between the novel word and known word. Furthermore, as the MMN was elicited automatically in the absence of attention to the speech stream, and thus without any specific processing goals, it provided a precise measure of the degree of phonological discrimination of the newly-learnt words. Notably, however, the lack of an uncorrelated-word MMN could have been in part due using a multi-feature MMN paradigm that required the fine-grained discrimination of two minimal novel words from a known word, which could be substantially more taxing than the learning and discrimination of a single minimal novel and known-word pair as in Shtyrov et al. (2010). The increase in phonological learning demands in the current study could have thus contributed to observing no stable MMN response for the uncorrelated words on Day 2.

It is also notable that the MMN is sensitive to the familiarity of linguistic stimuli, where it is evoked for familiar words rather than simply in response to a phonemic contrast. The MMN can distinguish native phonemic contrasts, where discrimination between native phoneme categories (e.g. /bɑ/-/dɑ/) elicits an MMN without any training (e.g. Dehaene-Lambertz, 1997; Näätänen et al., 1997; Phillips et al., 2000; Shestakova et al., 2002). However, when native phonemic contrasts are presented within novel words the MMN is significantly reduced (Pulvermüller, Kujala, Shtyrov, et al., 2001). Shtyrov and Pulvermüller (2002) tested whether this reduction of the MMN for phonemic contrasts in novel words was due to the unfamiliarity of novel word stimuli by comparing the MMN responses for i) word deviants against word standards, ii) word deviants against pseudoword standards, and iii) pseudoword deviants against word standards. The MMN elicited by word deviants (conditions i and ii) was significantly greater than for the pseudoword deviants (condition iii). This suggested that a critical factor in the MMN magnitude to linguistic stimuli was the familiarity of the deviant stimulus rather than simply a phonemic or lexicality difference between the deviant and standard stimuli, in which case the pseudoword deviant versus word standard should have elicited a comparable MMN (see also Korpilahti, Krause, Holopainen, & Lang, 2001, for similar results). Interestingly, this suggests that the MMN evoked by word stimuli may be based at least partly on a top-down influence of word representations benefiting discrimination. It is possible that the uncorrelated words did not establish strong enough representations to influence discrimination on Day 1 or Day 2 in the current study, and potentially had a slower time-course of establishing new phonological representations.

5.3.2 Offline consolidation of new phonological form representations

Offline consolidation can serve to both strengthen access to new word representations (by increasing recognition memory speed and accuracy, for example), and abstract new words from episodic knowledge. Recent research on consolidation effects in novel word learning has drawn on complementary learning systems (CLS) theories of memory to explain such consolidation effects (e.g. Davis & Gaskell, 2009; McClelland et al., 1995). The central tenet of these theories is that newly-learnt words are stored initially as episodic representations mediated by a fast-learning hippocampal store, and over a period of consolidation become less dependent on this episodic memory as they become integrated with existing knowledge and therefore represented neocortically. If this instantiation is correct, a greater contribution of episodic knowledge to phonological form representations would be expected immediately after learning, with a decay in this episodic contribution over time as newly-learnt words become increasingly lexicalized (see Tamminen & Gaskell, 2013, for a similar argument).

Whilst the MMN amplitudes showed no effect of day, suggesting consolidation did not serve to strengthen the correlated or uncorrelated word representations, correlational analyses suggested that consolidation may have aided abstraction of the correlated words from the episodic knowledge which initially benefited them. Accuracy in learning the semantic associations was tied to the correlated-word MMN amplitude on Day 1, but was unrelated to it on Day 2. The recognition memory analyses showed a similar pattern, in which correlated word MMN magnitude was unrelated to recognition accuracy on Day 2, but the uncorrelated MMN was related to recognition accuracy. A critical limitation on the interpretation of the recognition memory correlations, however, was the fact that eight participants were at ceiling (100%) in the correlated word condition, with no participants at ceiling in the uncorrelated word condition. A lack of relationship between the correlated word MMN and recognition memory on Day 2 could thus be attributable to this ceiling effect. Further, as recognition memory was not measured on Day 1 it was not possible to test for a change in the relationship between the correlated-word MMN and recognition memory over consolidation. The possible difference in the relationship between explicit recognition accuracy and the phonological discrimination of correlated and uncorrelated items after consolidation is nonetheless an interesting consideration; for example, it could be the case that the uncorrelated items may show a longer consolidation time-course in which the establishment of low-level phonological representations is slower, and these representations may therefore be reliant on explicit knowledge for a longer period before abstraction can occur. However, this would need to be tested with a recognition task sufficiently challenging to prevent ceiling effects, and to compare the association between phonological discrimination and recognition memory before and after consolidation.

Importantly, the lack of association between semantic learning and the correlated-word MMN on Day 2 was not necessarily due to participants simply forgetting the associations: the association recall accuracy data collected on Day 2 showed that participants retained strong knowledge of the correlated word-picture associations after consolidation, with 64.58% accuracy when selecting the correct referent from an array of the novel pictures. It is important to note that this was a substantially more difficult task than selecting from the two pictures presented in the learning task. Taken together, these data suggest that consolidation decreased the reliance of the correlated-word phonological forms on learnt associations from the training task, and that this decreased reliance may have been a specific consequence of consolidation, rather than a failure to retain memory of the associations overnight. These data are consistent with a CLS account (Davis & Gaskell, 2009; McClelland et al., 1995) and extant literature suggesting that consolidated knowledge can be represented independently of episodic knowledge (e.g. Tamminen & Gaskell, 2013; Tamminen et al., 2012; see also Gomez et al., 2006). It is important to nonetheless recognise that because the consolidation-based abstraction of the correlated words was based on a correlational change, rather than more direct evidence of independence from memory of the semantic associations, this finding would benefit from substantiation in future research.

Finally, it is worth considering the extent to which the observed learning effects reflect only episodic memory. Some accounts of lexical learning assert that words learnt in adulthood can only be represented episodically (e.g. Jiang & Forster, 2001; Qiao et al., 2009). However, the current data support evidence that is inconsistent with this claim (see also Dumay & Gaskell, 2012). If the newly-learnt words could only achieve an episodic representation, a post-consolidation relationship between the correlated-word MMN and semantic learning may have been observed. That this was not the case suggests that the new phonological forms may have been represented independently of episodic knowledge, and that this independent representation could require offline consolidation. However, it is critical to note that the current study did not measure the engagement of the newly-learnt words with existing lexical items (Leach & Samuel, 2007). It thus remains to be established what consequences this effect on phonological representations has for the engagement of these new representations in competition with existing lexical knowledge.

5.3.3 Conclusions and next questions

The data of Study 2 suggested that systematic exposure to picture referents could facilitate the acquisition of new phonological forms, relative to those without systematic picture referents. Whilst consolidation did not enhance the MMN potential, the correlational analyses suggested that consolidation may have aided in the abstraction of the correlated words from knowledge of the semantic associations that initially benefited them, but this potential abstraction requires further supporting evidence.

These findings nonetheless pose several questions for specifying the impact of semantics on the word learning process. Given the adverse effect of semantic exposure on the time-course of lexical integration (Dumay et al., 2004; Takashima et al., 2014; cf. Henderson, Weighall, & Gaskell, 2013), one possibility is that the semantic benefit on learning new phonological form representations observed here does not transfer to their offline integration with existing lexical items. This would suggest that phonological form learning and lexical integration reflect two separate stages of word memory formation, which are differentially impacted by semantic information. Alternatively, it could be the case that a learning task with semantic information must also recruit phonological information sufficiently well for the time-course of lexical integration to be unimpaired by semantic knowledge. Notably, however, the novel items in Study 2 had a large phonological neighbourhood size in contrast to the studies of Dumay et al. (2004) and Takashima et al. (2014), which utilised items with few close phonological neighbours (e.g. *cathedruke-cathedral*). Thus, it is also possible that semantic knowledge is beneficial only in the acquisition of new words with high phonological neighbourhoods, akin to the impact of imageability in skilled spoken word recognition for words in high competition cohorts only (e.g. Tyler et al., 2000; Zhuang et al., 2011). It is therefore the case that the semantic advantage observed in Study 1 and Study 2 may not translate to the learning of more phonologically distinct items. The way in which a semantic advantage for learning new phonological form representations relates to the offline impact of semantic knowledge on lexical integration therefore remains an important avenue for investigation. The next chapter thus addresses whether the semantic advantage for new phonological form representations observed after consolidation here translates to their offline lexical integration.

Chapter 6: The influence of meaning on the time-course of lexicalization

6.1 Introduction

In recent years the integration of new and existing lexical knowledge, a process known as lexicalization, has been established to occur usually within a 24 hour period of consolidation after learning. The lexicalization of new words within this timeframe can be facilitated by offline consolidation including sleep (e.g. Davis et al. 2009; Dumay & Gaskell, 2007, 2012; Gaskell & Dumay, 2003; Henderson et al., 2012; Tamminen et al., 2010), but under particular training conditions lexicalization has also been reported to occur during wake (e.g. Fernandes et al., 2009; Lindsay & Gaskell, 2013; Szmalec et al., 2012). In each of these studies lexicalization has proceeded in the absence of meaning, indicating that knowledge of a new phonological form alone is sufficient for engagement in lexical competition. Strikingly, however, associating a novel word with a meaning has been observed to *delay* this 24 hour time-course (Dumay et al., 2004; Takashima et al., 2014; cf. Henderson, Weighall, & Gaskell, 2013). This chapter addresses why this should be the case.

6.1.1 Lexicalization and semantic training

Only a handful of previous studies have specifically addressed the role of meaning in the lexicalization of new words. These were reviewed in Chapter 3 (in section 3.4.2), and will be returned to briefly here as a reminder of the key points of these studies. In the first of these studies, Dumay et al. (2004) set out to assess whether the overnight delay for lexical competition observed by Gaskell and Dumay (2003) was the result of impoverished training conditions which lacked meaning. Participants learnt novel words via phoneme monitoring, or embedded in sentential contexts through which a meaning could be acquired. After 24 hours only the words learnt via phoneme monitoring, with no associated meaning, showed evidence of lexical competition by slowing down reaction times to existing neighbours. It was only after one week that the words learnt with a meaning entered into lexical competition. A similar result was obtained by Takashima et al. (2014), whereby participants learnt novel words with or without picture referents via phoneme monitoring. Only the words trained in the *absence* of a picture referent showed evidence of lexical competition after 24 hours. These findings are thus consistent with the idea that semantic exposure can delay the twenty-four hour time-course in which lexicalization is normally observed[9].

In contrast, Leach and Samuel (2007) observed that only novel words trained with a meaning engaged with existing lexical knowledge, measured by the perceptual retuning of existing phoneme boundaries. Whilst these findings may initially suggest a semantic benefit for lexical engagement, it is important to note that Leach and Samuel (2007) probed the engagement of new words at the phoneme category level, rather than at the lexical level of establishing inhibitory links with existing words. As such, the extent to which this semantic training advantage relates to lexicalization is unclear; indeed, novel words have been observed to influence the phonemic perception of existing words immediately after learning (measured by place assimilation compensation; Snoeren et al., 2009; Lindsay, Sedin, & Gaskell, 2012). It has also been suggested that the hippocampal system, involved in the initial encoding of novel words, has direct access to lexical phonology (Davis & Gaskell, 2009) and as such novel words may be able to impact upon the perception of existing phonemic knowledge immediately after learning, even in the absence of consolidation-based engagement in lexical competition. Taken together, the findings of Leach and Samuel (2007) suggest that novel words may immediately affect the perception of existing phonemic knowledge when trained with a meaning, whilst the data of Dumay et al. (2004) and Takashima et al. (2014) are consistent in suggesting that meaning may delay the engagement of novel words with existing lexical-level knowledge.

An exception to the semantic delay in lexical competition was reported in children by Henderson, Weighall, and Gaskell (2013). Two separate groups of five to nine-year-olds learnt unfamiliar science words. One group learnt these words with a meaning via pictures and definitions, and the other via a form-only training using phoneme monitoring, with the orthographic form of the word appearing on a computer screen. Notably, this design had the benefit of ensuring that in both the semantic and form-only training conditions, the phonological form of the novel words were associated with another source of information (semantic or orthographic). Both the meaning-associated and form-only training groups showed a significant lexical competition effect

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[9] An alternative way of thinking about this is that phonological training promotes *faster* lexicalization than would be observed in a naturalistic learning environment, and the semantic 'delay' rather reflects a more natural timecourse akin to what would be observed when encountering a new word in an everyday context. However, for the purposes of this chapter the longer lexicalization timecourse for meaning-associated words will be referred to as a 'delay', with respect to the substantial body of literature observing lexicalization within 24 hours following phonological training. The issue of what more closely reflects a lexicalization timecourse akin to natural learning will be returned to in the following chapters of this thesis.

after 24 hours, measured by the slowing of responses to existing words in a pause detection task. In contrast to the adult studies, the engagement of the semantically-trained words in lexical competition after 24 hours suggested that semantic exposure does not universally slow down the time-course of lexicalization.

6.1.2 Contributions to a slow lexicalization time course

Based on the above data from studies testing the role of meaning in lexicalization, two main possibilities emerge. Firstly, it could be the case that learning a new word with a meaning has more potential for interference with existing knowledge, and thus requires a longer period of consolidation for the novel and existing word links to be established. Indeed, the integration of semantic information may proceed more slowly than the integration of new phonological form representations. Studies testing the integration of new words into semantic priming, such that a novel word with a trained meaning can prime an existing word with a related meaning, have observed that semantic priming emerges one week after learning (e.g. Tamminen & Gaskell, 2013). One possibility for this longer time-course of semantic integration may be that the high level of existing knowledge in semantic networks necessitates more gradual consolidation, to avoid interference with existing knowledge (McClelland et al., 1995; McCloskey & Cohen, 1989). Recall that in a study testing the semantic integration of novel words learnt in dense or sparse semantic neighbourhoods, Tamminen et al. (2013) observed that novel words learnt in sparse semantic neighbourhoods elicited greater spindle density and slow-wave activity in the night of sleep following training than words learnt in dense semantic neighbourhoods. Tamminen et al. (2013) suggested that one interpretation for this finding was that words learnt in dense neighbourhoods required a longer period of consolidation, due to having a greater potential for interference with existing semantic knowledge, and thus showed reduced sleep activity the night after learning. Interestingly, this may also be a contributing factor to why Henderson, Weighall, & Gaskell (2013) observed lexical competition for meaning-associated words after 24 hours in children: if children have sparser semantic networks than adults, the lexicalization of meaning-associated words may proceed more rapidly than in adults and thus emerge within a twenty-four hour timeframe. This view is consistent with a recent proposal by McClelland (2013) which conceptualises the consolidation time course as critically *prior-knowledge dependent*. Thus, when prior and new knowledge have a greater potential for interference, a more gradual offline interleaving into neocortical networks may be required.

A second possibility is that for successful lexicalization within a 24 hour time window, novel words may require a certain degree of phonological processing during learning. An associated meaning could interfere with online phonological processing by diverting attentional resources from the phonological forms of novel words during training, and subsequently result in a slower lexicalization process. Note that in Dumay et al. (2004), the form-only words were learnt via a task requiring a high degree of phonological processing (phoneme monitoring) and the meaning-associated words were acquired in sentence contexts, thus requiring substantially less fine-grained phonological processing. Whilst in Takashima et al. (2014) both the form-only and picture-associated words were learnt via phoneme monitoring, an important consideration is that in the picture-associated condition the pictures appeared prior to the onset of the novel word. It is therefore possible that over the course of the training task the picture-associated words did not receive the same degree of phonological processing for target detection as the form-only words, due to partially retrieving the phonological form from memory via the preceding picture. From these methodological considerations the extent to which semantic knowledge contributed to a slower lexicalization time-course due to increased capacity for interference, or due to less well-established phonological form representations in Dumay et al. (2004) and Takashima et al. (2014)[10], is unclear. The proposed importance of well-established phonological representations for lexicalization also aligns with the standard consolidation model (Squire & Alvarez, 1995; reviewed in Chapter 3) in which the learning of new memories is supported by the hippocampus and distributed cortical regions. The reactivation of hippocampal memory during consolidation is proposed to reinstate these cortical networks, promoting their strengthening and reorganisation, until the cortical representation becomes sufficiently stable to be independent of hippocampus. In the case of the lexicalization of new words into existing cortical networks, weaker phonological form representations in the hippocampus following learning may thus form more fragile links with existing phonological form representations in the neocortex. It follows that the reinstatement of these hippocampal-cortical links during consolidation would be weaker, making the

[10] Note that this suggestion of an absence of lexicalization after 24 hours for meaning-associated words due to reduced phonological processing should not be conflated with these words having weaker representations in general. Indeed, in both Dumay et al. (2004) and Takashima et al. (2014) both meaning-associated and form-only words had good recognition memory both immediately and after 24 hours (Dumay et al.: ~92% for both conditions in a 2AFC test; Takashima et al.: ~95% for both conditions in an old/new recognition test). This suggests that the lexicalization deficit for meaning-associated words was not tied to poorer learning in general.

existing cortical representations less amenable to reorganization, and subsequently resulting in a longer lexicalization time-course.

6.1.3 Summary

This chapter tackles the central issue of the lexicalization time-course for semantically-associated words in adults. This issue is underpinned by the observed slower lexicalization for semantically-associated words relative to phonological forms acquired in isolation (Dumay et al., 2004; Takashima et al., 2014; cf. Henderson, Weighall, & Gaskell, 2013), and the consideration that (at least) two key factors may contribute to this time-course: the potential for interference with existing knowledge (e.g. McClelland, 2013), and weaker phonological form representations resulting from semantic training.

Study 3 thus capitalized on the learning paradigm employed in Study 2, in which novel words acquired with a systematic semantic association established phonological form representations, which were stable over a 24 hour consolidation period. The same learning paradigm was used here to promote the learning of stable phonological form representations for semantically-associated words, and subsequently assess if these words entered into lexical competition. It was thus predicted that if phonological form representations are important for lexicalization, semantically-associated novel words acquired in this learning paradigm should show lexical competition effects, whilst the non-semantic novel words should have reduced or absent lexical competition effects following offline consolidation.

6.2 Study 3

Study 3 addressed two key research questions. Firstly, could semantically-trained new words from the current learning paradigm show lexicalization after one night of consolidation? Secondly, what aspects of word knowledge are benefited by offline consolidation, and how is this affected by the acquisition of semantic associations?

Figure 24 shows a schematic of the experimental design. Participants were trained on 16 novel words with an associated picture referent (*correlated condition*) and 16 novel words with no consistently associated referent (*uncorrelated condition*), using the same learning paradigm as that employed in Study 2, on Day 1 and Day 2. Participants thus learnt 64 new words over the course of Day 1 and Day 2. Importantly,

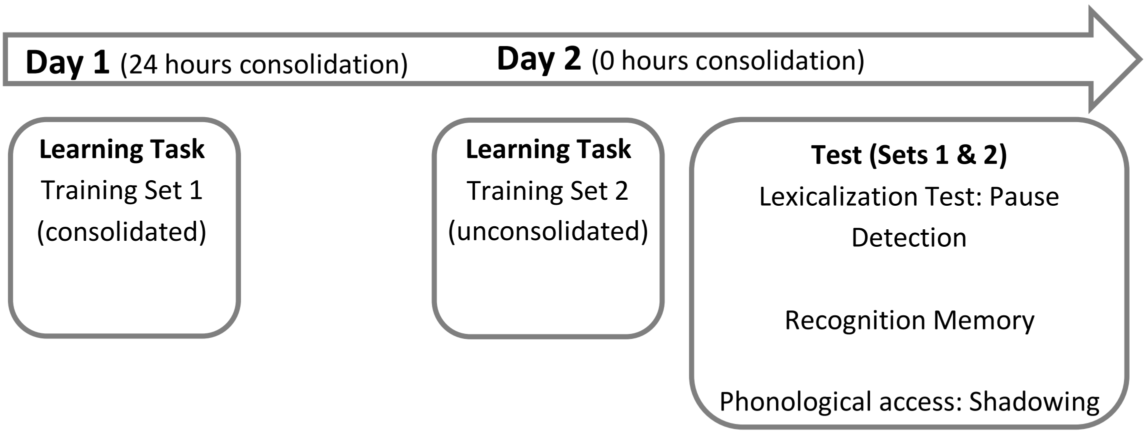

Figure 24. Schematic of the training and test design in Study 3.
Each training set contained 32 novel words, 16 of which were correlated and 16 of which were uncorrelated.

the novel words were all phonological competitors of existing words (e.g. *cathedruke-cathedral, biscal-biscuit*). After learning on Day 2, participants were tested on three tasks. Lexical integration was tested using a pause detection task (Mattys & Clark, 2002), in which participants' task was to detect pauses in existing phonological competitors of the trained words (e.g. *cathedr_al, bisc_uit*), and control words with no newly-learnt competitor. If the newly-learnt words have been lexicalized, the detection of pauses in existing phonological competitors should be slower due to increased lexical activation diverting processing resources from detecting the pauses (Mattys, Pleydell-Pearce, Melhorn, & Whitecross, 2005)[11]. A recognition memory test then probed explicit knowledge of the trained items, in which participants made a yes/no response to the 64 trained items (e.g. *cathedruke*) and 64 phonologically similar novel foils (e.g. *cathedruce*). A shadowing task then acted as a test of speeded access to the phonological form representations of the newly-learnt words.

6.2.1 Methods

6.2.1.1 Participants

Sixty-four participants took part in the study (mean age = 20.32 years, SD = 2.04, range 18-25; 17 males). The participants were native English speakers, with no second

[11] Pause detection as a test of lexicalization is based on spoken word recognition involving the activation and competition of multiple lexical candidates in parallel (explained in Chapter 3, section 3.4.1). If a newly-learnt word such as *cathedruke* has established a new lexical representation, upon hearing the speech fragment *cathedr-* there should be greater lexical activity, from the activation of both *cathedral* and *cathedruke*, compared to if no new competitor has been linked with the existing lexical entry (in which case only *cathedral* should be activated). Accordingly, a greater amount of lexical activity at pause onset means fewer processing resources are available for pause detection, resulting in slower response latencies.

language expertise above GCSE level. This was established via screening during recruitment and again when participants arrived at the lab. The participants had no known auditory, language or learning difficulties, and all were recruited from Royal Holloway and paid for their participation. The study received ethical approval from the Psychology Department Ethics Committee at Royal Holloway. Participants were paid as compensation upon the completion of both sessions, and debriefed about the study.

6.2.1.2 Materials and Design

Learning Task. The same learning paradigm was employed as in Study 1 and Study 2, with some minor modifications. Because Study 3 was assessing the impact of meaning acquisition on lexical integration, measured by response latencies to existing phonological neighbours, the learning paradigm only included a *correlated* and *uncorrelated* condition, with no known word condition. In the correlated condition there was again a systematic association between the novel words and visual referents, and in the uncorrelated condition there were no systematic word-picture associations.

The objective was for the learning task to be as similar to that used in Study 2 as possible, in order to assess the extent to which the phonological form learning observed in Study 2 pertained to the lexical integration of new words learnt in the same way. However, because the novel words used in the current study were more phonologically distinct from each other than in Study 2, in which items had a dense phonological neighbourhoods (which was a requirement for testing the mismatch negativity effect), it was possible that semantic association learning would be easier in the current study due to the novel words being less phonologically similar and thus easier to learn in association with novel objects. A pilot training session was therefore run where participants ($N = 3$) completed the Study 3 learning task, whereby the correlated words co-occurred with their referent object across 50% of trials, and occurred with different non-referent objects across the remaining 50% of trials. This yielded comparable association learning accuracy to Study 2 by the end of the learning task (Study 3 Pilot: $M = 77.71\%$, $SD = 18.80$; Study 2: $M = 74.38\%$, $SD = 19.69$). The Study 3 learning paradigm therefore used a ratio of 50% referent-present and 50% referent-absent trials for the correlated words, to equate the association-learning accuracy to that of Study 2, which used 66% referent-present and 33% referent-absent trials. On each trial participants could choose between one of two pictures as the correct referent object, or indicate that the referent was not present. The 50% association between a correlated word and its referent object was thus still clearly systematic across trials.

Apart from using only the correlated and uncorrelated conditions in the learning paradigm with no known-word condition, and the lower proportion of referent-present trials for the correlated words, the learning paradigm in Study 3 was identical in its set-up to Study 2. On each trial the auditory presentation of a novel word was followed by the presentation of two pictures. In the correlated-word condition one of these pictures was the correct referent on half the trials, and the other picture was always a non-referent foil object. On the other half of correlated-word trials a different referent picture from another correlated word was presented, alongside a foil object. In the uncorrelated word condition both pictures were always non-referent foil objects. After participants had been exposed to all 32 novel words and 128 novel pictures, the foil pictures were reassigned to different words on the following round of trials, and the correlated-word referent category pictures were reassigned to a different 'incorrect' correlated word for the referent-absent trials. After responding participants again received correct or incorrect feedback on each trial, where for the uncorrelated words 'correct' feedback was provided on 1/3 of trials distributed over the course of the task. There were again 40 exposures to each novel word over the course of the learning task, with 1280 trials in total.

Word stimuli. The word stimuli consisted of 80 monomorphemic base words (e.g. *cathedral*), from which two novel words were derived by a divergence at the final vowel (e.g. *cathedruke, cathedruce*). Sixty-four of these triplets were taken from the items used by Tamminen and Gaskell (2008) and 16 from the stimuli of Gagnepain, Henson, and Davis (2012). The triplets were such that all base words were bi or tri-syllabic, and 6-11 phonemes in length (M = 7.97, SD = 1.36). Importantly, all the known base words had an early uniqueness point prior to the final vowel (e.g. the uniqueness point of *cathedral* is at *cathe-*, at which point it diverges from its nearest existing neighbour, *cathartic*). Appendix 8 presents these triplets.

One of the novel words derived from the base word (e.g. *cathedruke*) was used as a trained novel word in the learning task, and the other novel word (e.g. *cathedruce*) was to be used as a foil in the later recognition memory test. The allocation of the novel words as trained and foil items was counterbalanced between participants. The 80 triplets were randomly divided into five groups of 16 triplets each. Four of these five groups were presented in each cell of the design: correlated day 1 training, uncorrelated day 1 training, correlated day 2 training, and uncorrelated day 2 training. In the fifth group, the existing base words were used as control items in the pause detection task for which no novel phonological competitor had been acquired. The five groups of novel words were counterbalanced between learning condition, day of training, and the control condition in the pause detection task. The 240 words were recorded by a female Southern British English speaker (with a monoaural recording at 22Hz), and edited with CoolEdit 2000 to match them for amplitude. Care was taken to ensure the items within each triplet were matched as closely as possible for duration and pronunciation. The same tokens were used in both training and test.

For the base words in the pause detection task, a 200ms pause was inserted at the uniqueness point. The point of pause insertion in the pause present items was the uniqueness point of the base words if a new competitor had been acquired. Pauses were inserted by creating a 200ms silence at the zero-crossing of the nearest cycle before the final vowel, to avoid clicks or other acoustic markers for pause onset in the speech file. A 200ms pause was chosen for two reasons: i) previous work suggests the shortest pause detectable as artificial and not part of natural speech (e.g. through articulatory pauses) is 150ms, and 200ms should thus be easily detectable as an artificial silence (e.g. Gaskell & Dumay, 2003), and ii) previous work using the pause detection paradigm to assess lexical competition has used 200ms pauses, and Study 3 thus followed this well-established paradigm (Davis et al., 2009; Dumay & Gaskell, 2007; Dumay & Gaskell, 2012; Dumay et al., 2004; Gaskell & Dumay, 2003; Henderson et al., 2012; Henderson, Weighall, et al., 2013; Henderson, Weighall, & Gaskell, 2013; Szmalec et al., 2012; Tamminen & Gaskell, 2008). Pause absent items were the same tokens as the pause-present items, with no pause inserted. All stimuli were edited using CoolEdit 2000.

For the pause detection task, 240 additional filler words were chosen (presented in Appendix 9). The filler words consisted of known words with similar properties to the experimental base words. These filler words were all monomorphemic, and either monosyllabic, bisyllabic or trisyllabic. The rationale for using fillers of existing words was to encourage lexical processing during the pause detection task, and to minimize the possibility of participants being explicitly aware of the overlap between the trained novel and base words (e.g. *cathdruke-cathedral*) and responding strategically or invoking episodic effects. A 200ms pause was inserted in each filler word at either the first, second or third syllable of each word, in equal proportions across the items. Pause occurrence was spread across these positions in the words to encourage participants to attend to the whole word and minimize expectation of pause occurrence at the end of the word. The filler words were again recorded by the same female Southern British English speaker as the experimental triplets, and equated for amplitude in CoolEdit 2000.

Novel object pictures. The novel pictures for the learning task consisted of 128 pictures of novel or unnameable objects. Eighty-three of these pictures were obscure objects selected via a Google image search as for Study 1 and Study 2. The remaining 45 were from the NOUN database (Horst & Hout, 2014). All pictures were in colour and presented on a black background, and were chosen to be similar in complexity (Appendix 10). For each participant these pictures were randomly divided into two groups of 64, one group of which was used in training on Day 1 and the other on Day 2. From each group of pictures 16 were randomly selected as the correlated-word referent pictures on each day, and the remaining 48 pictures were used as the foil objects. Participants thus learnt a different set of word-picture associations on each day.

6.2.1.3 Test Tasks

Pause Detection Task. The lexicalization test was the pause detection task, established by Mattys and Clark (2002). The pause detection task involved participants listening to the 80 known base words (e.g. *cathedral*), of which half contained a 200ms pause inserted before the final vowel (e.g. *cathedr_al*) and half were pause absent (e.g. *assassin*). Pause presence was counterbalanced between items across participants, such that all items occurred in pause present and pause absent conditions with equal frequency across the experiment. The stimuli consisted of the 80 experimental base words, of which 64 would have potentially acquired a new competitor (from the 16 novel words learnt in the *correlated* and *uncorrelated* training condition, on both Day 1 and Day 2) and 16 were the control base words for which no potential new competitor had been trained. Each of the 80 experimental base words and 240 filler items were presented once in a randomized order. Half of all filler items were pause present, and half were pause absent. Participants were required to respond “yes” for pause presence and “no” for pause absence via a button box.

Recognition Memory Task. In the recognition memory task participants heard the 64 novel words trained in the learning task on Day 1 and Day 2 (e.g. *cathedruke*), and 64 phonologically similar foils (e.g. *cathedruce*). Each word was presented in isolation to minimize ceiling effects often obtained with 2AFC, and participants were required to respond ‘yes’ or ‘no’ via a button press to indicate whether the word was one of the trained items. The trained novel words and foils were presented in a pseudorandomised order, in which half the novel words appeared before their foil, and the other half of the novel words were preceded by their foil. Additionally, at least four items were presented between each trained word and its foil (Tamminen et al., 2010).

Shadowing Task. In the shadowing task participants heard the 64 trained novel words via headphones, and their task was to repeat each word as quickly as they could. Each novel word was preceded by the 250ms presentation of a picture from the training task, which could either be a correlated-word referent picture or a foil picture. The aims of this task were twofold: i) to assess speeded online access to the phonological form of the trained novel words, and ii) to test the strength of the association between the correlated words and their trained referents by the emergence of a priming effect in the correlated-word condition, with faster responses to correlated words preceded by their referent picture ('primed') than those preceded by a foil picture ('unprimed'). In the correlated word condition, half of the words were preceded by their associated referent picture, and half were preceded by a non-referent foil picture from the same day of training as the word. In the uncorrelated word condition, half of the words were preceded by a correlated-word referent picture which was not used to prime the correlated words, and half were preceded by another foil picture from the same day of training. This priming manipulation thus matched the type of pictures primes in each novel word category. It was predicted that a priming effect for correlated words would emerge after consolidation (i.e. for Day 1 words), due to stronger associative links between the correlated words and their referents being promoted by overnight consolidation (e.g. Tamminen & Gaskell, 2013).

6.2.1.4 Procedure

On both days, participants listened to the auditory stimuli via headphones, and visual stimuli were displayed on CRT monitors. On Day 1 participants were trained in a quiet room, in groups of up to three. On Day 2 participants were staggered such that all participants completed the test phase one at a time (which included the pause detection task, recognition memory task, and shadowing task) to avoid interference between participants. Each participant was scheduled to complete their Day 1 and Day 2 sessions at similar times of day where possible (either in the morning, afternoon or early evening) to minimize circadian differences between each session.

Day 1. On Day 1 participants completed the learning task in E-Prime 2.0, with 16 correlated words and 16 uncorrelated words. As in Study 1 and Study 2, the instructions stated that participants' task was "to learn which pictures went with which words". The learning task started with a practice block of 12 trials, with novel words and pictures not used in the learning task. The learning task contained breaks every 10-15 minutes, and participants took approximately 2 hours to complete it.

Day 2. On Day 2 participants returned to the lab to complete the second learning task, with a different set of novel words and objects. After completing the second learning task participants were given a 5-10 minute break of restful wake before starting the test tasks. Participants then completed the pause detection, recognition memory and shadowing tasks, in this fixed order. Each test task was run in DMDX (Forster & Forster, 2003). Following the completion of the shadowing task participants were paid and debriefed.

In the *pause detection* test task participants were instructed that they would hear some words through the headphones, and their task was to respond on a button box with "yes" if a pause was present, and "no" if it was absent. The instructions stated that the pause could occur at any position within the word and participants should listen carefully for the presence of absence of a pause. Each trial began with a 250ms fixation cross before the onset of the word, and participants had 3000ms to respond following the onset of the word, with an inter-trial interval of 1000ms. The words were presented via headphones, and participants made a pause present/absent response to each item. The pause detection task had 320 trials and took approximately 15 minutes, with no breaks.

In the *recognition memory* test task participants were instructed that they would again hear a word through the headphones, and their task was to decide whether the word was familiar or not. Each trial began with the 500ms presentation of a fixation cross before the auditory presentation of a trained novel word or untrained foil word, to which participants responded "yes" or "no" via a button box. The instructions stated that some of the words could sound very similar, so participants should listen carefully to each word and respond quickly and accurately based on whether they thought the word sounded familiar. There were 128 trials in total and the task took approximately 8 minutes, with no breaks.

The final test task was the *shadowing task*. The instructions stated that participants would again hear a word via the headphones, and their task was to repeat it aloud as quickly as possible. Participants were further informed there may be a picture appearing before each word, but to ignore the picture and focus on simply repeating the spoken word. Each trial began with a 250ms central presentation of a fixation cross, before a 250ms presentation of a picture, immediately followed by the spoken word for participants to repeat. Participants had up to three seconds after the onset of the word to make a response. All 64 novel words were presented in the shadowing task, in a randomised order. The task took approximately 5 minutes to complete, with no breaks.

The total training and test time per participant was thus approximately 2 hours on Day 1, and approximately 2.5 hours on Day 2.

6.2.2 Results

6.2.2.1 Learning Task

Due to a program failure, two participants' learning task data did not save on Day 1, and one participant's learning task data did not save on Day 2, leaving sixty-one participants with complete data for analysis.

Accuracy. Accuracy and reaction times in the learning task on each Day were analysed by dividing the task into four blocks, whereby each block consisted of 10 exposures to all 32 novel words and pictures. Accuracy for the correlated-word picture associations was averaged over each block, and these mean accuracy scores were submitted to a Day (Day 1, Day 2) by Block (Blocks 1-4) repeated-measures ANOVA. This yielded a main effect of Block only, $F(3, 180) = 459.64$, $p < .001$ (Greenhouse-Geisser corrected). Follow-up paired t-tests on mean accuracy across Day 1 and Day 2 for each block verified a significant increase in mean accuracy over the course of the learning task, Block 1-Block 2: $t(63) = -19.99$, $p < .001$; Block 2-Block 3: $t(63) = -14.51$, $p <.001$; Block 3-Block 4: $t(63) = -4.87$, $p < .001$. There was thus significant learning of the correlated-word associations, which did not differ between each day of training. Mean accuracy in Block 4 (averaged across both days) was 83.02% (SD = 13.88). Figure 25 shows the learning curve for the correlated-word association learning for Days 1 and 2. Lastly, an independent t-test compared the association learning accuracy in Block 4 of training in Study 2 and Study 3, to assess whether success in learning the correlated-word associations by the end of training was equivalent across both studies. The independent t-test indicated significantly higher accuracy in Study 3 than Study 2 ($t(86) = -2.68$, $p < .01$; Study 2 M = 74.38%, SD = 12.29; Study 3 M = 83.02%, SD = 13.88). This may reflect items being more phonologically distinct in Study 3, aiding the learning of a one-to-one word-referent link.

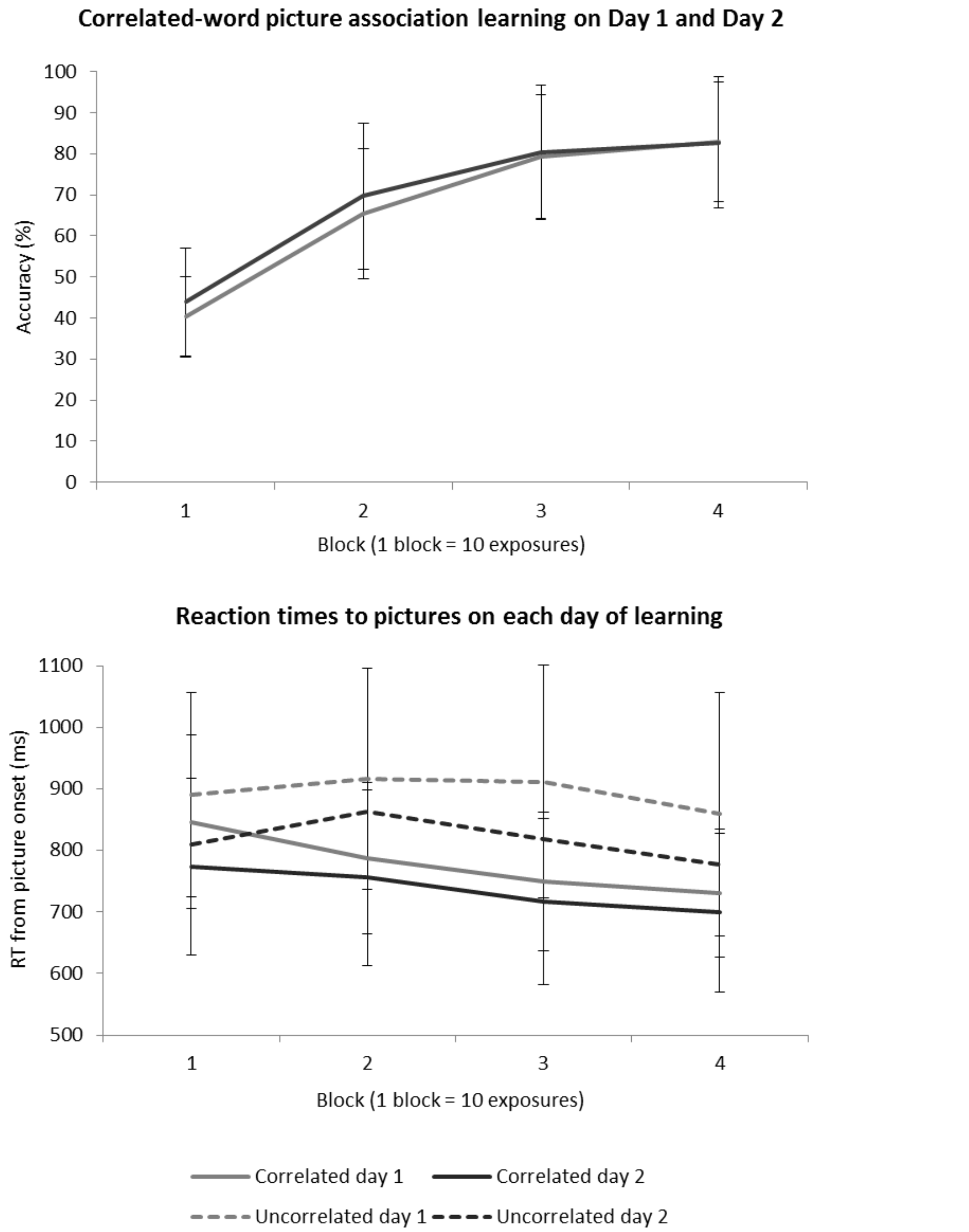

Figure 25. Training task data from Day 1 and Day 2.
Accuracy in learning the correlated-word picture associations on Day 1 and Day 2 of training (top panel), and reaction times to the pictures for Correlated and Uncorrelated words, on each day of training (bottom panel). Accuracy and reaction times are averaged over each block of training, and the error bars show the standard deviation of participants' average performance over each block.

Reaction times. Reaction times to the pictures for both correlated and uncorrelated words were again analysed by four blocks across the learning task, with 10 exposures to each novel word within each block. Participants' average reaction time for each block was submitted to a repeated-measures ANOVA with the factors of Condition (Correlated, Uncorrelated), Day of training (Day 1, Day 2) and Block (Blocks 1-4). This yielded a main effect of Condition, $F(1, 60) = 109.55$, $p < .001$, Day, $F(1, 60) = 37.28$, $p < .001$, and Block, $F(3, 180) = 19.12$, $p < .001$ (Greenhouse-Geisser corrected), with two-way interactions between Condition x Day, $F(1,60) = 20.91$, $p < .001$, and Condition x Block, $F(3,180) = 34.72$, $p < .001$ (Greenhouse-Geisser corrected). These effects were qualified by a three-way Condition x Day x Block interaction, $F(3, 180) = 5.37$, $p < .01$ (Greenhouse-Geisser corrected). The three-way interaction was followed up to assess whether the change in RTs over the learning task (that is, the effect of learning) differed between conditions and days. Participants' average RT in Block 4 was subtracted from their average RT in Block 1 to obtain a measure of the change in RTs over the learning session on each Day, and for each training condition. These RT changes were submitted to a Condition (Correlated, Uncorrelated) by Day (Day 1, Day 2) repeated-measures ANOVA. This yielded a significant main effect of Condition, $F(1,60) = 23.76$, $p < .001$, which was qualified by a Condition x Day interaction, $F(1,60) = 6.33$, $p < . 05$. Follow-up paired t-tests indicated that the reaction time change over blocks was greater on Day 1 than on Day 2 for correlated words, $t(60) = 2.78$, $p < .01$, but not for uncorrelated words, $t(60) = -.044$, $p = .965$. The effect of learning in the correlated-word condition was further shown by a greater speeding up of correlated word RTs than uncorrelated word RTs over both days (correlated vs. uncorrelated Day 1 change: $t(61) = 5.10$, $p < .001$; correlated vs. uncorrelated Day 2 change: $t(62) = 2.95$, $p < .01$). Figure 25 shows the reaction time data over the learning task on each Day.

6.2.2.2 Test tasks data analysis

Reaction time data from the test tasks was analysed by fitting linear mixed-effects models in order to simultaneously account for both by-subjects and by-items effects (Baayen, Davidson, & Bates, 2008). All analyses were conducted in SPSS 21 using the MIXED procedure, with the maximum-likelihood method. In each model random intercepts were included for subjects and items.

The approach taken to establishing the fixed effects structure of each model was to include the experimental effects of interest as fixed effects, and only include additional covariates as fixed effects if they significantly improved the fit of the model (Baayen et al., 2008). The additional covariates were trial order, the allocation of participants to item lists, and the grouping of items within lists. First, a full model was built which included fixed effects of the experimental variables of interest (such as training condition and day of testing) and the three additional covariates which could affect reaction times. Of the fixed factors which consisted of covariates, those which significantly contributed to the model were retained, and those which were not significant were excluded. The significance of the fixed effects was determined by the Type III test of fixed effects. The model was then re-run with a reduced number of additional fixed factors. The final fixed effects structure thus contained the experimental fixed effects of interest, and only the additional covariate fixed effects which significantly contributed to the model. The goal of this procedure was to produce the simplest model (i.e. with the fewest number of covariate fixed factors) to explain the data. The final fixed effects structure for each mixed model is reported in the text.

After establishing the fixed effects structure of each model, random slopes for subjects and items were included for the experimental fixed effects and their interaction (such as Condition, Day, and Condition x Day). These random slopes were only retained when they significantly improved the fit of the model[12]. Whilst there is no clear consensus in the psycholinguistic literature regarding the inclusion of random slopes, the approach of including them here if they significantly improved the fit of the model was consistent with that proposed by Baayen et al. (2008; Baayen & Milin, 2010; but cf. Janssen, 2012; Raaijmakers, 2003). The contribution of random slopes to the fit of the model was established by comparing the log likelihood ratio of the model with the maximal random effects structure, which included random slopes for subjects and items over all experimental fixed effects, to the log likelihood ratio of the model with no random slopes. The difference between the competing models was assessed by comparing the difference between the log likelihood of each model to a chi-square distribution, with the degrees of freedom as the difference in the number of parameters between the two models. Random slopes were not included in cases where they prevented the model from converging (due to a complex random effects structure with too few data points to fit to the model). In the case of each mixed model the retention or exclusion of random slopes is reported in the text.

After establishing the fixed effects and random effects structure of each model, the significance of experimental fixed effects in the final model was assessed by the Type III tests of fixed effects. Note that when the inclusion of random slopes did not

[12] The inclusion of random slopes in a linear mixed-effects model is to account for the fact that the magnitude of fixed effects may be different for different participants and items. For example, the manipulation of training condition could have a large effect on reaction times for some participants, and a much smaller effect for other participants. The difference, or slope, between levels of a fixed effect for is thus allowed to differ between subjects and items in a model including random slopes.

significantly improve the fit of the model, subject and item random slopes were included for any significant experimental fixed effects to verify that they remained so in the presence of subject and item-specific slopes. The inclusion of random slopes to verify significant effects of interest is reported in the text. The F-statistic and p-value associated with each fixed effect in the final model is reported.

All reaction time analyses were on log-transformed data, in order to satisfy the assumption of normality and to reduce the effect of outliers (Ulrich & Miller, 1994). Retransformed means of the data points in each condition are presented in figures and tables for ease of interpretation, unless stated otherwise. Error bars represent standard error for the participant-averaged means (due to being unable to calculate standard error from the data point averages used in the mixed models), corrected for within-participant contrasts where appropriate (Cousineau, 2005).

For ease of interpretation, from this point onwards the Day 1 condition will be referred to as the 'consolidated' condition (due to a night between training and test), and the Day 2 condition will be referred to as the 'unconsolidated' condition (due to no opportunity for offline consolidation between training and test).

6.2.2.3 Lexicalization Test

Pause detection data from forty-seven participants were retained in the final analysis. Due to an item-list error, data from five participants could not be used, and due to a button-box malfunction, data from five participants was not recorded. Of the remaining participants those who were particularly slow or error-prone were removed prior to analysis. This constituted five participants who made more than 50% of errors in one or more conditions, and two further participants whose response times were >2.5 standard deviations above the participant-averaged conditional mean. These participants were removed prior to analysis.

Pause detection reaction times were measured from the pause onset in pause-present items, and from the same point in pause-absent items. This approach was consistent with the pause detection method proposed by Mattys and colleagues (Mattys & Clark, 2002; Mattys et al., 2005) and the majority of extant studies using pause detection as a test of lexicalization (Dumay & Gaskell, 2007; Dumay & Gaskell, 2012; Gaskell & Dumay, 2003; Henderson et al., 2012; Henderson, Weighall, & Gaskell, 2013; Szmalec et al., 2012; but cf. Davis et al., 2009, in which reaction times were measured from word onset). Incorrect trials and reaction times faster than 200ms and slower than

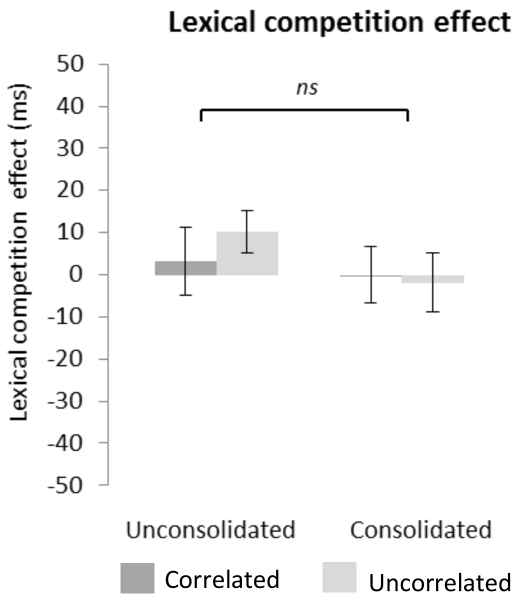

Figure 26. The lexical competition effect in Study 3.

The lexical competition effect for unconsolidated and consolidated novel words in each condition. The lexical competition effect is the difference between the base words which are existing neighbours of the trained novel words, and the control base words with no trained competitor; a positive lexical competition effect thus indicates slower responses to experimental compared to control base words.

2.5 standard deviations from each participant's conditional mean (including both pause present and pause absent trials) were removed (8.22% of the data[13]). Both pause present and pause absent trials were analysed[14].

The pause detection data were analysed by first assessing if there was any difference between reaction times for consolidated and unconsolidated correlated-word and uncorrelated-word base words. A linear mixed-effects model was fitted to the

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[13] Note that the trimming of erroneous responses and trials with latencies < 200ms or > 2.5 SDs from each participant's conditional mean is a reasonably common procedure for pause detection analysis (Fernandes et al., 2009; Henderson, Weighall, & Gaskell, 2013; Henderson, Weighall, et al., 2013).

[14] The analysis of both pause present and pause absent trials is consistent with the majority of existing studies using pause detection as a test of lexical competition (e.g. Dumay & Gaskell, 2007, 2012; Gaskell & Dumay, 2003; Henderson, Weighall, et al., 2013), but it is important to note that the original work by Mattys and colleagues (2002, 2005) focused on pause present trials as uniquely probing lexical activation. Mattys et al. (2005) proposed that the high sensitivity of pause present trials to lexical activation was due both to the processing resources required by pause detection, and the disruption of lexical expectancy from the presence of the pause. Both pause present and pause absent trials have been analysed here to remain consistent with the existing lexicalization literature using pause detection and to increase statistical power. In case any lexical competition effects were particularly sensitive and only elicited on pause present trials, an identical analysis to the one reported was run on pause present trials only, which yielded identical results.

reaction time data, with fixed effects of Condition (Correlated, Uncorrelated), Day of training (Day 1, Day 2) and the presence or absence of a pause in the base word (Pause Present, Pause Absent). The inclusion of trial order and the allocation of participants to item lists as additional fixed effects significantly contributed to the model and were thus retained. Subject and item-specific random slopes for the fixed effects of Condition and Day did not significantly improve the fit of model and were thus excluded. The only significant fixed effect was of pause presence, $F = 30.10$, $p < .001$, indicating faster responses to pause absent than pause present trials overall (pause present: $M = 670$ms, $SD = 231$; pause absent: $M = 643$ms, $SD = 227$). Faster responses to pause absent than pause present trials were also reported by Gaskell and Dumay (2003), which was suggested to be due to the presence of a pause disrupting processing and thus slowing responses. All other main effects and interactions were not significant ($Fs < 1.2$, $ps > .2$).

Due to the lack of an effect of Condition or Day on reaction times, responses to all experimental base words were then collapsed across both days and training conditions to test for the presence any overall lexical competition effect. A model with the fixed effect of competitor acquisition (Experimental vs. Control base words), with the inclusion of trial order and the allocation of participants to item lists as additional fixed effects, showed no effect of competitor acquisition ($F = 1.3$, $p = .26$). The pause detection analysis thus yielded no evidence of lexical competition effects[15]. Figure 26 shows the retransformed reaction time data, with the descriptive statistics for each test task reported in Table 4.

6.2.2.4 Recognition memory test

For the recognition memory test, two participants' datasets were not saved due to a program failure, and the button box did not record responses for five participants. Data for the remaining fifty-seven participants was included in the final dataset for analysis.

Recognition d'. Accuracy on the recognition memory test was analysed using signal detection measures (*d'*, Snodgrass & Corwin, 1988). Novel word recognition was measured by subtracting *z*-transformed rates of false alarms (incorrect "yes" responses to foil items) from hits (correct "yes" responses to trained items). The d' scores were submitted to a Condition (Correlated, Uncorrelated) x Day of training (Day 1, Day 2)

[15] An additional analysis checked whether a lexical competition effect would emerge in some participants based on a median split of recognition accuracy, but found no evidence to that effect.

Table 4. Performance across the pause detection, recognition memory and shadowing test tasks.

	Unconsolidated words (Day 2 training)	Consolidated words (Day 1 training)
Pause detection RT		
Correlated	657 (241)	653 (231)
Uncorrelated	664 (227)	652 (219)
Control	653 (221)	
Recognition memory RT		
Correlated	1266 (363)	1218 (342)
Uncorrelated	1276 (380)	1226 (351)
Recognition memory d'		
Correlated	2.02 (1.45)	2.67 (1.88)
Uncorrelated	1.88 (1.85)	2.03 (1.72)
Shadowing RT		
Correlated	1097 (200)	1076 (195)
Uncorrelated	1107 (199)	1086 (207)

Note. The standard deviation is shown in brackets. The reaction time means and standard deviations are from the data-point averages in each condition, and the recognition d' values are the participant-averaged means and standard deviations.

repeated-measures ANOVA for participants (F1) and items (F2), with item list as a between-subjects variable in the by-participants analysis, and the grouping of items within lists in the by-items analysis (Pollatsek & Well, 1995). This yielded a significant main effect of both Condition, $F_1(1,47) = 4.89$, $p < .05$, $F_2(1,155) = 5.09$, $p < .05$, and Day, $F_1(1,47) = 4.84$, $p < .05$, $F_2(1,155) = 38.89$, $p < .001$. The Condition x Day interaction did not reach significance by participants or by items, $F_1(1,47) = 3.17$, $p = .08$, $F_2(1,155) = .04$, $p = .83$. The main effect of Condition indicated that correlated-word recognition sensitivity was higher than uncorrelated-word recognition sensitivity overall (by-participants correlated M = 2.35, SD = 1.45; uncorrelated M = 1.95, SD = 1.52). The main effect of Day indicated better recognition sensitivity for consolidated words relative to unconsolidated words (consolidated: M = 2.35, SD = 1.61; unconsolidated: M = 1.95, SD = 1.39). Figure 27 shows the recognition d' scores.

Relationship between recognition memory and semantic association learning. The correlated-word advantage for recognition sensitivity suggested that the acquisition of the correlated-word associations supported declarative knowledge of the novel words. This was verified by testing the relationship between participants' recognition sensitivity for the correlated words and the degree of semantic association learning, measured by participants' average accuracy in the final block of the learning task. Participants with learning performance more than 2.5 standard deviations below group-level accuracy on each day were excluded (2 participants for Day 2, and 4 participants for Day 1). Bivariate correlations were run between correlated-word recognition d' and semantic learning accuracy for Day 2 (unconsolidated) and Day 1 (consolidated) words separately. This yielded a marginal positive correlation for unconsolidated words, $r(54) = .24$, $p = .075$, and a significant positive correlation for consolidated words, $r(52) = .27$, $p < .05$. These correlations thus suggested that recognition accuracy for both consolidated and unconsolidated correlated words was tied to the degree of semantic association learning, whereby participants with greater semantic association learning showed greater recognition sensitivity.

Recognition speed. Reaction times were analysed by fitting a linear mixed effects model to accurate responses (74.26% of trials) to both trained and foil items in each condition. The model included fixed effects of Condition (Correlated, Uncorrelated) and Day (Day 1, Day 2), with subjects and items as random factors. The inclusion of the additional fixed effect of trial order significantly improved the fit of the model. The model yielded a significant main effect of Day only, which remained significant with the

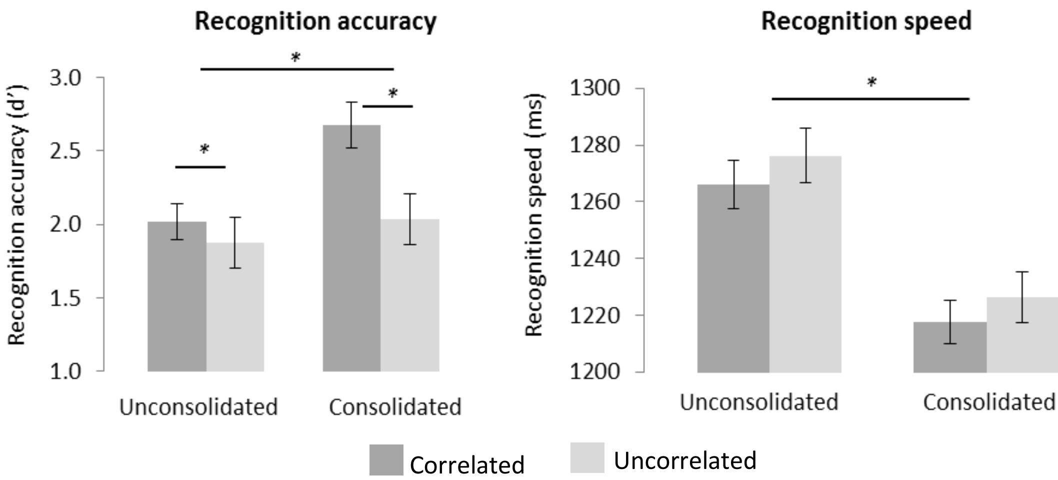

Figure 27. Recognition accuracy and recognition speed in Study 3.

These plots show the participant-averaged means, with identical findings in the by-items analysis. The error bars show standard error of the mean corrected for within-subject comparisons.

inclusion of subject-specific and item-specific random slopes for the effect of Day, F = 31.24, p < .001. Responses for consolidated (Day 1) items were 49ms faster than those for unconsolidated (Day 2) items (Day 1: M = 1222, SD = 346, Day 2: M = 1271, SD = 371). The effect of Condition, and interaction between Condition x Day, did not reach significance (both Fs < 1.7, ps > .2). Figure 27 shows the retransformed RTs.

6.2.2.5 Shadowing test

Shadowing data from nine participants could not be marked due to a microphone failure resulting in heavy static masking responses, and data from 55 participants thus remained in the dataset for analysis. The marking of shadowing responses was implemented in Check Vocal (Protopapas, 2007). Reaction time was measured from the onset of the word to be repeated to the onset of participants' spoken response. The onset of each spoken response was marked using the criteria for marking acoustic onsets described in Rastle, Croot, Harrington, and Coltheart (2005). Errors were marked as responses that deviated by one syllable or more from the item (e.g. repeating "albatran" instead of the correct "albatrum"). Participants made very few errors, with 0.14% erroneous trials overall, and no responses on 0.34% of trials overall. The data were additionally trimmed for responses faster than 300ms or slower than 2000ms, but all responses were within this range.

Shadowing reaction times were analysed by again fitting linear mixed effects models to log-transformed RTs of accurate responses. The first analysis examined the

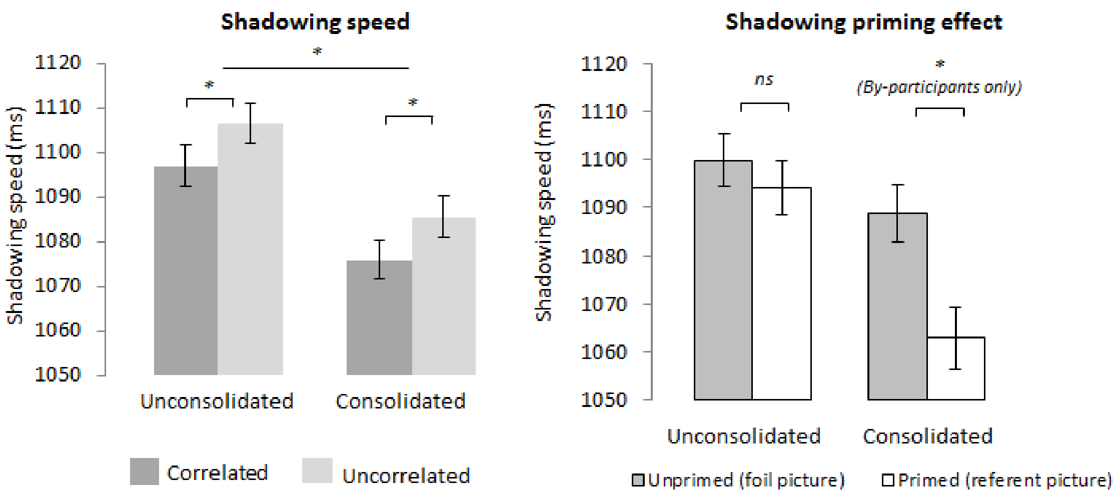

Figure 28. Shadowing reaction times in Study 3.

Shadowing speeds averaged across both primed and unprimed trials (left panel), and assessing the priming effect on correlated-word responses only (right panel). Both plots show the retransformed means of the data point averages over subjects and items.

effect of training condition (Correlated, Uncorrelated) and consolidation (Day 1, Day 2) on shadowing latencies, collapsing across referent-primed (‘primed’) and non-referent primed (‘unprimed’) trials in both conditions. The model included the fixed effects of Condition and Day, with subjects and items as random effects. The additional fixed effect of trial order significantly contributed to the model and was thus retained. The main effects of both Condition and Day were significant, and remained so in the presence of subject and item-specific slopes for the main effects of Condition and Day (Condition: $F = 5.04$, $p < .05$, Day: $F = 25.40$, $p < .001$). The Condition x Day interaction was not significant ($F < 1$, $p > .8$). The descriptive statistics indicated that shadowing latencies for correlated words were on average 10ms faster than those for uncorrelated words across both days (correlated $M = 1086$, $SD = 197$; uncorrelated $M = 1096$, $SD = 203$) and consolidated words were on average 21ms faster than unconsolidated words across both conditions (consolidated $M = 1081$, $SD = 201$; unconsolidated $M = 1102$, $SD = 199$). The left panel of Figure 28 shows the retransformed shadowing RTs.

Primed shadowing test. To assess the impact of referent priming on correlated word shadowing, the effect of prime type on correlated word trials was analysed separately. The correlated-word trials were fitted with a linear mixed effects model with the fixed effects of Prime Type (Referent, Foil) and Day (Day 1, Day 2), with subjects and items as random effects. No additional fixed effects contributed to the model. The model showed a significant main effect of Day only, which remained significant with subject-specific and item-specific random slopes for the effect of Day, $F = 15.70$, $p < .001$. Responses for consolidated words were 21ms faster than for unconsolidated words. The effect of Prime Type and the Prime Type x Day interaction did not reach significance (both $Fs < 2$, $ps > .2$).

However, there was a numerical trend towards a priming effect for consolidated words but not for unconsolidated words, in which the shadowing of primed correlated words was faster for consolidated words only (consolidated priming effect: 26ms; unconsolidated priming effect: 6ms). One possibility for this numerical effect failing to reach significance was a lack of power from splitting the responses by prime type (giving 8 data points per participant per cell), which could have resulted in the effect failing to generalise over items. The correlated-word shadowing data was thus analysed with separate by-participants (F1) and by-items (F2) analyses on the log-transformed reaction times. Repeated-measures ANOVAs with the factors of Prime Type (Referent, Foil) and Day (Day 1, Day 2), with a between-subjects factor of item list in the by-participants analysis and the grouping of items within lists in the by-items analysis, revealed a Prime Type x Day interaction which was significant by participants but not by items, $F_1(1,45) = 4.53$, $p < .05$, $F_2(1,107) = .08$, $p = .778$. Paired t-tests to follow-up the significant Prime Type x Day interaction by participants indicated significantly faster primed than unprimed responses for consolidated words, $t_1(54) = -2.74$, $p < .01$, but not for unconsolidated words, t_1 (54) = -.475, p = .637 (consolidated: primed M = 1063, SD = 187, unprimed M = 1089, SD = 202; unconsolidated: primed M = 1094, SD = 190, unprimed M = 1100, SD = 209). The right panel of Figure 28 shows the retransformed RTs for correlated words split by priming condition.

In summary, the shadowing reaction time data indicated a significant overall advantage for consolidated words over unconsolidated words, and correlated words over uncorrelated words, with no interaction between training condition and consolidation time. The priming effect on correlated words was not significant in either the linear mixed effect model or the by-items (F2) analysis, but was significant by participants (F1). This result suggests that a weak facilitatory priming effect may have been present for consolidated correlated words, but did not generalise over items.

6.2.3 Discussion

The objective of Study 3 was to assess whether novel words learnt with a semantic association entered into lexical competition, relative to words trained without an associated meaning. This question was motivated by the findings of previous investigations of the role of meaning in the lexicalization of novel words (Dumay et al., 2004; Takashima et al., 2014) which observed that the presence of meaning delayed the 24 hour time-course of lexicalization usually observed after form-only training (e.g. Davis et al. 2009; Dumay & Gaskell, 2007, 2012; Gaskell & Dumay, 2003; Henderson et al., 2012). The current study therefore used a learning task which demonstrably promoted the acquisition of new phonological form representations in Study 2. The use of this learning paradigm assessed whether weaker phonological form representations from semantic training in previous studies may have contributed to a slower lexicalization time-course, or whether semantic information contributed to a slower lexicalization time-course irrespective of a potential benefit for establishing new phonological form representations. Following training, new word knowledge was tested in terms of lexical competition with existing words (pause detection), explicit form recognition (recognition memory), and online phonological form access (shadowing). In contrast to the predictions, no lexical competition effects were observed following 24 hours of consolidation. Nonetheless, consolidation enhanced explicit memory and online access to the newly-acquired representations: a period of consolidation enhanced recognition sensitivity, recognition speed and shadowing speed for both correlated and uncorrelated words. Moreover, a semantic advantage was present in recognition sensitivity and shadowing speed, where correlated words showed faster shadowing than uncorrelated words. The findings therefore suggested that consolidation benefited explicit memory and online access, but in the absence of the new words' entry into lexical competition.

The lack of a robust lexical competition effect between consolidated novel words and existing phonological neighbours first raises the question of whether the current study design promoted sufficient learning of the novel words, and had adequate power for measuring any lexical competition effects. The learning phase consisted of forty exposures to the novel words, which was chosen to be close to existing lexicalization studies typically using thirty-six exposures to the novel words (e.g. Davis et al. 2009; Dumay & Gaskell, 2007, 2012; Gaskell & Dumay, 2003). Recognition memory of both correlated and uncorrelated words also suggested good explicit learning of the novel words. One possibility that deserves consideration is that this study was underpowered due to having 16 items per cell of the design, compared to extant studies that typically use 18-36 items per cell. However, when considering the number of participants used, this study yields a comparable number of data points per cell to previous studies. For example, in Dumay and Gaskell (2007) there were 768 data points per cell (24 items x 32 participants), and in the current study there were 752 data points per cell (16 items x 47 participants). Whilst a degree of reduced statistical power in the pause detection task could have contributed to an absence of group-level lexicalization, the marked similarity between experimental and control base word reaction times suggests this was a genuine null effect, which was not attributable solely to variability in response times or lack of power.

In particular, the absence of lexical competition for correlated words after consolidation was unexpected given that phonological form representations (measured by discrimination from minimal pair existing words) for correlated words were stable over a 24 hour period in Study 2. It may be the case that, given the difference in the phonological properties of the items between Study 2 and Study 3, the type of phonological processing that subserved learning was not identical in the two studies.

The items in Study 2 were minimal pairs, both with existing words and with another novel word in the stimulus set (i.e. *kite-kipe-kike*); in contrast, the items in the current study were phonologically distinctive, and had a high degree of overlap with only one existing phonological neighbour (i.e. *biscuit-biscal*). The phonological neighbourhood density of the items in Study 2 may have promoted more fine-grained phonological encoding during learning, which was enhanced by the correlated-word systematicity, and this contributed to their discrimination from existing minimal pairs both before and after consolidation. Subsequently, a coarser phonemic analysis would have been sufficient in Study 3 due to the uniqueness of the items, which could have contributed to these words not establishing a phonological form representation with the same precision as in Study 2 within the 24 hour time window. Although coarser phonological encoding of the novel words in Study 3 could have contributed to their lack of lexical competition, it is critical to note that such a suggestion assumes that highly specified phonological representations are the basis of the full lexicalization process. This is an issue that the current data cannot address in full and will be an important avenue for future work.

An intact time course of consolidation was evident for explicit knowledge and online access to the new word representations, consistent with previous studies showing an enhancement of access to declarative word knowledge and speeded online processing (e.g. Davis et al., 2009; Dumay et al., 2004; Tamminen et al., 2010, 2012). Across both the recognition memory and shadowing tasks there was a benefit for consolidated novel words, consistent with the complementary learning systems account that consolidation should speed up access to novel word representations (Davis & Gaskell, 2009). An important consideration is whether the advantage for Day 1 words was due to proactive interference, whereby the prior learning of Day 1 words impaired learning of the Day 2 words, rather than the Day 1 words being benefited by consolidation (Wixted, 2004). The current data cannot rule out this possibility. However, it is notable that learning task performance for correlated-word accuracy was equivalent on both days, and participants' responses in the learning task were faster overall on the second day of training. Tamminen et al. (2010) further observed a recognition memory advantage for consolidated novel words, whereby the magnitude of this consolidation effect was positively correlated with slow-wave sleep duration, suggesting that this specific aspect of sleep architecture supported faster recognition of novel words following offline consolidation. Taken together, these findings suggest that the consolidation of Day 1 words prior to testing may have supported their recognition, but the extent to which proactive interference contributes to this effect remains important to clarify. The semantic advantage observed in recognition memory accuracy further suggested that the correlated word systematicity facilitated their subsequent retrieval (e.g. Rueckl & Dror, 1994); possible mechanisms for this semantic advantage will be discussed later in this chapter. This semantic advantage further extended to online shadowing speed, but this effect is less clear to interpret[16].

The current findings thus suggested dissociable effects of consolidation on explicit knowledge and access to new words, and on their lexical integration. A previous report of consolidation-enhanced declarative memory in the absence of lexicalization came from Henderson et al. (2014). Typically developing children and children with autism spectrum disorder (ASD) learnt the phonological forms of novel spoken words, and were subsequently tested on lexical integration (with pause detection), recognition memory, and recall. Whilst both groups showed an enhancement of explicit word knowledge after 24 hours, measured by an increase in recognition and recall accuracy, only the typically developing children showed evidence of competition effects for the existing neighbouring words after 24 hours. The presence of offline consolidation for explicit memory of new words in ASD, without concurrent lexical competition effects, was suggested by Henderson et al. (2014) to be consistent with the dissociation between consolidation effects on explicit word knowledge and consolidation effects on lexical integration (see also Tamminen et al., 2010). This distinction is supported by a similar pattern in the current study.

Why should lexicalization differ from the consolidation of explicit word knowledge? Firstly, as pointed out by Dumay and Gaskell (2005), whilst the type of knowledge involved in new word acquisition is initially declarative, the lexicalization of novel words (such that they affect access to existing representations) implies that they influence the highly automatized perceptual skill of spoken word recognition. The lexicalization of novel words thus necessitates the transfer of new knowledge from

[16] A difficulty in interpreting the correlated-word benefit in the shadowing task comes from the fact that both the correlated and uncorrelated words were both preceded by a referent picture and a foil picture. Given that *only* the correlated words were exposed with the referent pictures during training, it is possible that the uncorrelated word responses were slowed by the preceding referent pictures (e.g. through different episodic contexts for the uncorrelated words and correlated word referent pictures, or the expectation of an upcoming correlated word), rather than access to the correlated words being faster per se. Whilst both the recognition memory and shadowing results align to suggest a semantic advantage, the interpretation of the shadowing effect is thus less clear-cut.

declarative to *procedural* memory. This transfer process may be a specific requirement for lexical competition to emerge, and may be why a consolidation effect on declarative memories (indexed by faster and more accurate responses to the newly-learnt words) can be observed in the absence of a consolidation effect facilitating lexical integration. Secondly, a core feature of lexicalization is the formation of links between novel and existing phonological forms (e.g. Takashima et al., 2014). In the complementary learning system account a possibility is that this integration process will require a longer period of consolidation if the new knowledge has a greater potential for interference with existing knowledge (McClelland, 2013; Tamminen et al., 2013). The time-course of lexicalization could thus be more susceptible to factors such as prior knowledge compared to declarative memory consolidation, which may contribute to the dissociable timeframes for these two aspects of word memory formation.

In sum, given that no evidence of group-level lexical competition was observed in the 24 hour time window of the current study, or for the meaning-associated words of Dumay et al. (2004) and Takashima et al. (2014), the range of training paradigms used suggests that words acquired with a potential meaning may require a slower lexicalization time-course. There are two lines of evidence to suggest that the words in the current study required more gradual lexical consolidation than in the time window tested. First, because the correlated and uncorrelated words in the current study were functionally equivalent to participants (i.e. both had a *potential* association), both could have had a degree of semantic context associated with learning (see also Davis et al., 2009, regarding participants' self-generation of meaning for meaningless novel words). One possibility is therefore that the novel words learnt in the current paradigm required a longer period of offline consolidation to enter into lexical competition due to this semantic context from training. Supporting this suggestion, the hippocampus has been implicated in the retrieval of semantic context aiding novel word recognition (Breitenstein et al., 2005; Flegal et al., 2014), and words encoded with higher degree of semantic context could thus require a longer time for lexical integration, due to increased hippocampal involvement at encoding (Takashima et al., 2014). Second, it is worth recognising that almost all extant reports of lexicalization in a twenty-four hour time window come from phonological training (e.g. Bakker et al., 2014; Brown et al., 2012; Davis et al., 2009; Dumay & Gaskell 2007, 2012; Dumay et al., 2004; Henderson et al., 2012; Henderson, Weighall, & Gaskell, 2013; Takashima et al., 2014) with lexicalization tests which involved a degree of phonological processing (lexical decision and pause detection). A mismatch between training and test can delay the time-course of lexicalization (e.g. Bakker et al., 2014), which may have additionally contributed to the lack of lexicalization in the 24 hour time window of the current study.

Taken together, one possibility is therefore that the novel words trained in Study 3 required longer than 24 hours to enter into lexical competition. This may have been the case due to the novel words obtaining a degree of semantic context from the learning task, and the mismatch between semantic associative training and phonological basis of the pause detection test. The long-term learning consequences of Study 3 are therefore addressed in the next part of this chapter.

6.3 Study 3: Long term follow-up

In Study 3 the lack of a robust lexical competition effect, alongside a consolidation advantage for explicit word knowledge and online access, suggested that lexical integration of the newly-learnt words was specifically disadvantaged. A follow-up to Study 3 therefore tested whether the new phonological forms were interleaved with existing words over a longer period of consolidation, and what the consequences of long term consolidation time were for explicit memory and online access to the novel word representations. Participants were recruited to return to the lab several months following training, to complete the pause detection, recognition memory and shadowing tasks. Participants had given their consent to be contacted for future studies, but were unaware they would be called back for Study 3 in particular. The follow-up study addressed two specific questions. First, did lexical competition effects emerge more gradually than in the 24 hour time window tested in Study 3? Second, to what extent was explicit knowledge of the novel words and speeded access retained over this delay?

6.3.1 Methods

6.3.1.1 Participants

Participants were recruited by emailing those who completed Study 3 and inviting them to return to the lab for a thirty-minute follow-up session. Twenty-five participants returned for the follow-up test (4 males; age M = 20.6 years, SD = 1.83, range 18-27). The average time between the original training/test and follow-up was 7.84 months (SD = 4.44), with a range of 3 months, 3 weeks to 15 months, 3 weeks. When scheduling participants care was taken to schedule them at the same time of day (morning or afternoon) as their original session. Participants were paid as compensation for returning to the lab.

6.3.1.2 Materials, Design and Procedure

The follow-up session consisted of the *pause detection, recognition memory* and *shadowing* tasks, run in the same fixed order as Study 3. The pause detection and recognition memory tasks were identical to those used in Study 3. The shadowing task again measured participants' response latency in repeating the trained novel words, but the priming manipulation was removed such that participants simply repeated each novel word aloud. This was in order to obtain a measure of participants' online phonological form processing without any additional response variability introduced by the presence of the picture primes.

For the *pause detection* task participants were required to respond to the 80 critical base words, 64 of which were existing phonological neighbours of the trained novel words and 16 of which were phonological neighbours of untrained novel words, embedded in 240 known filler words. The same base word and filler tokens were used as in the first training and test session. Participants were run on the same item list as in their original session, and therefore the same items were allocated to pause-present and pause-absent trials. The trials were in a different random order for every participant to their original session. To re-familiarize participants with the pause detection task they completed a practice run beforehand, consisting of 12 existing words which were not base words or fillers in the experimental lists, half of which were pause present and half of which were pause absent.

For the *recognition memory* task participants responded to the 64 trained novel words and 64 foils. They were instructed to decide as best they could whether the word was one they had learnt during their original session or whether it was an unlearnt word. The foils used were the same as those in the original session, as participants had only one exposure and were thus unlikely to have any familiarity with the foils. The tokens used were the same as the original session. Each participant's trial list was re-pseudorandomised such that half of the trained items were presented before their foil, and the other half of the trained items were presented after their foil.

For the *shadowing task*, the picture priming manipulation was dropped such that participants only heard and repeated the spoken word. The reason for this was to assess the relative speed of access to the correlated and uncorrelated phonological forms, without the potential confounds and response variability invoked by the picture prime. In addition, an *untrained* condition was added. The comparison of the correlated and uncorrelated shadowing latencies to that of untrained novel words provided a test of whether there was still a learning effect for the trained novel words after the long term consolidation period (i.e. with faster responses to the trained than untrained novel words) or whether the original training did not enhance access (i.e. equivalent responses to the untrained novel words). The untrained condition consisted of 16 bisyllabic and trisyllabic novel words which were phonological neighbours of existing words, and thus had the same properties as the trained novel words.

The experimental set-up and procedure was identical to that used in the test phase of the original session. The total re-test session took approximately 35 minutes.

6.3.2 Results

Reaction time data from the test tasks were again analysed using linear mixed-effects models. The same LME approach to including fixed effects and random slopes as Study 3 was adopted here (reported in 6.2.2.2).

All reaction-time analyses were again on log-transformed data to satisfy the assumption of normality and to reduce the effect of outliers (Ulrich & Miller, 1994), with retransformed data presented in tables and figures for ease of interpretation. In comparisons of performance between Study 3 and the long term follow-up, the data obtained in the Study 3 test are referred to as the 'initial test', and the data obtained on participants' return to the lab several months later are referred to as the 'follow-up test'.

6.3.2.1 Pause Detection Test

The pause detection data from all twenty-five participants were included in the analysis. Incorrect trials were excluded, and data were trimmed for reaction times faster than 200ms and slower than 2.5 standard deviations from each participant's conditional mean (on the basis of both pause present and pause absent trials). 6.10% of trials were excluded in total.

To first assess whether reaction times to the base words were affected by training condition or day of initial training, a linear-mixed effects model with the fixed factors of Condition (Correlated, Uncorrelated), Day of initial training (Day 1, Day 2) and Pause Presence (Pause Present, Pause Absent), with subjects and items as random effects, was run on the log-transformed reaction time data. The inclusion of all three

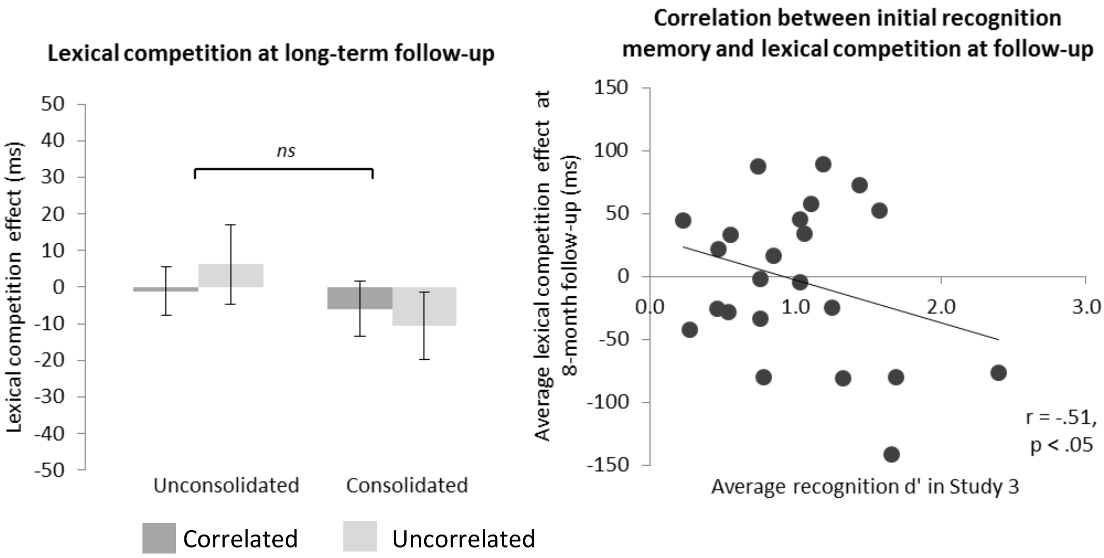

Figure 29. Lexical competition effects at the long term follow-up.

Left panel: The lexical competition effect at follow-up averaged across all participants. Right panel: The relationship between average recognition d' at initial test and average lexical competition effects at the eight-month follow-up.

additional covariates (trial order, the allocation of participants to item lists, and the grouping of items within experimental lists) significantly contributed to the model and were thus retained. The only significant fixed effect was the main effect of Pause Presence, F = 41.64, p < .001, again indicating that pause absent trials were responded to more quickly than pause present trials overall (pause absent M = 645, SD = 220; pause present M = 686, SD = 224). No other main effects or interactions were significant (Fs < 1.5, ps > .2).

As the fixed effects of condition, day of training, and pause presence did not affect reaction times, all responses to experimental base words were then compared to responses to control base words, to test for the presence of any lexical competition effect. A linear mixed effects model was fitted to the data with the fixed effect of competitor acquisition (Experimental vs. Control base word). The additional fixed effects of trial order and the allocation of participants to item lists significantly contributed to the model and were thus retained. The fixed effect of competitor acquisition was not significant (F = .991, p = .340), indicating no evidence of group-level lexical competition[17]. The lexical competition effects are shown in Figure 29, with descriptive statistics from the test tasks reported in Table 5.

[17] A further analysis checked whether lexical competition was present in some participants based on a median split of recognition accuracy at the initial test, but again found no evidence to that effect.

Contributions to relative lexicalization effects at follow-up. An additional analysis examined whether explicit word knowledge at the initial test and the consolidation delay contributed to the relative magnitude of lexical competition effects at follow-up. To assess this, a linear regression was run with average lexical competition effect at follow-up as the dependent variable, with predictor variables of participants' average recognition d' at the initial test, and the number of days of consolidation which elapsed between the initial test and follow-up. The model significantly predicted the follow-up lexical competition magnitude, explaining 30% of the variance in the lexical competition effect ($R^2 = .30$, $F(2,22) = 4.30$, $p < .05$). Both the average recognition d' at initial test and the number of days of consolidation were significant predictors (recognition d': $\beta = -.43$, $t(22) = -2,07$, $p = .05$; consolidation time: $\beta = -.57$, $t(22) = -2.76$, $p < .05$). The negative coefficient of the beta-value indicated that participants with relatively lower recognition d' at initial learning had a larger lexical competition effect at follow-up. Further, participants with less time elapsing between initial test and follow-up also had relatively larger lexical competition effects.

The results of the regression analysis thus suggested that both initial explicit knowledge of the novel words and the consolidation delay contributed to the variability in the lexical competition effects. Because of this, it was of interest whether initial explicit knowledge of the novel words would be related to competition effects at follow-up when the consolidation delay was controlled for. A partial correlation, controlling for the number of days of consolidation, was therefore run between participants' average recognition d' at the initial test, and the average lexicalization effect at follow-up. This yielded a significant negative correlation, $r(20) = -.51$, $p < .05$. Figure 29 presents a scatterplot of this correlation.

Summary. In sum, there was no evidence of lexical competition at the long term follow-up. However, a regression analysis indicated that both initial explicit recognition and the consolidation delay significantly predicted the magnitude of lexical competition effects at follow-up. A significant negative correlation between initial recognition and the magnitude of lexicalization at follow-up, when controlling for the consolidation delay, suggested that participants with weaker explicit word knowledge after learning showed relatively larger lexical competition effects at the long term follow-up.

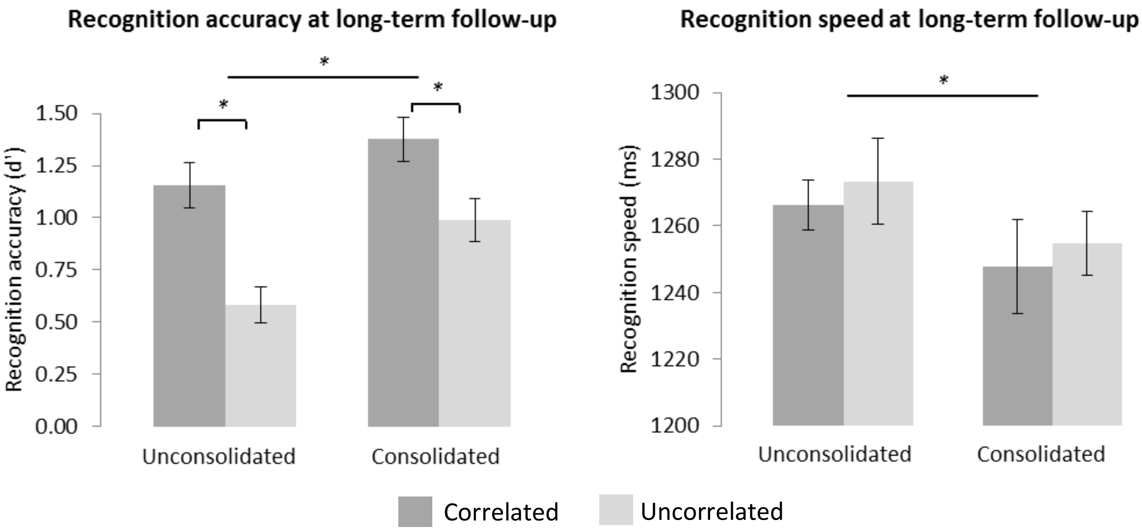

Figure 30. Recognition accuracy and speed at the long term follow-up.

These plots show the participant-averaged means, with identical findings in the by-items analysis. The error bars show standard error of the by-participants mean corrected for within-subject comparisons.

6.3.2.2 Recognition Memory Test

Recognition d'. Accuracy on the recognition memory test was again analysed using signal detection measures (*d'*, Snodgrass & Corwin, 1988), whereby novel word recognition was measured by subtracting the *z*-transformed false alarm rate from the *z*-transformed hit rate for each participant. The d' scores were submitted to Condition (Correlated, Uncorrelated) x Day of initial training (Day 1, Day 2) ANOVAs for participants (F1) and items (F2). The by-participants ANOVA included a between-subjects variable of item list, and the by-items ANOVA included a between-item variable of the grouping of items to lists (Pollatsek & Well, 1995). This yielded significant main effects of both Condition, $F_1(1,15) = 12.34$, $p < .005$, $F_2(1,155) = 17.53$, $p < .001$, and Day, $F_1(1,15) = 77.5$, $p < .05$, $F_2(1,155) = 11.59$, $p = .001$. The interaction was not significant (both Fs < .4, ps > .5). Follow-up paired t-tests confirmed that recognition sensitivity was significantly higher for the correlated than uncorrelated words, $t_1(24) = 4.39$, $p < .001$, $t_2(159) = 4.21$, $p < .001$, and for words trained on Day 1 than words trained on Day 2, $t_1(24) = 2.65$, p = < .05, $t_2(159) = 3.44$, $p = .001$ (Figure 30).

Recognition speed. Log transformed reaction times of all correct trials (65.84% of trials) were again analysed with a linear mixed effects model. The linear mixed-effects model included the fixed effects of Condition (Correlated, Uncorrelated) and Day of initial training (Day 1, Day 2), with subjects and items as random effects. The additional fixed effect of trial order significantly contributed to the model and was thus retained.

The only significant fixed effect was of Day, F = 4.41, p < .05, reflecting faster responses for words learnt on Day 1 in initial training (M = 1251, SD = 357) than on Day 2 (M = 1270, SD = 361; Figure 30). The effect remained significant with the inclusion of random slopes over subjects and items for the effect of Day.

6.3.2.3 Shadowing Test

Data were trimmed for trials faster than 300ms and slower than 2000ms, but all trials were within this range (0% removed). Trials with no response or an incorrect response (using the same criteria as Study 3) were removed (0.25% of trials). The correct log-transformed RTs were then fitted with a linear mixed effects model to assess if training condition or day of initial training impacted shadowing latencies at follow-up. The model included fixed effects of Condition and Day, with subjects and items as random effects. The additional fixed effect of the grouping of items within lists significantly contributed to the fit of the model and was thus retained. The main effects of Condition and Day, and their interaction, were not significant (Fs < 1.5, p > .2).

All responses for the trained novel words were thus compared to the responses for untrained items, to examine whether the trained words were repeated more quickly than the untrained items. A linear mixed effects model with the fixed factor of Training (Experimental trained, Control untrained), and subjects and items as random effects, was fitted to the data. The additional fixed effects of participants' allocation to item lists and the grouping of items within lists significantly improved the fit of the model and

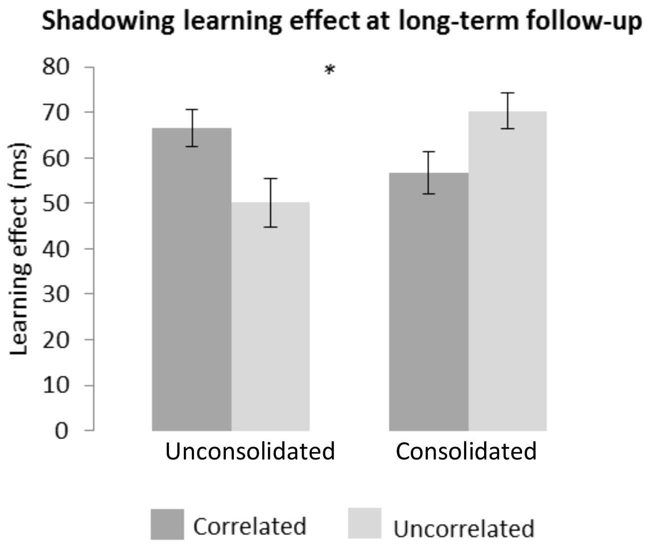

Figure 31. The shadowing learning effect at long-term follow up.
The learning effect in shadowing latencies, measured by the difference between the untrained word RTs and trained word RTs.

were thus retained. A significant main effect of Training was present, $F = 4.56$, $p < .05$, which remained significant with the inclusion of random slopes for subjects and items. The shadowing latency for trained novel words was 61ms faster than for untrained novel words on average (trained M = 1057, SD = 197; Untrained M = 1118, SD = 202). In sum, the shadowing data indicated that there was no effect of day of training or condition on reaction times at follow-up, but shadowing RTs for the trained novel words were faster than for the untrained novel words overall (Figure 31).

Table 5. Performance across the pause detection, recognition memory and shadowing test tasks at the long-term follow-up.

	Unconsolidated words (Initial Day 2 training)	**Consolidated words (Initial Day 1 training)**
Pause detection RT		
Correlated	666 (223)	661 (217)
Uncorrelated	674 (234)	657 (210)
Control	667 (230)	
Recognition memory RT		
Correlated	1266 (351)	1248 (351)
Uncorrelated	1273 (371)	1255 (363)
Recognition memory d'		
Correlated	1.15 (0.72)	1.38 (0.78)
Uncorrelated	0.58 (0.70)	0.99 (0.81)
Shadowing RT		
Correlated	1051 (200)	1061 (203)
Uncorrelated	1068 (190)	1047 (194)
Untrained	1118 (202)	

Note. The standard deviation is shown in brackets. The reaction time means and standard deviations are from the data-point averages in each condition, and the recognition d' values are the participant-averaged means and standard deviations.

6.3.3 Discussion

The goal of the Study 3 follow-up was to examine i) whether lexical competition emerged over a longer time-course than the 24 hour time window of Study 3, and ii) the extent to which explicit knowledge of the novel words and speeded access was retained over this delay. The novel words did not enter into competition with phonological neighbours over the consolidation delay: there was no slowing of RTs for phonological neighbours of the trained words relative to control words. Despite this, representations of the novel words learnt in Study 3 were retained over several months, evidenced by explicit recognition and online processing, whereby shadowing latencies to the trained words were faster than for untrained words[18]. In sum, these findings indicated that participants retained a representation of the novel words over the delay, but that these representations did not engage with the lexicon of existing words.

Previous studies have demonstrated novel word learning effects several months after training (e.g. Breitenstein & Knecht, 2002; Takashima et al., 2006; Tamminen & Gaskell, 2008; Salasoo et al., 1985). The current lack of longer-term lexicalization in particular contrasts with the findings of Tamminen and Gaskell (2008), in which lexical competition was found up to 8 months after learning. The authors examined order-of-acquisition (OoA) effects in novel word learning by training and testing participants over a 33-week period, whereby participants learnt new words in weeks 1, 2 and 19 (early, middle, and late-acquired words, respectively). All novel words showed lexical competition with existing neighbours one week after learning and continued to do so for the remaining test points. The durability of the lexical representations in Tamminen and Gaskell (2008) is at odds with the absence of lexical competition in the current study. A critical difference between the Tamminen and Gaskell (2008) work and the current study, however, is the type of novel word processing subserving learning: Tamminen and Gaskell (2008) trained participants using phoneme monitoring and repetition, in contrast to the current training focusing on the acquisition of word-meaning links. One possibility is thus that the degree of phonological processing which subserves learning contributes to whether novel words can successfully engage in lexical competition, where a reduced degree of phonological processing during initial acquisition increases the difficulty of establishing inhibitory links between novel words and their existing

[18] Whilst it is important to note that this trained novel word benefit could reflect priming from previous exposure in the recognition test, this seems unlikely given i) the relatively large magnitude of the effect (61ms), and ii) the lack of a condition effect or day of training effect on shadowing responses, both of which were present in the recognition memory test.

phonological neighbours, as suggested in the introduction to this chapter. This may be particularly true given that lexical competition (when measured by pause detection) reflects the co-activation of lexical candidates based on the unfolding of phonological input in speech perception.

The current data reveal two further interesting findings. Firstly, a long term semantic benefit was present in recognition accuracy, in which greater recognition accuracy was present for correlated than uncorrelated words. What mechanism could explain this prolonged benefit for the retrieval of semantic-associated words? One possibility is that participants became aware of the systematic relationship between the correlated words and an associated picture, and this supported their long-term retention. This proposal is consistent with the idea of an adaptive consolidation mechanism (e.g. Rasch & Born, 2013) which provides selective retention of new memories based on their potential future relevance. Several cases of such a selective consolidation mechanism have been reported in the literature. For example, Rauchs et al. (2011) used a directed forgetting paradigm to teach participants a list of words which were cued as ‘to be remembered’ or ‘to be forgotten’. In a recognition test three days later participants had greater recognition sensitivity for ‘remember’ cued items than the ‘forget’ cued items. Interestingly, the failure to recognise the ‘forget’ cued items was more pronounced for participants who slept after learning than those who were sleep-deprived, suggesting that selective forgetting was promoted by sleep-based consolidation. A similar finding was obtained by van Dongen, Thielen, Takashima, Barth, and Fernandez (2012), whereby picture-location associations were better recalled when they were expected to be subsequently tested than when they were not. Moreover, the effect of testing expectation was mediated by sleep, whereby only participants who slept after learning recalled more of the to-be-remembered cued items than the irrelevant items (for similar findings see also Saletin, Goldstein, & Walker, 2011; Werchan & Gomez, 2012; Wilhelm et al., 2011). One possibility is thus that the systematic associations of the correlated words cued them as being particularly relevant or important for memory purposes, which contributed to greater retention over time than the uncorrelated words. An additional mechanism for this correlated-word benefit is suggested by the Rauchs et al. (2011) study: the ‘remember’ cued items, which were selectively recognised at the later test, were associated with greater hippocampal activation at encoding than the ‘forget’ items, which showed poorer recognition at the later test. Given that the associative learning of novel word-to-referent mappings is also correlated with greater hippocampal activation at encoding (Breitenstein et al., 2005), a speculative hypothesis is that the systematicity of the correlated words promoted greater hippocampal activity during encoding, which led to subsequent protection against forgetting these words at follow-up.

This account of selective retention implies that explicit knowledge of the correlated-words at follow-up was tied to a general memory consolidation mechanism, rather than the semantic nature of their associations playing any specific role. An alternative account for the correlated-word recognition benefit at follow-up which takes into account semantics is that of memory schemas. A body of recent evidence suggests that new information is better integrated if it is consistent with an existing knowledge schema (e.g. Tse et al., 2007; van Kesteren et al., 2010). Whilst the role of knowledge schemas in language learning is often drawn upon in reports of rapid lexicalization (e.g. Coutanche & Thomson-Schill, 2014), one possibility is that a degree of semantic context during training may also facilitate the integration of new words into existing semantic networks, and subsequently reduce their vulnerability to forgetting over time (a similar argument is also made by Henderson, Weighall, & Gaskell, 2013)[19]. It is important to recognise that the current study trained participants on novel objects with no rich semantic meaning; however, given reports that participants can allocate a degree of meaning to novel words (e.g. Davis et al., 2009) it is viable that learning the novel picture associations nonetheless involved an implicit consideration of their semantic category (e.g. tool, toy, household object, etc). One means of extending the current data to test the contribution of semantic schemas to long-term declarative memory would be to train participants on novel words with new meanings that fell into dense or sparse semantic neighbourhoods (e.g. as in Tamminen et al., 2013), with the prediction that novel words showing greater semantic integration should show greater subsequent gains in declarative memory. Nonetheless, it is viable that both selective retention and semantic knowledge contributed to a long-term benefit in declarative memory for the correlated words, and the involvement of each mechanism may be tied to both the nature of novel word encoding and the semantic properties of the new words. It is thus a goal for future work to assess what factors mediate the relative contribution of

[19] Interestingly, the long-term retention of semantically-associated new word forms, via their integration into existing semantic networks, implies that these new words should engage in *semantic* competition with existing related word meanings (e.g. Tamminen & Gaskell, 2013). The pause detection task measured only phonological lexical competition, which raises the consideration of whether the new words in the current study engaged in another form of competition.

general consolidation mechanisms (i.e. selective retention) and semantic knowledge (i.e. schemas) to long-term declarative word memory.

The second interesting finding emerging from the follow-up data was an explicit memory benefit for words which were consolidated before the initial test, in terms of enhanced recognition accuracy and recognition RTs for Day 1 words (learnt with an opportunity for consolidation prior to the initial test) relative to Day 2 words (learnt immediately before the initial test, and thus with no opportunity for consolidation). A possible mechanism for enhanced recognition memory for Day 1 words may be that of decreased susceptibility to interference due to undergoing offline consolidation prior to test. There is evidence to suggest that new memories become vulnerable upon retrieval and must therefore be re-stabilised, or *reconsolidated* (e.g. Nader, 2003; Walker, Brakefield, Hobson, & Stickgold, 2003). This memory reconsolidation process has been demonstrated primarily in the procedural memory domain, but recent reports suggest declarative memory is also susceptible to disruptions in reconsolidation after retrieval (Forcato et al., 2007; Chan & LaPaglia, 2013). Given that the new memories can undergo both stabilisation during wake and sleep-based enhancement in the first 24 hours after learning (Walker et al., 2003), a speculative interpretation is that the Day 1 words were less susceptible to interference upon retrieval due to being stabilised during the consolidation period prior to testing, whereas Day 2 words had greater interference at test due to undergoing retrieval without any opportunity for consolidation[20].

One way of conceptualising the impact of prior consolidation on retrieval of declarative memories may be that unconsolidated new memories require retrieval from the hippocampus, which contains detailed episodic representations relatively prone to interference, whilst the retrieval of consolidated new memories with stronger neocortical representations activates more stable, abstract representations which are thus less prone to interference upon reconsolidation. This effect of prior consolidation on the relative amount of interference at the Study 3 test may then have had a subsequent impact on the retention of declarative memories at follow-up. However, it is notable that the proposal of multiple stages of consolidation and reconsolidation involved in long-term memory stabilisation suggest that this time-course may be more

[20] A caveat to this suggestion of a benefit for words consolidated prior to testing is that if proactive interference contributed to poorer recognition performance for Day 2 relative to Day 1 words at the initial test, the benefit for Day 1 words at follow-up may be due simply to poorer learning for the Day 2 words. Whilst suggestions against the proactive interference account were given in section 6.2.3, it is important to recognise that the current data cannot rule out this possibility.

nuanced (Stickgold & Walker, 2007), and further factors such as proactive interference may have affected the long-term retention of explicit knowledge for the Day 1 and Day 2 words.

Finally, it is important to stress that this study involved a substantially lower number of participants returning for re-test than those included in Study 3, which contributes both to reduced power and a potential self-selection of participants opting to return to the lab. Thus, whilst these findings indicate i) no lexicalization for novel words acquired in the current associative learning paradigm, ii) a long-term declarative memory benefit for semantic-associated words, and iii) a long-term declarative memory benefit for words consolidated prior to testing, the present data would benefit from extension in a larger sample in future work.

6.4 General Discussion and Chapter Summary

Two questions were posed at the outset of this chapter. Firstly, could semantically-trained new words show lexicalization within a 24 hour time window? Secondly, what aspects of word knowledge are benefited by offline consolidation, and how is this affected by the acquisition of semantic associations? On the whole, the findings of this chapter suggest that acquiring novel words via a task focusing on word-referent association learning was not sufficient to promote lexicalization, despite the consolidation of explicit word knowledge. Table 6 summarises the consolidation and semantic benefit observed across Study 3 and at the follow-up. The findings of Study 3 were thus consistent with the idea that, rather than a general deficit in offline consolidation, the novel words showed a specific difficulty with lexical integration. The same was true of the long-term follow-up: whilst explicit recognition and online access to the novel word representations was retained over several months (despite being reduced relative to the initial test), no lexical competition effects were observed. The below discussion thus focuses on i) the extent to which semantic training contributes to word memory formation, and ii) the factors which may constrain the success and time-course of lexicalization.

6.4.1 Word memory formation and meaning

The findings of this chapter align with the view that semantic knowledge can benefit declarative word memory formation (e.g. Henderson, Weighall, & Gaskell, 2013;

Table 6. Summary of findings across Study 3 and the long term follow-up.

	Study 3		**Long term follow-up**	
	Day 1 advantage	Semantic advantage	Day 1 advantage	Semantic advantage
Pause Detection	No	No	No	No
Recognition d'	Yes	Yes	Yes	Yes
Recognition RTs	Yes	No	Yes	No
Shadowing RTs	Yes	Yes	No	No

Note. The table shows the tasks in which there was a consolidation effect (Day 1 advantage) and semantic advantage (for correlated over uncorrelated words) observed in the Study 3 test and at the long term follow-up.

Rodd et al., 2012; Rueckl & Dror, 1994; Takashima et al., 2014). It is important to consider, however, whether the current learning paradigm promoted a greater semantic advantage than that which would be otherwise observed in natural learning. As considered in relation to the phonological form learning advantage for correlated words in Study 2, one possibility is that the current findings reflect a relative disadvantage of the uncorrelated words rather than an advantage for the correlated words, due to the interference created by a lack of systematic referent with the learning goal of acquiring one. Indeed, previous work has indicated that new object-label associations are more difficult to learn when the label is of low probability in a segmentation task (i.e. containing low-probability syllable transitions) than when the label is high-probability or neutral (Mirman, Magnuson, Graf Estes, & Dixon, 2008). This converges with the view that inconsistent cues impair associative learning in general (a similar result was also obtained by Fernandes et al., 2009). However, it is important to again note that varying the associative systematicity between the correlated and uncorrelated words potentially provided a learning scenario more akin to real-world learning, where it is not uncommon to experience a word such as *bug* in different contexts across exposures (e.g. Rodd et al., 2012) and thus struggle to extract a specific meaning. Hence, a reasonable interpretation is that the current semantic advantage mirrors that which may be obtained in more everyday learning scenarios, but it is important to take into account that the extent and prevalence of a semantic learning advantage is likely to depend on factors such as the instructions of the learning task and type of semantic knowledge being acquired.

An additional consideration is whether any trade-off in learning strategies was present between correlated and uncorrelated words, due to being interleaved during training. In one previous study which found lexical competition effects for semantically-trained words after one night of consolidation (Henderson, Weighall, & Gaskell, 2013) it is notable that the children were trained in separate groups for the semantic and form-only training. This may have partially contributed to the semantically-trained words engaging in lexical competition, due to minimising the trade-off between phonological and semantic learning strategies. The present data cannot address the extent to which different learning strategies were used for encoding the correlated and uncorrelated words, but the contribution of encoding to the subsequent stages of word memory formation will be an important avenue for future work.

6.4.2 Constraints on lexicalization

A core tenet of the CLS model (McClelland et al., 1995), and standard consolidation models more generally (Squire & Alvarez, 1995; Frankland & Bontempi, 2005) is the loss of hippocampally-represented episodic and explicit word knowledge over time, as neocortical representations become stabilised. A key question is thus to what extent lexicalization is constrained by i) the initial strength of new word memories, and ii) the role of well-established phonological representations for hippocampal-neocortical transfer.

Across extant reports of lexicalization, there appears to be no consistent level of declarative memory which enables lexicalization. For example, whilst high recognition memory scores immediately after learning have often been reported alongside successful lexicalization after a night of sleep (e.g. Davis et al., 2009; Dumay & Gaskell, 2007, 2012; Takashima et al., 2014), lexicalization has also been observed following a decrease in recognition memory (Bakker et al., 2014) and appears to be dissociable from the mechanisms enabling declarative memory enhancement during overnight consolidation (Tamminen et al., 2010). In the current study, the negative correlation between recognition memory and the magnitude of lexical competition at follow-up was also suggestive that any relationship between lexicalization and declarative memory is not clear-cut. A particularly interesting dissociation between declarative memory performance and lexicalization was observed by Coutanche and Thompson-Schill (2014). In two experiments participants learnt novel word forms and associations by 'fast mapping' (FM), 'explicit encoding' (EE), and 'implicit encoding' (IE). The fast mapping condition presented the image of a novel item alongside a known item, accompanied by a question containing the new item's name and a perceptual feature, with which the mapping between the new item and its name could be inferred (e.g. "Is the tail of the Torato pointing up?" with pictures of an unknown insect and a cicada). In the explicit encoding condition the new item was presented with its label (e.g. a picture of an unknown insect with the sentence, "Remember the Torato"). In the incidental encoding condition the new item was presented with the same perceptual question as in the FM condition, but without a picture of a known item (e.g. a picture of an unknown insect with the sentence, "Is the tail of the Torato pointing up?"). Whilst recognition memory was superior after explicit encoding (84.8%) it was only after fast mapping that the novel words showed lexical competition, despite low recognition memory in the fast mapping condition (49.4%). Interestingly, the incidental encoding condition also showed low recognition memory (41.0%) but no lexical competition. Based on observing lexicalization in the fast mapping but not the incidental encoding condition Coutanche and Thompson-Schill (2014) interpreted their findings in terms of learning schema in which the presence of a known meaningful picture during encoding activated overlapping, semantically related concepts, and the activation of this network enabled rapid lexical integration of the associated novel word (see also Lindsay & Gaskell, 2013). These data are consistent with the idea that successful lexicalization is not necessarily tied to a particular level of explicit word knowledge, but rather to the *type* of learning that subserves the acquisition of new explicit knowledge (also cf. Fernandes et al., 2009; Szmalec et al., 2012; reported in Chapter 3). It is thus possible that, above a certain threshold of declarative memory[21], lexicalization is at least partially constrained by the processes involved in novel word acquisition.

A related consideration is that successful lexicalization may be partly characterised by a loss of contextual detail linked to learning. The transformation hypothesis of Wincour and Moscovitch (2011) suggests that loss of episodic detail as memories progress from the hippocampus to extra-hippocampal structures may in part be required for representation outside hippocampal structures. This idea can be

[21] It should be noted that the minimum level of declarative knowledge sufficient for lexicalization may be at least partially determined by the nature of the training and test tasks used, and the relationship between them.

extended to the lexical integration of novel words: establishing an inhibitory link between novel words and their existing phonological neighbours may require strong links between the new and existing phonological forms, which is weakened if learners have other sources of information (such as picture associations or contextual knowledge) to build memory on (a similar argument is made by Takashima et al., 2014). It may thus have been the case that the additional training context provided by the novel pictures in the current learning paradigm increased the difficulty of linking the new and existing phonological forms.

A final constraint on lexicalization to consider therefore concerns the establishment of well-specified phonological representations from initial learning. Interestingly, an examination of extant lexicalization studies indicates that lexical competition effects have been almost universally obtained with phonological training tasks (e.g. Davis et al., 2009; Dumay & Gaskell, 2007, 2012; Henderson et al., 2012, 2014; Gaskell & Dumay, 2003), although reports of lexicalization from non-phonological training tasks are becoming increasingly prevalent (Coutanche & Thompson-Schill, 2014; Fernandes et al., 2009; Szmalec et al., 2012, all using implicit learning tasks). One possible mechanism for the importance of detailed phonological representations for subsequent lexical competition with existing words could be in part due to the required co-activation of lexical candidates in speech perception for competition effects to be observed. Accordingly, it could be that reduced phonological encoding during initial acquisition may increase the difficulty of establishing inhibitory links between novel words and their existing phonological neighbours (e.g. Bakker et al., 2014; Takashima et al., 2014).

This account suggests that new word representations with only a coarse level of phonological detail in the hippocampus would be delayed, or unsuccessful, in transferring to stable, integrated neocortical representations. Theoretical support for this proposal comes from the standard consolidation model (Squire & Alvarez, 1995). As explained in the Introduction to this chapter (section 6.1.2), it may be the case that weaker phonological form representations in the hippocampus are less amenable to the cortical stabilisation and reorganisation process which underpins memory consolidation. Takashima et al. (2014) further put forward empirical support for this proposal. The necessity of strong links between novel and existing phonological forms for lexical competition was suggested by a positive correlation between functional connectivity (between the auditory cortex and posterior middle temporal gyrus) and the lexical competition effect for words trained via phoneme monitoring (form-only), relative to words trained with an additional picture association. This finding suggested that participants with greater functional connectivity for form-only relative to picture-associated words showed larger lexical competition effects after consolidation, supporting the view that a coupling between novel and existing phonological forms may be tied to lexical competition. The importance of a specified phonological representation from novel word encoding could be particularly true in the case of pause detection, which is a substantially phonological task. The two lines of evidence concerning i) the non-linear relationship between declarative word memory and lexicalization, and ii) the suggested importance of well-established phonological representations for hippocampal-neocortical transfer together suggest that the lexicalization of new words may have specific constraints that other aspects of word memory consolidation are not subject to.

6.4.3 Conclusions

The central finding of this chapter is the distinction between impaired lexicalization and the intact consolidation of explicit and online access to new word knowledge. On balance, this distinction suggests that the learning paradigm may not have promoted acquisition of new word representations in a sufficient way for lexical competition. Given the review of extant studies of lexicalization and a consideration of the requirements for lexical competition effects to emerge, one possibility is that the degree of the phonological encoding which subserved learning was not sufficient to promote lexicalization in the present study. It may therefore be the case that a more substantial degree of phonological encoding during the acquisition of novel words is a central factor contributing to subsequent lexicalization. This is the question investigated in the next chapter.

Chapter 7: Phonological processing, meaning, and lexicalization

7.1 Introduction

The successful integration of new words with existing lexical items has been predominantly obtained following phonological training (e.g. Bakker et al., 2014; Brown et al., 2012; Davis et al., 2009; Dumay & Gaskell 2007, 2012; Dumay et al., 2004; Henderson et al., 2012; Henderson, Weighall, et al., 2013; Takashima et al., 2014; cf. Coutanche & Thompson-Schill, 2014; Fernandes et al., 2009; Szmalec et al., 2009), with the presence of a semantic association sometimes delaying this time-course (Dumay et al., 2004; Takashima et al., 2014; cf. Henderson, Weighall, & Gaskell, 2013). The previous chapter investigated whether the time course of lexicalization for novel words trained with and without an associated meaning could be equated when acquired in a learning task requiring the learning of novel form-meaning mappings. A dissociation was observed between lexical integration and the consolidation of explicit word knowledge: no robust lexical competition was observed, but consolidation was observed to enhance recognition and online access to the new words. One possibility for this specific lexicalization deficit was that the degree of phonological encoding which supported the initial acquisition of the novel words was not sufficient to enable their entry into lexical competition. The present chapter thus addresses whether the processing allocated to phonology during the initial acquisition of novel words contributes to their successful lexicalization.

7.1.1 Phonological processing and lexicalization

The proposal that phonological processing[22] during the acquisition of new words supports subsequent lexicalization stems from the argument that specified representations of the phonemic structure of novel words are better able to engage in lexical competition with existing onset competitors (Henderson, Weighall, et al., 2013). Novel word lexicalization is primarily measured by the engagement of new words in lexical competition, and a common method indexing this has been the pause detection

[22] From this point on, 'phonological processing' is used to refer to the *level of processing allocated to the phonology of a novel word* during acquisition. This includes attending to the syllables, phonemes, and onset/rime of novel spoken words. 'Phonemic processing' will refer to attending specifically to the phonemes within spoken words and thus having a specific awareness that the novel word *cathedruke* consists of the phoneme structure /kəthēdrʊk/, for example.

task (e.g. Dumay & Gaskell 2007, 2012; Henderson et al., 2012; Henderson, Weighall, & Gaskell, 2013; Mattys & Clark, 2002; Takashima et al., 2014), as employed in the previous chapter. The pause detection task capitalises on the properties of spoken word recognition, whereby lexical candidates compatible with the speech input are activated in parallel and mutually inhibit each other until the speech signal uniquely matches one lexical candidate (e.g. Gaskell & Marslen-Wilson, 1997; McClelland & Elman, 1986). Critically, because spoken word recognition is online and incremental, each segment of a word must be well specified in order to engage in lexical competition with phonologically overlapping lexical items[23]. The accurate and ordered retention of phoneme sequences contributing to successful phonological form learning is further indicated by the association between immediate serial recall and phonological form learning (Baddeley et al., 1998; Gupta, 2003; Page & Norris, 2009; Papagno & Vallar, 1992). From both the online and incremental nature of spoken word recognition, and the contribution of serial recall to phonological form learning, it thus follows that new word representations must contain a precisely specified phonological structure in order to be evoked by the spoken input and thus engage in competition.

An important clarification concerns the relationship between this argument and the semantic advantage for phonological form learning observed in Study 2 (Chapter 5) in this thesis. Study 2 investigated whether semantic learning influenced the acquisition of new phonological form representations. The results suggested that novel words acquired with a systematic semantic referent established new phonological form representations, which were stable after a twenty-four hour period of consolidation. Such a finding may appear at odds with the proposal that novel words acquired in Study 3 (using the same learning paradigm) did not establish precisely specified phonological form representations, and this contributed to their failure to enter into lexical competition. A critical difference between Study 2 and Study 3 may account for this apparent discrepancy: in Study 2 monosyllabic novel words were learnt, which were minimal pairs of existing words (e.g. *pite-pipe*, *kite-kipe*). In contrast, Study 3 required

[23] It is noteworthy that this assumption aligns more closely with the Cohort model (Marslen-Wilson, 1987) and Distributed Cohort Model (Gaskell & Marslen-Wilson, 1997) of spoken word recognition than the TRACE model (McClelland & Elman, 1986). A key property of TRACE is the ability to recover from the early underspecification of spoken words, such that underspecified inputs nonetheless engage in competition. It follows that if newly-learnt words are phonologically underspecified, they may nonetheless be able to engage in lexical competition within the framework of TRACE. In the Cohort model underspecified words would be discarded as lexical candidates early in the competition process, and thus be unlikely to increase the time for recognition of existing words.

the learning of bi and tri-syllabic novel words which were close phonological neighbours with just one existing word (e.g. *cathedruke-cathedral, assassin-assassool*). In Study 2 the critical measure of phonological form learning was participants' discrimination between the novel and existing minimal pairs, based on the stop consonant after the vowel (e.g. *pite-pipe)*. Conversely, in Study 3 the critical measure of lexical competition was the level of lexical activity at the final vowel of the existing word, which required the ongoing activation of the novel neighbour up until this uniqueness point at which the existing word diverged (e.g. *cathedruke-cathedral).* It is thus possible that the goal of meaning acquisition in the learning paradigm enabled (and advantaged) the acquisition of the phonological forms of the monosyllabic novel words, but that such a focus on meaning acquisition for the bi and tri-syllabic novel words in Study 3 contributed to a more weakly specified phonological structure overall. This proposal is consistent with a report of greater importance given to novel word onsets than offsets in paired-associate learning (Creel & Dahan, 2010; see also White et al., 2013). Such a finding suggests that the offsets of the novel words in Study 3 may have been poorly specified, which subsequently impaired their entry into competition with existing phonological neighbours with late uniqueness points. It is important to emphasise that this argument does not suggest qualitatively different learning mechanisms between Study 2 and Study 3, but simply that a greater degree of processing allocated to phonology (rather than meaning) may be required to support the acquisition of specified phonological form representations for complex bi and tri-syllabic words.

A relevant report on the issue of the type of phonological analysis supporting word learning comes from Leach and Samuel (2007). The authors tested whether novel word meanings supported perceptual learning, by training participants on novel words with or without an association and testing their impact on the perception of words with an ambiguous phoneme. Novel words with a /sh/ sound (e.g. *bibershack*) were observed to shift the phonetic boundary of ambiguous words towards /s/ on the /sh/-/s/ continuum, but only when the novel words were acquired with picture associations or via story contexts; items trained via phoneme monitoring, with no associated meaning, did not produce such a perceptual learning effect. Leach and Samuel (2007) interpreted these findings as suggestive of a semantic requirement for novel words to support perceptual learning (as reported in Chapter 3). Critically, however, the spoken repetition of the novel words during semantic exposure reduced the perceptual learning effect. This is indicative that, at least in the case of perceptual learning, the type of phonological processing underpinning initial acquisition may be of key importance for lexical engagement (note that the a similar argument is made by Dumay & Gaskell, 2012, pp. 130). Extending this argument to lexical competition specifically, it is possible that a phonemic analysis of novel words during learning may be a key factor in their entry into lexical competition within 24 hours.

7.1.2 Attentional focus during learning

The above argument suggests that one component of learning contributing to lexicalization may be attentional focus to the phonological forms of novel words during learning. The contribution of attentional focus to learning has been explored by assessing how task instructions enhance attention to different psycholinguistic attributes. Yoncheva et al. (2010) investigated the impact of attentional focus during learning to read novel words written in an artificial script. Attentional focus was manipulated by instructing two groups of participants either to attend to grapheme-phoneme correspondences or to the whole-word forms, during learning the correspondences between the orthographic and phonological forms of the same set of novel words. They measured the impact of attentional focus with the N170 response, an ERP potential which becomes left-lateralized with expertise for visual word forms, whereby this left-lateralization has been suggested to emerge from successful grapheme-phoneme decoding of orthographic forms. The left-lateralized N170 response emerged only for participants who were instructed to focus on the grapheme-phoneme correspondences during learning, for both trained items and during generalisation to untrained items. Interestingly, behavioural accuracy in verifying whether an untrained orthographic string matched a spoken word (from the learnt visual-spoken stimuli correspondences) was also significantly higher for the grapheme-phoneme focus group than the whole-word focus group. This emergence of an expertise effect for the grapheme-phoneme group only, despite the stimulus set and exposure time being equivalent for the whole-word group, therefore suggests that attentional focus to different psycholinguistic attributes during training can substantially impact upon the learning outcome.

Complementary effects of focusing attention on specific linguistic attributes have been obtained during the processing of existing words. Ruz and Nobre (2008) addressed whether attentional cueing of existing visually-presented words could selectively enhance the processing of specific psycholinguistic attributes. Prior to the onset of each word participants were cued to attend to the orthography, phonology or semantics on a trial-by-trial basis. The authors predicted that this attentional cueing would modulate ERP components associated with each linguistic attribute: the N200, N350 and N400 for orthographic, phonological and semantic processing, respectively. In accordance with their predictions, the attentional cueing increased the negativity of the specific ERP potential associated with each linguistic attribute, relative to the ERP potentials of the un-cued attributes. These data are consistent with the idea that the goal of focusing on specific linguistic attributes can modulate and enhance subsequent stages of word processing. Consistent with Yoncheva et al. (2010) and Ruz and Nobre (2008) it is therefore possible that the goal of acquiring novel word-meaning mappings enhances processing of the semantic attributes of novel words, and thus results in a reduced attentional focus on the phonological forms of the novel words.

7.1.3 Summary

The above lines of evidence converge to suggest that the degree of processing allocated to the phonological structure of novel words may be a key factor in their entry into lexical competition after 24 hours[24]. In line with this proposal, a possible mechanism for the delayed lexicalization time course of meaning-associated words (as in Dumay et al., 2004 and Takashima et al., 2014), and failure to observe lexical competition in Study 3 in this thesis, could be due to meaning reducing the degree of phonological processing allocated to novel words during learning. The current chapter therefore investigated the impact of phonological attention and meaning on the lexicalization time course of novel words. It was predicted that with instructions to attend to the phonological form of novel words during learning (as in Yoncheva et al., 2010), and thus focusing attention on the phonological structure of the novel words, novel words acquired with a meaning should exhibit an equivalent lexicalization time course to those learnt with no associated meaning.

The training task used to increase processing of the phonological structure of novel words was the phoneme monitoring task. Phoneme monitoring is a training task in which participants are required to attend to the phonemic structure of a spoken word and identify the presence or absence of a target phoneme as the spoken input unfolds

[24] A notable exception to this comes from Coutanche & Thompson-Schill (2014) who observed immediate lexical competition for novel words trained with a meaning via a 'fast-mapping' procedure. The discussion of this chapter will consider the implications of this finding in more detail.

(see Connine & Titone, 1996, for review). It is thus a case of focused phonological processing during learning, and studies using phoneme monitoring as a training method for novel words have consistently found an overnight delay between learning and the emergence of lexical competition effects (e.g. Davis et al., 2009; Dumay et al., 2004; Dumay & Gaskell, 2007; Dumay & Gaskell, 2012; Gaskell and Dumay, 2003; Tamminen & Gaskell, 2008; cf. Lindsay & Gaskell, 2013). One previous study has investigated the contribution of meaning acquisition to lexicalization using training on a phoneme monitoring task. In Takashima et al. (2014) participants learnt novel words in a phoneme monitoring task, in which half of the novel words were associated with a picture referent. After 24 hours of consolidation, only the words learnt *without* a picture referent slowed responses to existing phonological neighbours, and the picture-associated words showed no lexical competition effects. From these findings Takashima et al. (2014) suggested that when there is more than one source of information to base a novel word memory on (such as an associated picture) this reduces the ease with which a novel form can be linked with an existing neighbour.

This may indeed be the case, but there are two critical points about Takashima et al's methods to recognise. Firstly, participants were instructed to remember the word-picture associations in the case of the picture-associated words. As discussed above, these task instructions may reduce the degree of processing allocated to the phonological structure of novel words. Secondly, in the picture-associated condition the pictures appeared 200ms before the onset of the novel words, and participants' phoneme detection responses to the picture-associated words were subsequently 61ms faster overall than those to the form-only words, suggesting that the novel picture aided retrieval of the associated novel word to speed up phoneme detection (as noted in the previous chapter). However, an additional effect of pictures aiding word retrieval could have been a reduced requirement to attend to the phonological structure of the picture-associated words during training. A reduction in online phonological processing of the picture-associated words may have thus been a contributing factor to their lack of lexicalization after 24 hours.

The study in this chapter therefore sought to equate the phonological processing of form-only and meaning-associated words in a paradigm mirroring that used by Takashima et al. (2014). Participants learnt novel words in a phoneme monitoring task, where half the words were consistently associated with the same picture referent on every trial (*picture-associated*) and half the words had no associated picture (*form-only*). To focus attention on the phonological structure of the novel words in both conditions, two critical changes were made to the methods. Firstly, participants were instructed to learn the forms of the novel words, with no explicit goal of learning the associated pictures. From the findings of Yoncheva et al. (2010), it is evident that task instructions can substantially impact upon learning, and altering the task instructions in the current study thus provided an opportunity to assess the impact of attentional focus on the lexicalization of semantically-associated words, relative to the Takashima et al. (2014) study. Secondly, the onset of the picture for the picture-associated words was temporally matched to the onset of the spoken word, in contrast to Takashima et al. (2014); the picture-associated word could therefore not be retrieved based on the picture alone, with the objective that this would promote greater focus on the phonological structure of the picture-associated novel words for target detection in the phoneme monitoring task. In addition to these methodological changes, the new word representations were tested immediately (Day 1), 24 hours (Day 2), and one week (Day 8) after learning to track the development of lexical competition and declarative word knowledge over a longer time frame than the 24 hour window tested in Study 3 and Takashima et al. (2014).

Three explicit predictions were made. Firstly, it was predicted that lexical competition effects would emerge on the same day of testing for the picture-associated and form-only words; that is, the lexicalization time course for the picture-associated words would not be delayed relative to the form-only words (as in Dumay et al., 2004 and Takashima et al., 2014). Second, declarative word knowledge should be enhanced over consolidation, consistent with previous studies (e.g. Dumay & Gaskell 2007, 2012; Henderson, Weighall, & Gaskell, 2013; Henderson et al., 2014; Tamminen et al., 2010). Finally, it was hypothesised that if phonological processing during initial acquisition supports the subsequent entry of new words into lexical competition, performance on the phoneme monitoring training task should modulate the magnitude of any subsequent lexical competition effects.

In sum, this chapter investigated whether recruiting phonological processing sufficiently well during training allows the lexicalization time course to be unimpaired by the acquisition of semantic knowledge. Study 4 therefore addressed whether attention to the phonological structure of novel words during learning is required for successful lexicalization, and whether such an attentional focus could reduce the delay observed in the lexicalization of meaning-associated novel words.

7.2 Study 4

7.2.1 Methods

7.2.1.1 Participants

Thirty participants took part in the study, and were recruited from Royal Holloway, University of London. Participants were native English speakers, with a mean age of 20.93 years (SD = 3.53, range = 18-37, 6 males). Participants had no second language expertise above GCSE level, with the exception of one participant who spoke both English and Greek; however, English was the participants' first language for the first five years of life (fulfilling the native speaker criteria) and they were thus retained in the dataset. The study received ethical approval from the Psychology Department Ethics Committee at Royal Holloway. Participants were paid as compensation for their participation upon completion of all three sessions, and debriefed about the aims of the study.

7.2.1.2 Materials

Word stimuli. The word stimuli consisted of 160 triplets consisting of a monomorphemic existing base word (e.g. *cathedral*), and two novel words which diverged from the base word at the final vowel (e.g. *cathedruke, cathedruce*). All items were bi or tri-syllabic. Eighty of the triplets were those used in Study 3, from Tamminen

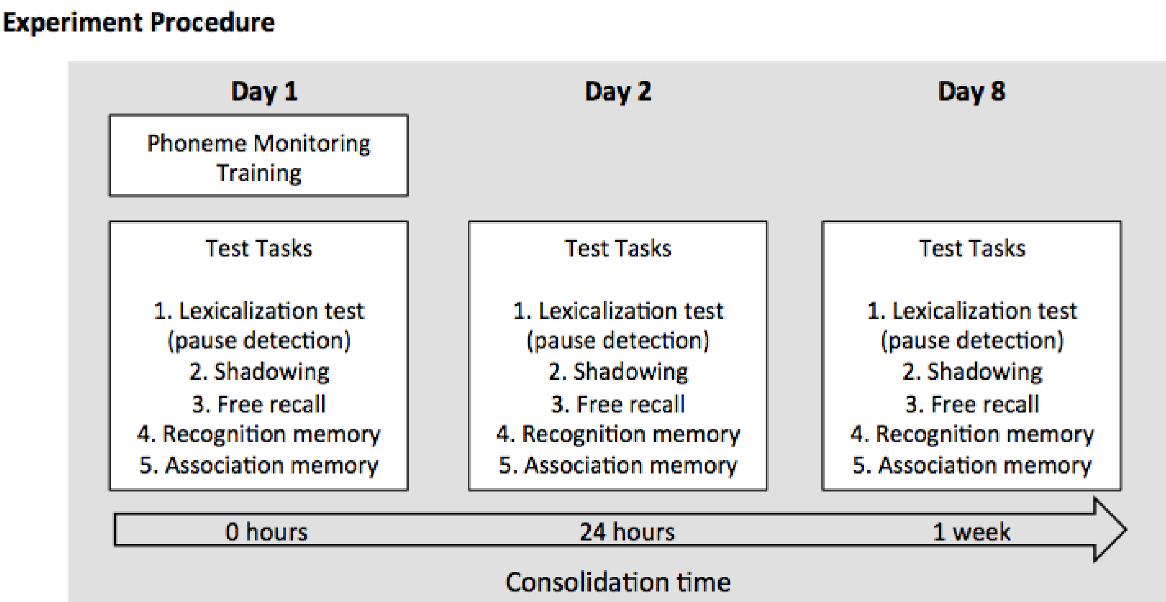

Figure 32. A schematic of the experimental procedure in Study 4.

and Gaskell (2008) and Gagnepain et al. (2012), and 80 further triplets were selected from the stimulus set of Gagnepain et al. (2012; presented in Appendix 11).The additional 80 triplets from the Gagnepain et al. set were selected as those in which the novel words deviated from the base word at the final vowel, and thus closely matched the items used in Study 3. Of the final 160 triplets, 4 were ‘embedded’ items where the base word was embedded within the novel word (e.g. *veranda-verandaf*) and the remaining 156 triplets derived the novel words from the base words by a divergence at the final vowel (e.g. *revenue-revenyol*). The base words were between 4 and 11 phonemes in length (M = 6.81, SD = 1.14) and had a log CELEX total frequency between 0 and 1.7 occurrences per million (M = .61, SD = .35; Baayen et al., 1996). The uniqueness point of the base words, the phoneme where the base word diverged from all existing cohort neighbours, varied between the 2rd and 9th phonemic position (M = 4.36, SD = 1.18). The uniqueness point was always before the final vowel in the case of deviation items, and at the final vowel in the case of the embedded items. All 160 triplets were randomly divided into five lists of 32 items each, which did not significantly differ on the log frequency of the base word, the number of syllables, the number of phonemes and the phonemic position of the uniqueness point (all Fs < 1.1, ps > .3). A different set of untrained control words were used on each day of testing, and as such the five item lists were counterbalanced between each cell of the design: picture-associated, form-only, untrained control day 1, untrained control day 2, and untrained control day 8. For two item lists one set of novel words was the trained picture-associated and form-only novel words, and the corresponding base words were used in the pause detection task on each day of testing. The other set of novel words for these triplets were then used as untrained foils in the recognition task. For the remaining three item lists, the base words from one list were used as untrained control words in the pause detection task on each of the three days of testing. One set of novel words from each of these lists was then used in the shadowing task on each day of testing, as the untrained novel words.

For the pause detection task, an additional 288 filler words were chosen. The 3:1 ratio of filler words to experimental base words was the same as that used in Study 3, and chosen to minimise participants recognising the relationship between the experimental base words and trained novel words[25]. The filler items were existing words to encourage lexical processing. Two-hundred and eight were from the set used in Study

[25] Note that the Takashima et al. (2014) study used a 1:1 ratio of experimental and filler items.

3, and an additional 80 existing hermit words were chosen (presented in Appendix 12). All filler words were monosyllabic (N = 59), disyllabic (N = 125) or trisyllabic (N = 104) monomorphemic words, with an average phoneme length of 5.64 (SD = 1.40) and log frequency of 0.83 (SD = 0.42).

For the base words in the pause detection task, a 200ms pause was inserted at the uniqueness point with an identical procedure to Study 3 (Chapter 6, section 6.2.1.2) using the rationale of Gaskell and Dumay (2003). The filler words again had 200ms pauses inserted towards the beginning, middle or end of the word with equal frequency to encourage participants to attend to the whole item (and not predict pause presence occurring towards the end of the word). As in Study 3, amplitude was also matched as closely as possible across items. All stimuli were recorded and edited using CoolEdit 2000, with the same Southern British English speaker as Study 3.

Picture stimuli. The referents for the picture-associated words consisted of 32 pictures of obscure objects selected from the stimulus set used in Study 3, presented in Appendix 13. The pictures from the Study 3 set were chosen to be closely matched to each other on distinctiveness and complexity. Thirty of the chosen pictures were obscure items without a clear label selected via a Google image search, and 2 were from the NOUN database (Horst & Hout, 2014). The pictures were presented in colour on a black background, and were 500 x 500 pixels in size. Each participant was allocated a different word-picture mapping for the picture-associated training condition.

7.2.1.3 Design and Procedure

Experimental procedure. On Day 1, participants completed the phoneme monitoring task to learn the 64 novel words. Participants were informed that they were taking part in a word learning study, in which they would learn some new words and be tested on them later. Following training there was a 5-minute break in which demographic information was collected. Participants then completed five test tasks: a lexicalization test (pause detection), shadowing, free recall, recognition memory, and association memory. The phoneme monitoring and association recall tasks were run in E-Prime 2.0, and the pause detection, shadowing, and recognition memory tasks were run in DMDX (Forster & Forster, 2003). Participants returned at the same time the following day for a second test session 24 hours after learning (Day 2) and again one week after the training session (Day 8). Most participants were scheduled at similar times of day for the three sessions (in the morning, early afternoon or late afternoon) to minimise circadian differences between each test session. Participants completed training in groups of up to three in a quiet testing room, with their start time staggered such that no two participants were tested at the same time. Participants completed the subsequent Day 2 and Day 8 test sessions in isolation. The phoneme monitoring training took approximately 2 hours, and each test session took approximately 1 hour. Each participant was thus tested for approximately 5 hours in total. A schematic of the experiment can be seen in Figure 32, with the training and test tasks procedure depicted in Figure 33.

Phoneme monitoring training. On Day 1 participants were trained on the 64 novel words in the phoneme monitoring task, where 32 of the novel words were presented as phonological forms in isolation (*form-only*) and 32 were presented with an associated picture referent on the screen (*picture-associated*). The task instructions stated, “This is a task for learning new words, and your goal is to memorise as many of the new words as you can. In this task you will hear some new words, and your aim is to listen for a target sound in these new words. Sometimes a picture may appear with a word. These pictures may help you, but remember your main goal is always to learn the new words and memorise as many as you can.” Importantly, these instructions emphasised the learning of the novel phonological forms as the task goal, with no goal of learning the word-picture associations.

The phoneme monitoring task consisted of 36 blocks, where each novel word was presented once per block in a randomized order. There were thus 36 exposures to the novel words over the course of the task. In each block participants listened for the presence or absence of one of six target phonemes (/k, n, t, m, l, s/). Each phoneme was monitored for six times in that fixed order. The phonemes were chosen such that they appeared in all positions across the words, with rates of occurrence as similar as possible across the five word lists. The mean rate of target occurrence across lists was 34% (SD = 9). At the start of each block the target phoneme was presented on the screen, with a written example (e.g. “Listen for /k/, as in ‘book’”), and participants then heard two repetition of the target phoneme via headphones before beginning the task. During the task participant heard each word via headphones, and responded “yes” via a button box if they heard the target sound or “no” if they did not hear the target sound. Every word therefore required a response (Gaskell & Dumay, 2003). For the picture-associated words the picture appeared in the centre of the screen at the same time as the onset of the spoken word, to prevent participants predicting word identity on the

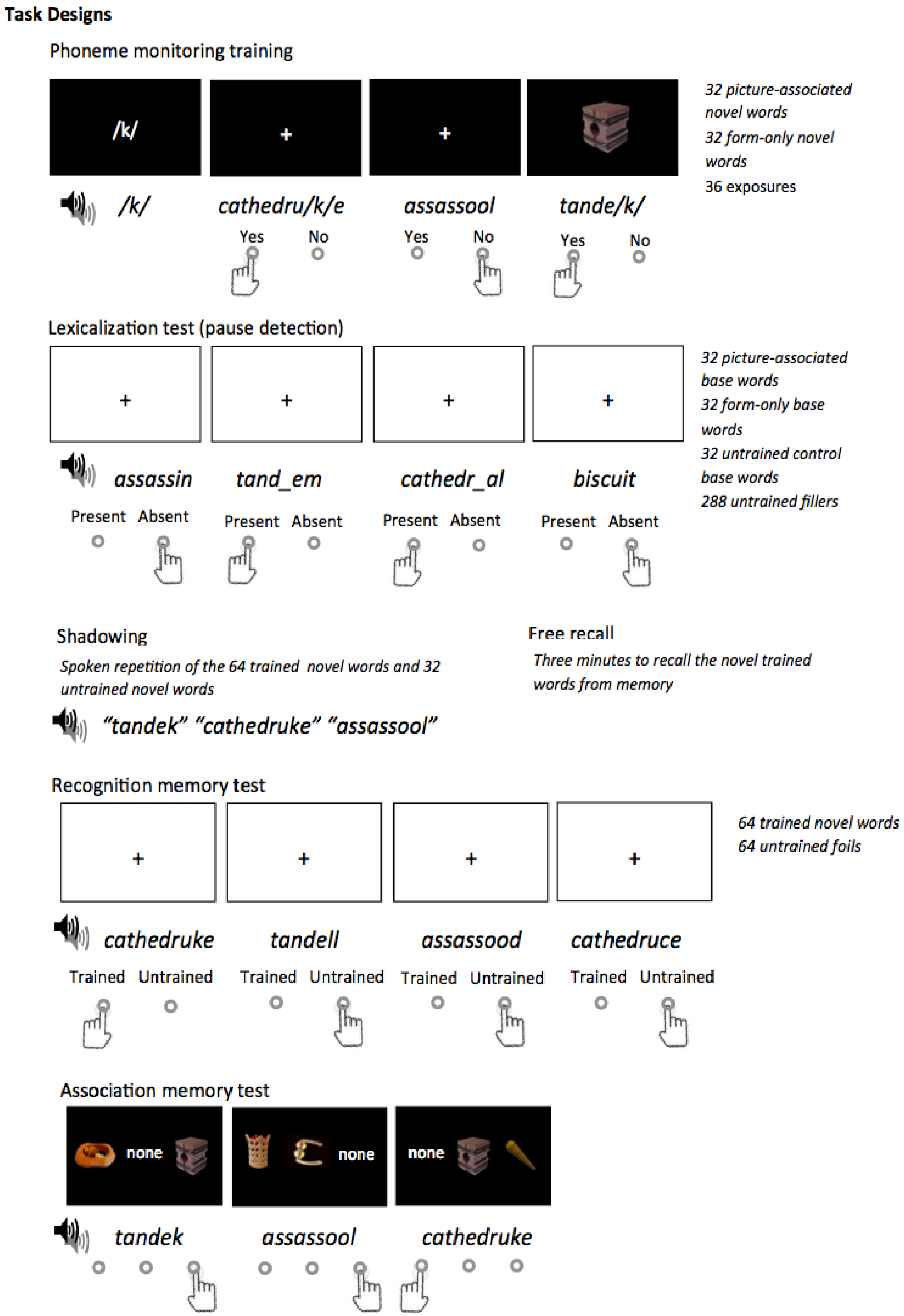

Figure 33. The design of the training and test tasks used in Study 4.

basis of the picture, and stayed on screen for 1000ms after the offset of the word (as in Takashima et al., 2014). A fixation cross was presented in the centre of the screen during form-only trials. Participants had 3000ms after the onset of the word to make a response, and the inter-trial interval was 700ms. Every quarter of the task a break screen informed participants how far they had progressed through the training, and they were encouraged to take a break to maintain motivation and attentiveness.

Lexicalization test: Pause Detection. In the pause detection task participants were required to detect the presence or absence of a 200ms pause (Mattys & Clark, 2002) in the 96 experimental base words and 288 fillers, presented in a randomised order. Participants were instructed they would hear a word via the headphones, and to press the "yes" button if a pause was present and the "no" button if a pause was absent. Responses were made via a button box. On each day of testing a different set of 32 untrained control base words were used, following the procedure of Takashima et al. (2014). Because of the multiple testing sessions, the use of different control words on each day minimised practice effects leading to faster response times (and apparent lexicalization effects) to the control base words. A practice block preceded the pause detection task on Day 1, with 12 existing words not used in the experiment. In the task, each trial began with a 250ms fixation cross before the onset of the word. Participants had 3000ms to respond following the onset of the word, with an inter-trial interval of 1000ms. During the task there was a break every 100 trials. The procedure of counterbalancing the items between pause present and pause absent trials across participants and item lists was identical to that used in Study 3. No feedback was given during the task.

Shadowing. In the shadowing task participants heard one of the 32 picture-associated novel words, 32 form-only novel words and 32 untrained novel words via headphones, presented in a randomized order. The 32 untrained novel words were those derived from the control base words in the pause detection task on each day, to allow counterbalancing of the five novel word lists between picture-associated trained, form-only trained, day 1 untrained, day 2 untrained, and day 8 untrained conditions. Participants were instructed to repeat the word aloud as quickly and accurately as they could. Each trial started with the 250ms presentation of a fixation cross, and participants had 3000ms to respond. Responses were recorded via a Beyerdynamic microphone.

Free recall. In the free recall task participants were given 3 minutes to verbally recall as many of the trained novel words as they could remember from the training session. The instructions specified that participants should try to remember the words from the learning task they completed, to prevent participants recalling items from the pause detection or shadowing tasks. Responses were recorded in Audacity.

Recognition memory. The recognition memory test presented participants with the 64 trained novel words (e.g. *cathedruke*) and 64 untrained foils (e.g. *cathedruce*). Participants heard each word via headphones and their task was to respond whether the word was one they learnt during the phoneme monitoring task. Responses were made via a button box, with participants responding “yes” if the word was one they had learnt previously and “no” if the word was not learnt previously. The instructions again specifically referred to the learning task to minimize participants responding “yes” to the foil words based on familiarity with their phonological forms on the Day 2 and Day 8 test. Each trial began with a 500ms fixation cross before the onset of the word, to which participants had 3000ms to respond. Trials were presented in a pseudorandomised order with the same procedure as Study 3. A different pseudorandomised order was used for each participant on each day of testing.

Association memory. The association memory task tested participants’ recall of the picture associations for the picture-associated words, and memory of no association for the form-only words. The 64 trained novel words were presented via headphones, with three response options presented on the screen: two pictures from the phoneme monitoring task, and an option of ‘none’. For the picture-associated words, one picture was always the correct referent for that word and one picture was the referent for another word from the training task. In the case of the form-only words, both pictures were associated with two of the picture-associated words from the training task. The incorrect pictures presented with each word remained the same across each day of testing, to prevent participants from learning associations by co-occurrences between the picture-associated novel words and their correct referent across the testing days. The location of the two pictures and ‘none’ option on the screen (i.e. left, right, middle) was different for each word on each day of testing. The instructions stated that participants’ task was to remember which words and pictures went together from the training task, and to select ‘none’ if they thought the word did not have an associated picture. Participants responded via keyboard to indicate their choice, and there was no time limit on responses.

7.2.2 Results

7.2.2.1 Phoneme monitoring

Twenty-five participants were included in the phoneme monitoring analysis, due to a program error failing to save the output file for five participants. For the accuracy and reaction time analysis, the 36 exposures to each novel word over the course of the phoneme monitoring task were divided into six blocks of six exposures each. Performance in the phoneme monitoring task is shown in Figure 34. Here and in ANOVA analyses in the subsequent tasks, Greenhouse-Geisser corrected F-statistics, degrees of freedom and p-values are reported where assumptions of sphericity were violated.

Accuracy. The overall error rate in the phoneme monitoring task was 14.23% (SD = 6.14). A repeated-measures ANOVA on percentage accuracy, with the within-subjects factor of Condition (Picture-associated, Form-only) and Block (1-6), and word list as a between-subjects dummy variable (Pollatsek & Well, 1995), revealed no significant main effects of Condition, Block, or any interaction between these factors (all Fs < 1, ps > .5). There was thus no significant difference between the picture-associated and form-only words in terms of accuracy. Because the average rate of target phoneme occurrence across lists was 34%, it was also verified that accuracy was significantly above chance levels of 66% (the average accuracy if participants responded “no” on every trial). Phoneme monitoring accuracy, averaged across all blocks and both conditions, was indeed significantly above chance, $t(24) = 16.09$, $p < .001$.

Reaction times. A repeated-measures ANOVA was run on reaction times from correct trials only (85.77% of trials), again with the within-subjects factor of Condition and Block, and word list as a between-subjects variable. This yielded a significant main effect of Block only, $F(5,100) = 5.51$, $p < .005$, in which responses sped up significantly between the first and final block of training ($t(24) = 3.01$, $p < .05$; Block 1 M = 1160, SD = 124; Block 6 M = 1082, SD = 128). The main effect of Condition was not significant ($F(1,20) = .23$, $p = .64$). However, the Condition x Block interaction was marginally significant, $F(5,100) = 2.14$, $p = .067$; whilst this effect was marginal, due to the speeding-up of phoneme monitoring responses to picture-associated words in Takashima et al. (2014) it was important to verify that phoneme monitoring speed was equivalent for the novel word conditions over the course of training. Paired t-tests between the average reaction time in each condition for each block separately yielded significantly faster reaction times for picture-associated than form-only words in Block 4 only, $t(24) = -2.24$, $p < .05$ (picture-associated M = 1087, SD = 130; form-only M = 1101,

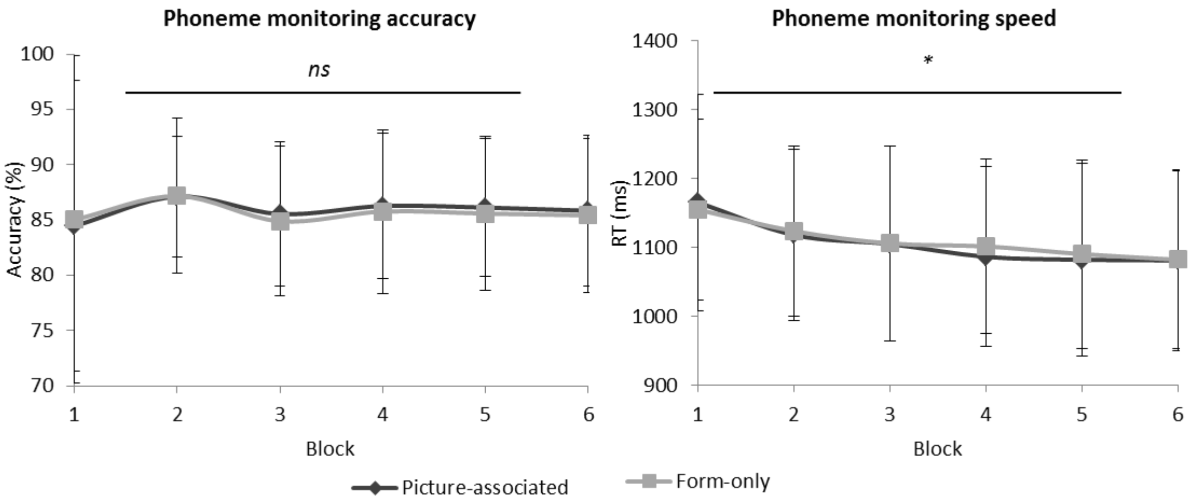

Figure 34. Phoneme monitoring performance.
Accuracy (left panel) and reaction times (right panel) across the six blocks of the phoneme monitoring task. Each block contained six exposures to the novel words. Error bars represent standard deviation of participants' average performance in each block.

SD = 126). The reaction time difference in all other blocks was not significant (ts < 1.5, ps > .15). Along with the lack of a main effect of Condition, this indicated that the speed of target detection did not significantly differ between the two training conditions across the task.

7.2.2.2 Test tasks analysis

Reaction time data from the test tasks were again analysed by fitting linear mixed-effects models to simultaneously account for both by-subjects and by-items effects (Baayen et al., 2008; Baayen & Milin, 2010). The same procedure for building each mixed-effects model was used as in Study 3, and is described in full in section 6.2.2.2. To briefly reiterate, the fixed-effects structure was established using the same procedure of model simplification, where a full model was built including the experimental fixed effects of interest (i.e. condition, day of testing) and the additional covariate fixed effects of trial order, the allocation of participants to item lists, and the grouping of items within lists; only those additional fixed effects which significantly contributed to the model were retained (Baayen et al., 2008). After establishing the fixed effects structure of each model, random slopes for the experimental fixed effects of interest were only included if they significantly improved the fit of the model (unless the inclusion of random slopes prevented the model from converging). In cases where random slopes did not improve the fit of the model but experimental fixed effects of interest were significant, random slopes for that effect were included to verify it remained significant in the presence of item and subject-specific slopes. All models contained random intercepts for subjects and items.

Analyses were conducted in SPSS 21 using the MIXED procedure, and the significance of fixed effects was assessed using the Type III tests of fixed effects. The contribution of random slopes to model fit was determined by comparing the difference in log likelihood values of two competing models to a chi-square distribution, with the degrees of freedom of the number of parameters differing between the models. In each case it is stated in the text which additional fixed factors were included in the model, along with the presence of any random slopes for subjects and items. The F-statistic and p-value associated with each experimental fixed effect in the final model is reported.

All reaction-time analyses were again on log-transformed data to satisfy the assumption of normality and to reduce the effect of outliers (Ulrich & Miller, 1994). Retransformed data is presented in tables and figures for ease of interpretation. Error bars represent standard error for the participant-averaged means (due to being unable to calculate standard error from the data point averages used in the mixed models), corrected for within-participant contrasts where appropriate (Cousineau, 2005).

7.2.2.3 Pause detection

The pause detection data from all thirty participants were included in the analysis. No participants were excessively slow (with reaction times >2.5 SDs from the group-level condition mean) or error prone (>50% errors in one or more conditions) and all were therefore retained. Incorrect trials were excluded, and data were trimmed for reaction times faster than 200ms and slower than 2.5 standard deviations from each participant's conditional mean (on the basis of both pause present and pause absent trials)[26]. 8.15% of trials were excluded in total.

The first analysis assessed whether reaction times to picture-associated and form-only base words changed over consolidation, and whether this change was affected by training condition. A linear mixed-effects model with the fixed effects of Condition (Picture-associated, Form-only), Day of testing (Day 1, Day 2, Day 8), and Pause Presence (Pause Present, Pause absent) with subjects and items as random effects, was fitted to the reaction time data. This fixed effects structure was the same as that employed to analyse the pause detection data in Study 3. The additional covariate

[26] Note that the procedure for data trimming used here was identical to that in the previous chapter, and has been used in extant studies testing lexicalization using pause detection (e.g. Fernandes et al., 2009; Henderson et al., 2012; Henderson, Weighall, & Gaskell, 2013).

fixed effects of trial order, the allocation of participants to item lists, and the grouping of items within lists did not significantly contribute to the model and were thus excluded. The maximal inclusion of random slopes for the main effects of Condition, Day and their interaction prevented the model from converging[27] and were also excluded. The model yielded a significant main effect of Day only, F = 11.63, p < .001, and a significant Condition x Pause Presence interaction, F = 9.78, p < .01. All other main effects and interactions were not significant (Fs <2, ps > .15).

The Condition x Pause Presence interaction was first followed up by fitting a linear mixed-effects model with the fixed effect of Condition (Picture-associated, Form-only) to pause present and pause absent trials separately. In both models the additional covariate fixed effects did not significantly contribute to the model. A significant main effect of Condition was found for pause absent trials only, F = 7.72, p = .01, which remained significant with the inclusion of random slopes for subjects and items for the effect of Condition. Picture-associated base words were responded to more slowly than form-only base words overall (picture-associated pause-absent M = 794, SD = 368; form-only pause-absent M = 762; SD = 371; effect of Condition in pause-present trials F = 1.53, p = .216). This condition effect may have reflected greater sensitivity of the pause-

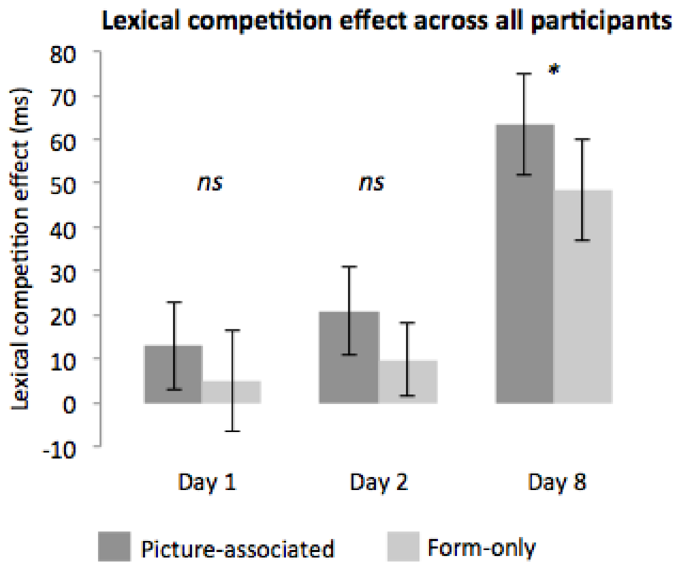

Figure 35. The lexical competition effect in Study 4.
The magnitude of the lexical competition effect on each day of testing, averaged over all data points for participants and items. The error bars show the standard error of the mean corrected for within-subjects comparisons.

[27] A linear mixed effects model is unable to fit to the data when it contains an effects structure which is too complex given the number of datapoints (such that the datapoints allocated to each level of the model are not sufficient for the model to be fitted). This process is referred to as the model being unable to converge.

absent trials to the effect of training condition on lexical competition, or possibly a Type I error, given the suggested sensitivity of pause-present rather than pause-absent trials for probing lexical activation (Mattys & Clark, 2002; Mattys et al., 2005).

The critical main effect of Day was then followed up by comparing responses for both picture-associated and form-only base words between each day of testing. Because both Condition and Pause Presence did not interact with Day in the first mixed model, they were excluded as factors in subsequent analyses assessing only the effect of Day on responses. A linear mixed-effects model compared reaction times between Day 1 and Day 2, with no additional covariate fixed effects contributing to the model. The effect of Day was not significant with the inclusion of random slopes, $F = .64$, $p = .43$. A comparison of responses between Day 2 and Day 8, with no additional covariate fixed effects significantly contributing to the model, yielded a significant fixed effect of Day, $F = 4.97$, $p < .05$, which remained significant in the presence of random slopes for subjects and items. Responses were thus slower on Day 8 than on Day 2 for both the picture-associated and form-only words, but did not significantly differ between Day 1 and Day 2 (Table 7). These results suggested that lexical competition emerged only on Day 8 of testing. This was confirmed by a significant difference between experimental and control base word reaction times on Day 8 only ($F = 10.23$, $p = < .01$, with random slopes for the effect of Day; Day 1: $F = .03$, $p = .86$; Day 2: $F = .29$, $p = .59$; all models with no

Table 7. Pause detection reaction times in Study 4.

	Day 1 test		**Day 2 test**		**Day 8 test**	
	RT ms (SD)	Lexicalization effect (SD)	RT ms (SD)	Lexicalization effect (SD)	RT ms (SD)	Lexicalization effect (SD)
Picture-associated	770 (324)	13 (80)	764 (355)	21 (58)	808 (375)	63 (51)
Form-only	762 (343)	5 (84)	753 (353)	10 (57)	792 (370)	48 (37)
Control	757 (311)		742 (329)		744 (327)	

Note. The lexicalization effect is the difference in milliseconds between the experimental (picture-associated and form-only) base words and control base words reaction times on each day. A larger lexicalization effect indicates slower responses to the experimental base words with a newly-learnt competitor compared to control base words with no new competitor, suggesting that the newly-learnt words have entered into lexical competition with their existing base words, thus slowing reaction times. The standard deviation of the lexicalization effect from the data-point averages could not be calculated, and the standard deviation is thus from the participant averages.

additional covariate fixed effects, or random slopes for Day 1 and Day 2).

In sum, there was thus a significant lexical competition effect on Day 8 of testing, for both picture-associated and form-only words, indicating that training condition did not affect the time-course of lexicalization. No evidence of lexical competition was observed on Day 1 or Day 2. Figure 35 shows the lexical competition data.

Recognition memory and lexical competition. The pause detection analysis indicated that lexical competition effects did not emerge until Day 8 (for both picture-associated and form-only words). However, lexical competition effects were present on Day 2 in the Takashima et al. (2014) study (for form-only words only). One possibility for this discrepancy was due to weaker initial encoding of the novel words in the current study due to learning 64 items on Day 1, compared to only 40 items to learnt in Takashima et al. (2014). The next analysis therefore considered whether participants with greater recognition memory of the novel words on Day 1 (immediately after learning, indicating stronger encoding) would subsequently show lexical competition on Day 2.

To test this, a median split was conducted on participants' average recognition memory accuracy (measured by *d'*) on Day 1. This yielded a low recognition group with a mean d' of 1.00 (SD = .37) and a high recognition group with a mean d' of 2.22 (SD = .72; median = 1.44). Participants' *lexicalization effect*, the difference between the picture-

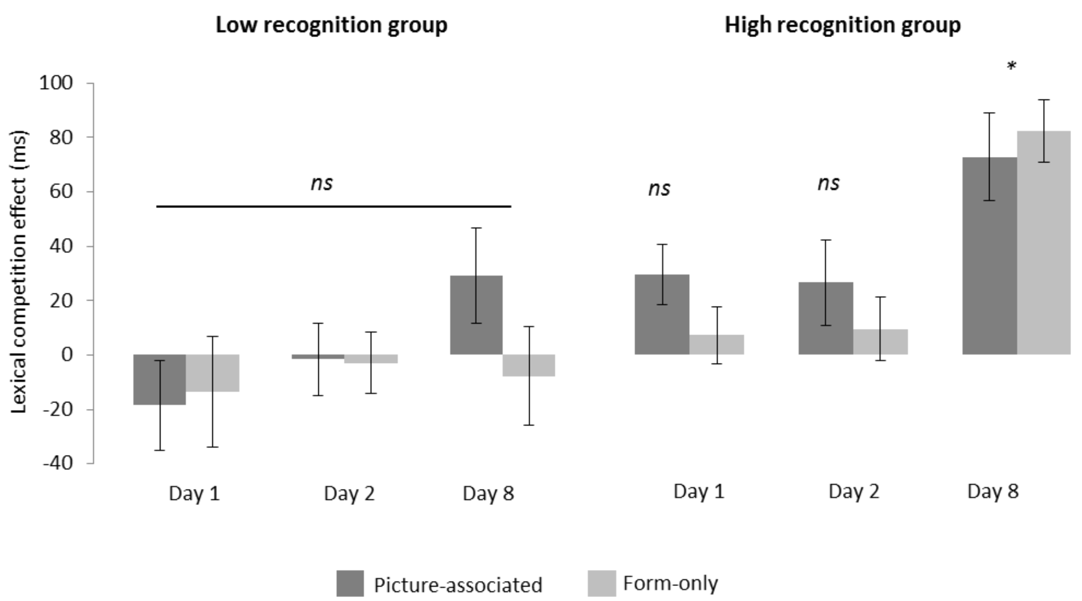

Figure 36. The lexical competition effect in Study 4, by recognition memory group.
The magnitude of the lexical competition effect on each day of testing, split by whether participants had high or low recognition *d'* of the novel words immediately after training. The error bars show standard error of the mean corrected for within-subjects comparisons.

associated and form-only base word reaction times and the control base word reaction times on each day of testing, was submitted to a mixed ANOVA with within-subjects factors of Condition (Picture-associated, Form-only) and Day (Day 1, Day 2, Day 8), with Recognition Group (Low, High) and item list as a between-subjects factor. This yielded a significant within-subjects effect of Day, $F_1(2,40) = 3.6$, $p < .05$, which was qualified by a Condition x Day x Recognition Group interaction, $F_1(2,40) = 4.87$, $p < .05$. The between-subjects main effect of Recognition Group did not reach significance ($F_1 = 3.01$, $p = .1$), and all other within-subjects main effects and their interactions were not significant (Fs < 1.1, ps > .4)[28].

The three-way interaction indicated that the effect of Condition and Day on lexicalization differed between the recognition memory groups, suggesting that memory strength influenced the time-course of lexicalization. To verify this, the three-way interaction was followed up by separate Condition (2) x Day (3) mixed ANOVAs on each recognition group separately, with item list as a between subjects variable. In the high recognition group this yielded a significant main effect of Day, $F_1(2,20) = 5.31$, $p < .05$ (all other Fs < 2.02, ps > .16). Planned comparisons revealed no significant increase in the magnitude of the lexical competition effect between Day 1 and Day 2 ($t_1(14) = .26$, $p = .80$), but a significant increase between Day 2 and Day 8 ($t_1(14) = -3.14$, $p < .01$; Day 1 mean lexicalization effect = 18ms, SD = 63; Day 2 M = 18, SD = 59; Day 8 M = 77, SD = 98). It was further verified that reaction times to the experimental and control base words did not differ on Day 1 or Day 2, but only on Day 8 of testing (Day 1: $t_1(14) = 1.05$, $p = .31$; Day 2: $t_1(14) = 1.04$, $p = .32$; Day 8: $t_1(14) = 3.62$, $p < .01$), with significantly slower responses to experimental than control base words. Participants with high recognition memory therefore showed lexical competition on Day 8 of testing, with no lexicalization on Day 2.

In contrast to the high recognition group, the low recognition group showed no main effect of Day ($F_1(2,20) = .58$, $p = .57$), with only a trend-level Condition x Day interaction, $F_1(2,20) = 2.91$, $p = .08$. It was therefore the case that only the high recognition memory participants showed a statistically significant increase in the

[28] The exception to this was the within-subjects main effect of Condition, which showed trend-level significance, $F(1,20) = 3.36$, $p = .082$.

Table 8. Pause detection reaction times split by recognition memory group.

	High recognition memory group					
	Day 1 test		**Day 2 test**		**Day 8 test**	
	RT ms (SD)	Lexicalization effect (SD)	RT ms (SD)	Lexicalization effect (SD)	RT ms (SD)	Lexicalization effect (SD)
Picture-associated	720 (158)	29 (18)	730 (234)	26 (18)	755 (219)	73 (78)
Form-only	698 (153)	7 (63)	714 (244)	10 (59)	764 (213)	82 (98)
Control	691 (141)		704 (210)		682 (145)	
	Low recognition memory group					
	Day 1 test		**Day 2 test**		**Day 8 test**	
	RT ms (SD)	Lexicalization effect (SD)	RT ms (SD)	Lexicalization effect (SD)	RT ms (SD)	Lexicalization effect (SD)
Picture-associated	727 (172)	-20 (91)	715 (214)	2 (60)	764 (231)	29 (73)
Form-only	732 (164)	-15 (100)	712 (215)	-1 (51)	725 (246)	-9 (78)
Control	747 (190)		713 (213)		735 (247)	

Note. These are the participant-averaged means and standard deviations. The lexicalization effect is again the difference in milliseconds between the experimental and control base word RTs.

lexicalization effect after one week of consolidation[29]. These findings thus indicated that whilst memory strength constrained subsequent lexicalization, it did not contribute to a lexicalization effect on Day 2 of testing (Figure 36; Table 8).

Summary. In sum, the analysis of the lexical competition effect, split by whether participants had high or low recognition memory of the novel words immediately after learning, suggested that initial encoding affected subsequent lexicalization. Only participants with *high* recognition memory of the novel words after learning showed a statistically significant increase in the magnitude of the lexical competition effect over consolidation, replicating the group-level analyses with a lexical competition effect emerging on Day 8 only. However, no lexical competition was found on Day 2 for the high recognition memory group. Finally, the *low* recognition memory group showed no statistically significant increase in the lexical competition effect over consolidation. The Day 8 lexicalization observed in the group-level analysis was thus driven by the

[29] Note that the same analysis in a linear mixed-effects model yielded identical results to those reported here, whereby the high recognition memory group showed a significant effect of competitor acquisition on Day 8 only ($F = 13.37$, $p = .002$), whilst the low recognition memory group did not ($F = .96$, $p = .34$).

participants with good explicit knowledge of the novel words immediately after learning, but these participants failed to show lexical competition effects on Day 2.

7.2.2.4 Shadowing

The onset of shadowing responses was again marked using Check Vocal (Protopapas, 2007), using the criteria for marking speech onsets described by Rastle et al. (2005). Reaction times were measured from the onset of the to-be-repeated word to the onset of participants' response. The same error criteria as Study 3 were used, whereby erroneous responses were considered to be omissions (i.e. trials with no response) and incorrect productions, in which participants often replaced a syllable towards the end of the target word with another syllable (e.g. saying *albatran* instead of the correct *albatrum*). Erroneous trials were rare (0.32%) and were excluded from the shadowing analysis. Responses faster than 300ms were additionally excluded (0.13%), and no responses were slower than 2500ms.

Shadowing reaction times were first fitted with a linear mixed-effects model with the fixed effects of Condition (Picture-associated, Form-only) and day of testing (Day 1, Day 2, Day 8) to assess if training condition or consolidation time impacted response latencies. The model included the additional fixed effect of trial order only, which significantly contributed to the model. A maximal random effects structure with random slopes for the fixed effects of Condition, Day, and the Condition x Day interaction significantly improved model fit, $\chi^2(6) = 48.53$, $p < .001$, and was therefore included. The model showed no significant main effect of Day ($F = 2.07$, $p = .14$), Condition ($F = .12$, $p = .73$), or interaction ($F = .463$, $p = .63$). As neither training condition nor consolidation time influenced shadowing latencies, response times for all trained novel words were compared to response times for untrained words collapsed across each day of testing, in a model with the fixed effect of Training (Experimental trained vs. Control untrained) only. No additional fixed effects contributed to the model, but random slopes for the fixed effect of Training significantly contributed to the model and were therefore included, $\chi^2(2) = 8.89$, $p < .05$. The effect of training did not reach significance ($F = 1.34$, $p = .27$). There was a numerical trend towards a learning effect on each day of testing, however (Table 9), with faster shadowing latencies for trained novel words than untrained novel words.

In sum, there was no effect of training condition or consolidation time on shadowing latencies. Shadowing reaction times indicated a numerical trend towards

Table 9. Shadowing reaction times in Study 4.

	Day 1 test		Day 2 test		Day 8 test	
	RT ms (SD)	Learning effect (SD)	RT ms (SD)	Learning effect (SD)	RT ms (SD)	Learning effect (SD)
Picture-associated	1097 (174)	31 (27)	1057 (150)	38 (38)	1045 (160)	42 (33)
Form-only	1094 (176)	34 (30)	1058 (155)	37 (25)	1047 (157)	40 (26)
Untrained	1128 (176)		1096 (153)		1087 (163)	

Note. The learning effect is the trained novel word shadowing RT (in milliseconds from word onset) subtracted from the untrained novel word shadowing RT, for each training condition on each day of testing. A positive learning effect thus indicates faster shadowing latencies for trained words than untrained words. The standard deviation is that of the learning effect across participants.

faster responses for trained than untrained items on each day of testing, but this did not reach significance.

7.2.2.5 Free recall

The use of ANOVAs for analysis of categorical data. The free recall task involved categorical responses (where participants could either recall a word or not). The use of ANOVAs has been suggested as inappropriate for the analysis of categorical data, as they can yield spurious null results and spurious significance (Jaeger, 2008). Mixed logistic regression was thus suggested by Jaeger (2008) as appropriate for the analysis of categorical data, permitting the combined modelling of random subject and item effects. However, it is not possible to implement mixed logistic regression in SPSS 21, as used for the analyses in this thesis. Combined by-participants and by-items ANOVAs on arcsine-transformed percentage accuracy were chosen as an alternative approach for analysis of the free recall data. It is recognised that mixed logistic regression may have been a more conservative approach, but three considerations mitigate the possibility of the findings reflecting spurious results.

Firstly, a substantial number of recent psycholinguistic studies analysing categorical data (in most cases free recall and meaning recall) have used F1 and F2 ANOVAs, supporting this as an appropriate approach to adopt (Bakker et al., 2014; Davis et al., 2009; Dumay & Gaskell, 2012; Henderson, Weighall, & Gaskell, 2013; Henderson et al., 2014; Takashima et al., 2014; Tamminen et al., 2010; Tamminen et al., 2013; but cf. Gaskell, Warker, Lindsay et al., 2014 and Tamminen & Gaskell, 2013, for the use of mixed logistic regression). Second, the percentage accuracy scores in the free recall and association memory tasks were arcsine transformed to better meet the assumption of normality for an ANOVA (e.g. as in Tamminen et al., 2010). Third, because the current study explicitly predicted the obtained effects in free recall, which are also consistent with the previous studies (e.g. Henderson, Weighall, & Gaskell; Takashima et al., 2014) this goes some way towards mitigating the possibility of the results reflecting inflated Type I and/or Type II effects from the use of ANOVAs to analyse categorical data.

Free recall analysis. The free recall data were analysed by calculating the percentage of total words recalled correctly. These percentages were arcsine-transformed to better meet the assumption of normality for percentage/proportion data, and submitted to separate by-participants (F1) and by-items (F2) ANOVAs. Both ANOVAs included the within-subject factors of Condition (Picture-associated, Form-only) and Day of testing (Day 1, Day 2, Day 8), with the between-subjects factor of item list in the by-participants analysis, and the grouping of items within lists in the by-items analysis (Pollatsek & Well, 1995). A significant main effect of Day was present, $F_1(2,50)$ = 91.66, $p < .001$, $F_2(2,310)$ = 128.01, $p < .001$. Recall increased significantly between both Day 1 and Day 2, $t_1(29) = -8.87$, $p < .001$, $t_2(159) = -9.48$, $p < .001$, and Day 2 and Day 8, $t_1(29) = -5.97$, $p < .001$, $t_2(159) = -6.59$, $p < .001$. There was additionally a main effect of Condition, which was significant by items but not by participants, $F_1(1,25) = 1.38$, $p = .25$, $F_2(1,155) = 5.55$, $p < .05$. The by-item recall of picture-associated words was higher than form-only words overall (picture-associated by-items M = 15.45%, SD = 11.87; form-only M = 12.95%, SD = 12.84; $t_2(159) = -2.25$, $p < .05$). The interaction between training condition and day of testing did not reach significance ($F_1 = 1.59$, $p = .21$; $F_2 = 2.35$, p = .097). In sum, the free recall analysis indicated a significant consolidation benefit in the percentage of items recalled both 24 hours and one week after training, with a recall advantage for picture-associated words that was significant by items only. Figure 37 and Table 10 show the untransformed percentages.

7.2.2.6 Recognition memory

Recognition d'. Accuracy in the recognition of the trained words was analysed using signal detection measures (*d'*, Snodgrass & Corwin, 1988). Novel word recognition was measured by subtracting *z*-transformed rates of false alarms from *z*-transformed rates of hits. Trials with no response (0.69% of all trials), and responses faster than 300ms and slower than 2500ms (0.92% of all trials) were excluded from participants' *d'* calculation. Recognition *d'* was then submitted to separate Condition (Picture-

Table 10. Declarative memory task performance in Study 4.

	Day 1 test		Day 2 test		Day 8 test	
Free recall	Accuracy (%)	RT	Accuracy (%)	RT	Accuracy (%)	RT
Picture-associated	6.56 (7.54)	-	16.46 (11.63)	-	23.33 (14.44)	-
Form-only	6.35 (5.34)	-	12.71 (8.53)	-	19.79 (13.57)	-
Recognition memory	Accuracy (d')	RT	Accuracy (d')	RT	Accuracy (d')	RT
Picture-associated	1.45 (0.81)	1295 (332)	2.24 (1.17)	1206 (321)	2.65 (1.32)	1121 (294)
Form-only	1.51 (0.80)	1285 (341)	2.25 (1.16)	1204 (318)	2.80 (1.48)	1135 (306)
Association memory	Accuracy (%)	RT	Accuracy (%)	RT	Accuracy (%)	RT
Picture-associated	69.86 (21.16)	1633 (768)	59.36 (20.84)	1377 (663)	52.54 (21.25)	1353 (662)
Form-only	79.36 (19.43)	1705 (753)	84.58 (18.12)	1400 (647)	81.11 (19.40)	1335 (686)

Note. These data are the by-participant averages, with standard deviation shown in brackets.

associated, Form-only) by Day of testing (Day 1, Day 2, Day 8) repeated-measures ANOVAs for participants (F1) and items (F2). The between-subjects factor of item list was again included as a dummy variable in the by-participants analysis, with the grouping of items within lists as the dummy variable in the by-items analysis. There was a significant effect of Day only, $F_1(2,50) = 36.37$, $p < .001$, $F_2(2,310) = 76.77$, $p < .001$. Recognition sensitivity increased between both Day 1 and Day 2, $t_1(29) = -5.84$, $p < .001$, $t_2(159) = -6.38$, $p < .001$, and between Day 2 and Day 8, $t_1(29) = -3.37$, $p < .05$, $t_2(159) = -6.12$, $p < .001$. There was no significant effect of Condition on recognition sensitivity, or a Condition x Day interaction (Fs < 1, ps > .4). There was thus a significant enhancement of recognition memory on each day of testing in both conditions, with no impact of training condition. Table 10 shows the average recognition d' over subjects and items.

Recognition speed. Reaction times were analysed by fitting a linear mixed-effects model to correct responses only (81.29% of trials) to both trained and foil items in each condition[30]. Trials with no response (0.69%), and responses faster than 300ms

[30] Note that a model fitted to correct responses to trained words only ("hits") yielded an identical result.

and slower than 2500ms (0.92%) were also excluded prior to analysis. The model included fixed effects of Condition (Picture-associated, Form-only) and Day of testing (Day 1, Day 2, Day 8), with subjects and items as random effects. Only the additional fixed effect of trial order significantly contributed to the model. A maximal random effects structure including both experimental fixed effects and their interaction prevented the model from converging and was therefore excluded. A significant main effect of Day was present, $F = 15.00$, $p < .001$, with the inclusion of random slopes for the fixed effect of Day. Neither the main effect of Condition nor the Condition x Day interaction reached significance ($Fs < 2.2$, $p > .1$). A model contrasting recognition speed on Day 1 and Day 2, with the experimental fixed effect of Day (Day 1 vs. Day 2), and the additional fixed effect of trial order only, indicated faster responses on Day 2 ($M = 1205$, $SD = 319$) than Day 1 ($M = 1290$, $SD = 337$), $F = 6.38$, $p < .05$, which remained significant with random slopes for the fixed effect of Day. A model comparing Day 2 and Day 8, again with the additional fixed factor of trial order only, indicated that recognition speed further benefited from consolidation between Day 2 and Day 8, $F = 13.55$, $p = .001$ (Day 8 $M = 1128$, $SD = 299$), which remained significant with the inclusion of random slopes for the effect of Day. Table 10 shows the retransformed recognition reaction times by training condition and day. In sum, the reaction time analysis indicated that recognition speed was increasingly faster on each day of testing, and was unaffected by training condition.

7.2.2.7 Association memory

Accuracy. The association memory test assessed participants' recall of the picture referent for the picture-associated words, and memory of 'no association' for the form-only words. Because three response categories were present in the task (either picture or 'none') accuracy was scored using the percentage of correct responses for each novel word type (rather than *d'*). The association memory data were thus categorical (because participants could correctly remember a word's association or not). For this reason identical considerations to those for the free recall data applied, explained in 7.2.2.5, and the association memory data were thus analysed with by-participant and by-item ANOVAs (as in e.g. Henderson, Weighall, & Gaskell, 2013; Tamminen et al., 2013). The percentages were again arcsine transformed and, as with the free recall data, the obtained findings were also consistent with both the predictions and previous reports (e.g. Tamminen & Gaskell, 2008), which mitigated the possibility of the findings reflecting spurious results from the use of ANOVAs on categorical data.

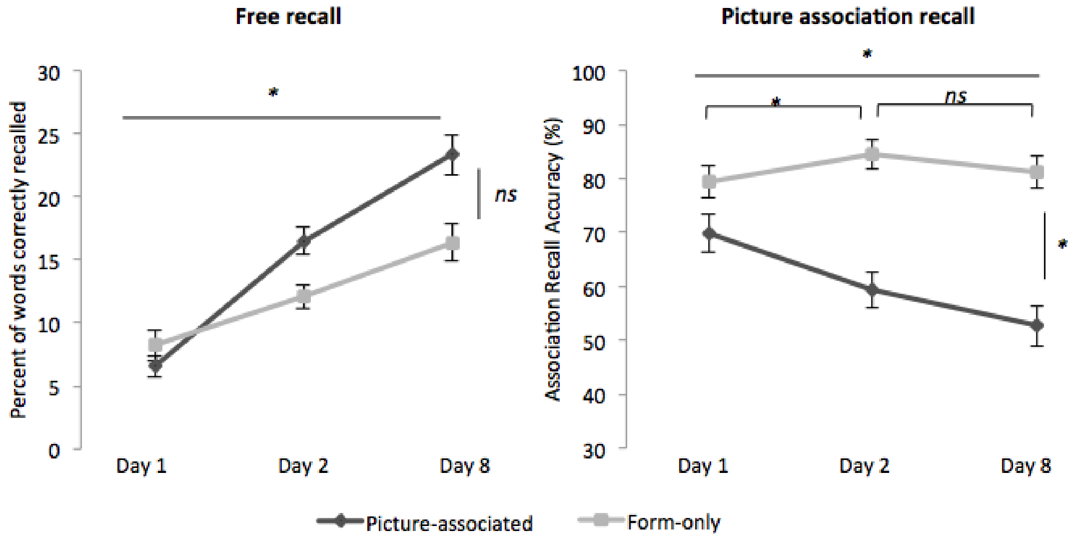

Figure 37. Free recall and picture association memory performance.

Free recall performance (left panel) and picture association memory performance (right panel) across each Day of testing. Both plots show the participant-averaged means and standard errors.

Trials faster than 300ms were excluded (0.31%). The arcsine-transformed percentage accuracy scores were analysed with repeated-measures ANOVAs by-participants (F1) and by-items (F2) including the within-subjects factors of Condition (Picture-associated, Form-only) and Day (Day 1, Day 2, Day 8), and the between-subjects factor of item list in the by-participants analysis, and the grouping of items within lists in the by-items analysis. The analysis yielded significant main effects of Condition, $F_1(1,25) = 34.01$, $p < .001$, $F_2(1,155) = 187.21$, $p < .001$, and Day, $F_1(2,50) = 12.56$, $p < .001$, $F_2(2,310) = 17.90$, $p < .001$ (see Table 10, and Figure 37). Both picture-associated and form-only memory showed decreased between Day 2 and Day 8. These main effects were qualified by a significant Condition x Day interaction, $F_1(1.56, 38.87) = 7.35$, $p < .01$, $F_2(1.91, 296.22) = 18.11$, $p < .001$. The interaction was followed up by two-way ANOVAs to assess the Condition x Day interaction separately on Day 1 to Day 2, and on Day 2 to Day 8. The interaction was significant from Day 1 to Day 2 ($F_1(1,25) = 23.96$, $p < .001$, $F_2(1,155) = 25.73$, $p < .001$) but not from Day 2 to Day 8 ($F_1(1,25) = .17$, $p = .69$; $F_2(1,155) = .12$, $p = .73$). Pairwise comparisons revealed a decrease in association memory performance from Day 1 to Day 2 for picture-associated words, whilst performance for form-only words increased ($t_1(29) = 4.70$, $p < .001$, $t_2(159) = 5.04$, $p < .001$). The decrease in association memory from Day 2 to Day 8 was equivalent for picture-associated and form-only words (ts < .5, ps > .6). From Day 2 to Day 8, a main effect of condition indicated worse recall for picture-associated words overall ($F_1(1,25) = 44.11$, $p < .001$; $F_2(1,155) = 199.38$, $p < .001$), and worse recall for Day 8 than Day 2 words overall

($F_1(1,25) = 16.47$, $p < .001$; $F_2(1,155) = 21.95$, $p < .001$). The association memory accuracy analyses thus indicated a decrease in picture-associated memory from Day 1-Day 2, whilst form-only memory increased. Between Day 2 and Day 8 association memory for both picture-associated and form-only words showed an equivalent decrease, with poorer performance for the picture-associated words and Day 8 test overall.

Reaction times. Correct responses only were analysed (71.56% of trials) and responses faster than 300ms were removed (0.31% of trials). Log-transformed reaction times were analysed by fitting a linear mixed-effects model with the fixed effects of training Condition (Picture-associated, Form-only) and Day (Day 1, Day 2, Day 8), with only the additional fixed effect of trial order significantly contributing to the model. A maximal random effects structure with random slopes for Condition, Day and their interaction significantly improved the fit of the model and was therefore included, $\chi^2(6) = 183.89$, $p < .001$. This model yielded a significant main effect of Day, $F = 43.27$, $p < .001$, which was qualified by a Condition x Day interaction, $F = 3.42$, $p < .05$. The two-way interaction was followed up by assessing the effect of Day on each condition separately. The picture-associated responses times showed a main effect of Day, $F = 20.60$, $p < .001$, significant with random slopes for the fixed effect of Day and the inclusion of trial order as an additional fixed effect. Responses significantly sped up between Day 1 and Day 2, $F = 24.90$, $p < .001$, but not between Day 2 and Day 8, $F = .297$, $p = .59$ (with both models including the additional fixed effect of trial order, and random slopes for the effect of Day). Conversely, a main effect of Day on the form-only words, $F = 49.70$, $p < .001$, resulted from a speeding up of responses between both Day 1 and Day 2, $F = 62.67$, $p < .001$, and between Day 2 and Day 8, $F = 4.10$, $p = .05$ (all models with the additional fixed effect of trial order significantly contributing to the model, and with random slopes for the effect of Day). The reaction time analysis thus indicated that access to meanings for the picture-associated words sped up only between Day 1 and Day 2, with no improvement with one week of consolidation, whereas rejecting any possible referent for the form-only words sped up between both Day 1 and Day 2, and Day 2 and Day 8. Table 10 shows the retransformed reaction times.

7.2.2.8 Contributions to lexicalization on Day 8

The pause detection analyses indicated that training condition did not impact upon the time course of lexicalization, where both picture-associated and form-only novel words showed lexical competition effects after one week of consolidation. Indeed, the critical extension of the current study from Takashima et al. (2014) was to promote phonological processing of the picture-associated words during learning by i) instructing participants to learn the forms of the novel words, with no goal to learn the word-picture associations, and ii) coinciding picture onset with word onset for the picture-associated words. Given the equivalent time course of lexicalization for picture-associated and form-only words, compared to previous reports of semantically-associated words showing a delayed time-course relative to those acquired as phonological forms only (Dumay et al., 2004; Takashima et al., 2014; cf. Henderson, Weighall, & Gaskell, 2013), correlational analyses thus aimed to firstly determine the contribution of phonological processing during training to lexicalization after one week. The first correlational analysis looked for a relationship between phoneme monitoring accuracy during training, as an index of participants' engagement with the phonological forms of the novel words during acquisition, and the magnitude of the lexical competition effect on Day 8. Given that only participants *high* in recognition memory after training showed a significant lexical competition effect after one week, a second correlation analysis further assessed whether the strength of recognition memory on Day 1 was supported by phoneme monitoring accuracy during training, and thus subsequently supported lexicalization.

One participant was removed from these analyses due to having a lexical competition effect and a d' score > 2.5 standard deviations from participants' mean, and being a clear outlier on the scatterplots. All correlations were bivariate, and each measure was averaged across both picture-associated and form-only words due to no effect of training on phoneme monitoring accuracy, recognition accuracy or lexical competition being present in the main analyses. The first correlation analysis indicated that the contribution of phoneme monitoring accuracy to lexical competition on Day 8 was not significant, $r(24) = .25$, $p = .25$. However, the second correlation analysis indicated that phoneme monitoring accuracy was positively correlated with recognition memory immediately after learning, where participants with greater phoneme monitoring accuracy during the training task showed greater recognition memory accuracy in the Day 1 test, $r(24) = .67$, $p < .001$. Because the second correlation suggested that higher phoneme monitoring accuracy was tied to stronger recognition memory immediately after learning, it was assessed whether recognition memory subsequently contributed to lexicalization after one week (as suggested by the median split analyses). Recognition memory accuracy on Day 1 was indeed positively correlated with the magnitude of the lexical competition effect on Day 8, r(29) = .37, p < .05. These correlational analyses thus suggested that stronger recognition memory immediately after learning was tied to higher phoneme monitoring accuracy, and stronger recognition memory subsequently supported lexicalization after one week of consolidation. Figure 38 presents scatterplots of these correlations.

A second question was then whether lexicalization of the picture-associated words after one week was also tied to a decrease in memory of the associated pictures. A previous report of an increase in the semantic integration of novel words over the course of one week, in parallel with a decline in explicit recall of the novel word meanings (Tamminen & Gaskell, 2013), suggested that the successful integration of new and existing knowledge may partially be tied to a loss of episodic knowledge associated with novel words. The final correlational analysis thus assessed whether the emergence of lexical competition on Day 8 for the picture-associated words specifically was tied to a parallel decrease in explicit memory of the picture associations (cf. Dumay & Gaskell, 2007). A bivariate correlation tested the relationship between the change in the lexical competition effect for picture-associated words from between Day 2 and Day 8, the period over which lexicalization emerged, and the change in association memory for the

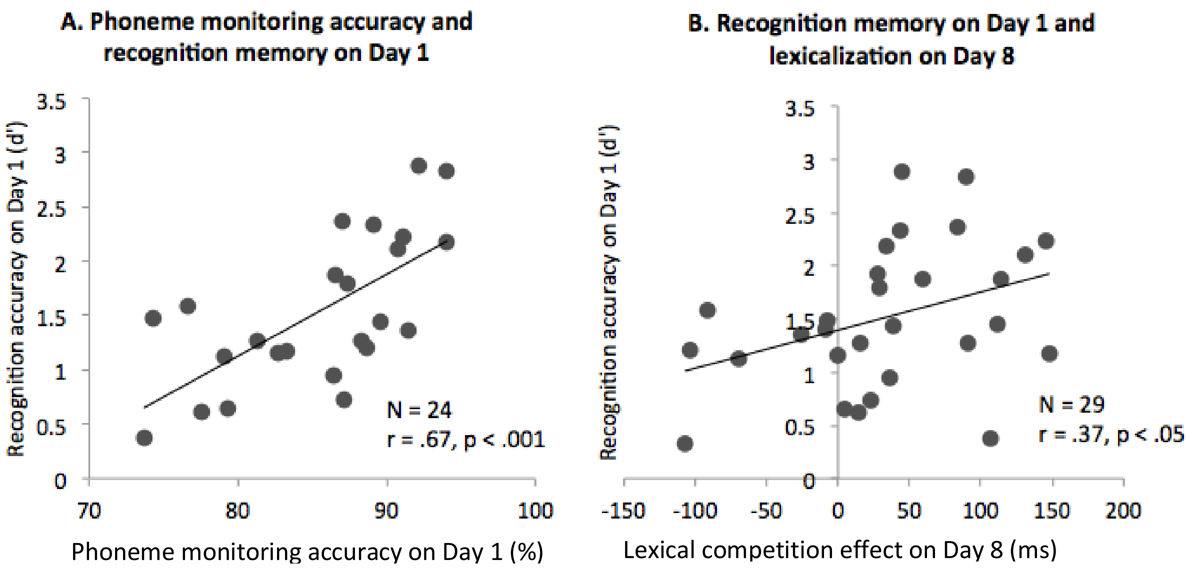

Figure 38. Relationship between phoneme monitoring, recognition memory and lexicalization.
A) The relationship between phoneme monitoring accuracy and recognition memory at the immediate test, and B) the relationship between recognition memory at the immediate test and the magnitude of the lexical competition effect after one week of consolidation. Each data point is a participant's average score across both form-only and picture-associated words.

picture-associated words between Day 2 and Day 8. The correlation was not significant, $r(29) = -.18$, $p = .36$. There was thus no significant relationship between a loss of explicit association memory for the picture-associated words and their subsequent entry into lexical competition.

7.3 Discussion

Study 4 sought to investigate whether the time course of lexicalization could be equated for words with and without a semantic referent, when phonological processing was recruited sufficiently well during training. This question was motivated by the consideration that a slower lexicalization time course for semantically-associated words in two previous adult studies (Dumay et al., 2004; Takashima et al., 2014), and Study 3 in this thesis, could have partially been due to a reduced degree of phonological processing during learning (Ruz & Nobre, 2008; Yoncheva et al., 2010) from a task focus on learning word-meaning mappings. In an extension of the method used by Takashima et al. (2014), participants thus learnt novel words in a phoneme monitoring task, where half of the words had a consistent picture association, and half were phonological forms in isolation. Critically, however, participants were instructed to learn the novel word forms, with no explicit instruction to learn the picture referents for the picture-associated words. It was predicted that a greater degree of processing allocated to phonology than meaning during learning would support the acquisition and lexicalization of novel words both with and without an associated referent.

Overall, the study yielded three key findings. First, an equivalent lexicalization time-course for the picture-associated and form-only words was observed, with both novel word sets entering into lexical competition after one week of consolidation. Second, consistent with the proposal of phonological processing supporting novel word acquisition, a positive correlation between phoneme monitoring accuracy (as a measure of phonological processing during learning) and recognition memory at the immediate test suggested that greater phonemic attention during acquisition supported stronger new word representations; however, there was no association between phoneme monitoring accuracy and the magnitude of the lexical competition effect. Further, recognition memory immediately after learning constrained lexicalization, where participants with stronger initial recognition showed larger lexical competition effects one week later. Third, there was an additional consolidation benefit for measures of declarative word knowledge in recognition memory and free recall, but with no overall semantic benefit for the picture-associated words. Taken together, the current study suggests that the initial acquisition of new words can impact upon the subsequent consolidation and integration of new lexical representations.

7.3.1 Consolidation of lexical and declarative word knowledge

Previous evidence of task instructions influencing attentional focus to different levels of linguistic representations (Ruz & Nobre, 2008; Yoncheva et al., 2010), and the utilization of the phonological structure of words for lexical competition in spoken word recognition (e.g. Marslen-Wilson, 1987), led to the hypothesis that novel words may require a certain degree of phonological processing during acquisition to subsequently enter into lexical competition. Specifically, it may be the case that novel words learnt with semantic associations must also recruit phonological processing sufficiently well during training to prevent a delay in the lexicalization time course (as in Dumay et al., 2004)[31]. In the current study participants were thus given instructions to learn the novel word forms, with no explicit goal of learning the word-picture associations for the picture-associated words, in contrast to Takashima et al. (2014). Slower pause detection latencies, indexing lexical competition, emerged for both novel word conditions after one week of consolidation (on Day 8). The picture-associated words were therefore not delayed relative to the form-only words in their entry into lexical competition, suggesting that the degree of processing allocated to the phonological forms in the current study may have supported lexicalization of the picture-associated words, relative to Takashima et al. (2014).

An important issue in interpreting these findings is the emergence of lexicalization after one week of consolidation, rather than the typically observed 24 hours (e.g. Davis et al., 2009; Dumay & Gaskell, 2007, 2012; Henderson, Weighall, et al., 2013; Takashima et al., 2014; cf. Fernandes et al., 2009; Lindsay & Gaskell, 2013; Tamminen et al., 2010). The key consideration here is whether the data reflect a delay in the form-only words' lexicalization, rather than more efficient lexicalization of the picture-associated words relative to Dumay et al. (2004) and Takashima et al. (2014). Lexicalization may have emerged over one week in the current study due to relatively weak representations of the newly-learnt words, from exposure to 64 novel items in a single session compared to the 40 used by Takashima et al. (2014) (and 36 typically

[31] It is important to emphasise that whilst the focus in this chapter is on phonological processing, many other factors could contribute to the time-course and success of lexicalization. These will be discussed in turn later in this chapter and in the following chapter.

being used in previous lexicalization studies). Whilst participants with higher recognition memory scores also showed lexicalization only after one week, recognition memory at the 24 hour test was substantially below that of Takashima et al. (current study: 74.27%[32]; Takashima et al.: 94.90%). Weaker representations of the novel words in the current study may therefore have contributed to a delay in the lexicalization time-course of the form-only words. Critically, any memory constraints that affected the form-only words would have equally affected the picture-associated words, as there was no recognition memory benefit for the picture-associated words. This suggests that if the picture-associated words had a slower lexicalization time-course by virtue of learning a form-meaning mapping, the picture-associated words should have showed lexical competition at a later time point than the form-only words. The current findings thus suggest that there is no lexicalization advantage for form-only novel words when equating the learning goals between form-only and picture-associated words, in contrast to Takashima et al. (2014). It will nonetheless be valuable in future work to assess whether the current training paradigm can enable the lexicalization of semantically-associated words after only one night of consolidation, by using fewer items to enable stronger recognition memory after learning.

Declarative memory of the novel word forms was also enhanced by consolidation, as indicated by the recognition memory and free recall measures. Both 24 hours of consolidation and an additional six days enhanced recognition accuracy, recognition speed, and the percentage of trained novel words recalled. Due to the multiple test points in the current study, however, one concern is whether the novel words were benefited by memory consolidation or simply through repeated exposure during testing (e.g. Karpicke & Roediger, 2008). Although the contribution of multiple tests to memory improvement is a possibility, a recognition memory benefit for consolidated words has also been found with a single test session the day after training (relative to words trained immediately before testing) in Davis et al. (2009), and also in Study 3 in this thesis. Further, the testing effect on novel words was assessed by Tamminen et al. (2010), by including only a subset of newly-learnt words in an immediate test, and all words in subsequent 24 hour and one week tests. No effect of additional exposure in the immediate test was observed in the two subsequent tests (in terms of word recall, recognition memory and lexical competition), suggesting that additional exposure did not substantially enhance declarative word memories above the

[32] This value was calculated using the same method for calculating the recognition memory percentages reported in Takashima et al. (2014), pp 270.

improvement observed after consolidation without repeated testing. Tamminen et al. (2010) also observed that faster recognition memory RTs were present only after sleep and not an equivalent time of wakefulness. The degree of recognition improvement was tied to slow-wave sleep duration, further suggesting that offline consolidation (in this case involving sleep) was the critical factor enhancing recognition speed. Whilst the benefit of repeated testing cannot be ruled out, the data of Davis et al. (2009), Tamminen et al., (2010), and Study 3 provide convergent evidence to suggest that declarative knowledge in the current study was benefited at least in part by consolidation.

Whilst there are several reports of both recognition and free recall benefiting from 24 hours of consolidation (e.g. Brown et al., 2012; Davis et al., 2009; Henderson, Weighall, & Gaskell, 2013; Henderson et al., 2014; Dumay et al. 2004 Exp. 2; cf. Bakker et al., 2014) it is not always the case that both continue to be enhanced by a further six days and nights of consolidation. Dumay and Gaskell (2012) observed no further enhancement of recognition memory after 24 hours of consolidation, but free recall continued to improve one week after learning. The lack of a further improvement in recognition memory after the 24 hour test could reflect ceiling effects from the use of 2AFC in Dumay and Gaskell (2012), whereas the old/new recognition test used here may have been more challenging and thus less susceptible to such ceiling effects. Further, given the substantial number of items to learn in the current study, weaker memory traces of the novel words could have been further strengthened by consolidation up to one week after learning, in line with the proposal of a greater sleep-based consolidation benefit for weaker than stronger memories (Diekelmann et al., 2009; but cf. Dumay & Gaskell, 2012).

Declarative memory enhancement co-occurring with the emergence of lexical competition raises the question of whether the observed lexical competition effects reflect the engagement of new words with existing lexical items, or a slowing of responses to existing words due to the consolidation of episodic traces. Such an alternative episodic account of lexical competition effects was proposed by Qiao et al. (2009), positing that the slowing of reaction times to existing words phonologically similar to the trained words comes from a post-access checking of the existing words against the highly similar novel words (cf. Qiao & Forster, 2013). An implication of the episodic account is that the emergence of lexical competition should co-occur with consolidation-based improvements in episodic memory. This was indeed the case in the current study: the emergence of lexical competition between the 24 hour and seven day test co-occurred with improvements in recognition memory and free recall over the same timeframe. However, it is notable that recognition memory and free recall were also enhanced between the immediate and 24 hour test, yet no emergence of lexical competition was observed in this timeframe. Further, a consolidation enhancement of recognition memory was not sufficient to promote lexical competition at the twenty-four hour test in Study 3. In line with this, reports of lexical competition emerging with no declarative memory enhancement within the same timeframe (e.g. Dumay et al., 2004, Exp. 1; Gaskell & Dumay, 2003, Exp. 3; Takashima et al., 2014; Tamminen & Gaskell, 2008) and even after a drop in recognition performance following consolidation (Bakker et al., 2014), converge on the conclusion that lexicalization effects are unlikely to be due to the consolidation of declarative memory.

A further line of evidence supporting the lexical basis of post-consolidation response inhibition comes from establishment of the pause detection task as a marker of lexical competition not only for close neighbours of existing words (Mattys & Clark, 2002), but also for embedded competitors (i.e. *lir<u>muck</u>toze*, Dumay & Gaskell, 2012), which are less clearly related to their existing competitors than the onset-aligned competitors (used in the current study and majority of extant lexicalization studies). To further clarify the argument that lexical competition effects draw primarily on lexicalized rather than episodic word representations, Dumay and Gaskell (2012) utilised word segmentation as a lexicalization test, in which it was predicted that an episodic representation of *lirmucktoze* should facilitate spotting of the embedded existing competitor *muck*. Contrary to this prediction, Dumay and Gaskell (2012) observed slower word-spotting responses to trained than untrained novel words following overnight consolidation, suggesting that the new words slowed down responses due to lexical rather than episodic traces. Overall, whilst episodic representations may partially contribute to lexical competition, and the consolidation of episodic memory traces could thus be an important contributor to word memory formation, this convergent evidence is more consistent with lexical competition effects drawing on lexicalized rather than episodic representations.

In contrast to the enhancement of declarative memory for the novel word forms over consolidation, explicit memory for the referents of the picture-associated words decreased over consolidation. An important consideration is whether this loss of episodic detail for the picture-associated words contributed to their lexicalization.

Whilst the decline of memory for the picture-associated word referents was not correlated with the magnitude of the lexical competition effect, a decline in episodic detail associated with learning is suggested to be an important factor in neocortical learning (Wincour & Moscovitch, 2011, as discussed in Chapter 6). Similar data were obtained by Tamminen and Gaskell (2013), in which the semantic integration of novel words emerged one week after learning, with a parallel decay in explicit recall of the new word meanings (see also Dumay & Gaskell, 2007; Tamminen et al., 2012). Whether the time course of a decay of episodic knowledge and the emergence of abstract lexical representations are functionally linked or merely co-occurring is an interesting avenue for further investigation.

7.3.2 The contribution of learning goals to word memory formation

Whilst declarative memory of the novel word forms benefited from consolidation, no robust advantage for the picture-associated words was observed. This lack of a semantic benefit is particularly interesting given that the current study included no explicit instructions to learn the word-picture associations. In the recognition memory test there was no benefit for the picture-associated words, and only a by-item benefit for the picture-associated words in free recall. This lack of a strong semantic benefit for declarative word memory is at odds with previous reports of a semantic advantage for word recognition and recall (e.g. Forster, 1985; Henderson, Weighall, & Gaskell, 2013; McKague et al., 2001; Rueckl & Olds, 1993; Rueckl & Dror, 1994; Takashima et al., 2014; Whittlesea & Cantwell, 1987); interestingly, however, in these studies participants had an explicit goal to learn the correspondence between novel word forms and meanings. In contrast, the acquisition of word-meaning mappings *implicitly* may have a reduced benefit on word recognition and recall compared to when word-meaning mappings are learnt explicitly. For example, Coutanche and Thompson-Schill (2014) trained participants on novel words for which associations between a novel word and its meaning were inferred or explicitly indicated. Recognition accuracy of the novel word forms was significantly lower for novel words in the inferred meaning conditions than in the explicit condition. Similarly, Rodd et al. (2012) trained participants on new meanings for existing words that were either related or unrelated to the existing word meaning, where an advantage for learning new meanings which were related to the existing word meanings emerged when participants explicitly focused on learning the new word-meaning mappings (but cf. Rabovsky et al., 2012, for an effect of semantics on implicit word learning). These data suggest that the beneficial impact of word semantics on recognition may (at least in some cases) be attenuated when acquired implicitly, without explicit instructions to do so. Such a proposal is consistent with the lack of a semantic benefit on recognition in the current study, compared to the semantic advantage observed in Study 2 and Study 3, both of which had an explicit goal to learn the word-meaning mappings. Moreover, it is not the case that participants simply failed to learn the picture-word associations in the current study: memory of the picture-word associations was at 70% immediately after learning (as in e.g. Chen, Wang, & Yang, 2014; Rabovsky et al., 2012). Importantly, this suggests that despite acquiring the word-picture associations, these associations failed to benefit the strength of new word representations (recognition memory) or their retrieval (free recall). It may thus be the case that learning goals impact upon the extent of semantic recruitment in the encoding and subsequent retrieval of novel words.

An important implication of the findings concerns of the role of initial acquisition on the offline lexicalization of novel words. Recognition memory for the novel words immediately after learning constrained lexical competition one week later: participants with stronger recognition memory at the initial test showed larger lexical competition effects after one week. This was corroborated by both a positive correlation between recognition memory on Day 1 and the magnitude of lexical competition on Day 8, and a median split on recognition scores in the Day 1 test, in which only the high recognition memory group showed a robust lexical competition effect on Day 8. The impact of initial acquisition on subsequent word knowledge is consistent with a previous finding by Dumay and Gaskell (2012), in which participants' level of free recall and recognition memory after learning positively correlated with the magnitude of improvement after one week of consolidation, suggesting that stronger initial acquisition may support greater strengthening of new representations offline. Extending this proposal to the current findings, it is possible that initial acquisition must provide stable new word representations for their interleaving with existing lexical items offline. Critically, however, Study 3 demonstrated that good declarative knowledge of novel words alone is not sufficient for lexicalization. Consistent with this, Lindsay and Gaskell (2013) observed no correlation between participants' recognition memory performance and the magnitude of lexical competition effects within testing sessions. Taken together, these findings indicate that the strength of new form representations may not directly modulate lexicalization.

As such, it may be the case that the *type* of processing engaged during learning is one of the key factors contributing to lexicalization, rather than the strength of new word memories per se. The current study specifically suggests that the degree of processing allocated to phonology during initial acquisition may be a cardinal factor in subsequent lexicalization. This proposal is supported by the positive correlation between phoneme monitoring accuracy, as an index of phonemic processing during training, and recognition memory in the immediate test, alongside the positive correlation between immediate recognition memory and the lexical competition effect after one week. Whilst there was no significant relationship between phoneme monitoring accuracy and lexical competition, these correlational analyses suggest that the degree of phonological processing may support the strength of explicit new word memories, and stronger new word memories with such phonological detail may thus enable lexicalization. Such importance of phonological detail in new word representations may be for novel words to utilize the phonological structure of existing words in order to enter into competition during spoken word recognition. Indeed, identifying a shared structure between new and existing knowledge is proposed by the complementary learning systems account (McClelland et al., 1995) as a core tenet of interleaving new with existing representations. It follows that new word representations encoded with a greater degree of phonological detail may show faster or deeper lexicalization than new words with poorly encoded phonological detail.

Therefore, the key suggestion for the observed lexicalization in Study 4 but not in Study 3 is that the former promoted a greater degree of processing for the phonology of novel words during acquisition, which facilitated their integration with existing phonological neighbours over one week of consolidation. However, there is an alternative possibility. Pause detection was used as a measure of lexicalization because it is sensitive to online lexical activity during spoken word recognition (e.g. Mattys & Clark, 2002; Mattys et al., 2005). Spoken word recognition is a highly automatized perceptual skill, however, which draws on the phonological structure of lexical representations to evoke competition between phonologically overlapping neighbours (e.g. Marslen-Wilson, 1987). It is thus possible that phonological processing during learning may be important for the successful lexicalization of novel words, but critically when the lexicalization test *necessitates* fine-grained phonological knowledge. Such an effect of transfer-appropriate processing has a strong empirical basis (e.g. Craik & Lockhart, 1972; Lockhart, 2002; Morris, Bransford, & Franks, 1977; Rajaram, Srinivas, &

Roediger, 1998), where memory is enhanced when the nature of encoding and retrieval are compatible. An additional possibility raised by the current findings, and their comparison to Study 3, is of the role of transfer-appropriate processing in the emergence of lexical competition effects.

Two reports in the literature speak to this transfer-appropriate processing issue with respect to lexicalization. The first comes from the report by Coutanche and Thompson-Schill (2014) of immediate lexicalization following the fast mapping of novel written forms to visual referents. Lexicalization was not tested by pause detection but by a semantic categorization task: participants were required to categorize existing words which were orthographic neighbours of the newly-learnt words (e.g. *torato-tomato*) as natural or man-made. It is possible that the semantic basis of both the novel word acquisition and lexicalization test enabled lexical competition effects, and that a task such as pause detection (had the novel words been acquired in the spoken modality) would not have yielded such competition effects. Second, in a study of crossmodal lexical competition Bakker et al. (2014) observed that one week of consolidation was required for visually trained words to enter into lexical competition in the spoken modality, using pause detection. However, when trained spoken words were tested in the visual modality using a semantic categorisation task, lexicalization was present at the twenty-four hour test. These data suggest that novel words acquired with fine-grained processing (as in phoneme monitoring) may show lexical engagement in a task where less fine-grained representations are required, but that lexical competition effects in a test task requiring more fine-grained representations than those encoded during training (such as pause detection) either the same training modality or a longer lexicalization time course may be required. Therefore, a broader question concerns how to measure lexicalization: whilst lexicalization can be considered the interaction of new and existing word knowledge, new lexical representations can be probed in a range of ways. Utilizing a range of lexicalization measures will thus be of key importance in future research to clarify the time-course of lexicalization across different levels of processing between training and test.

7.3.3 Summary and conclusions

This chapter set out to investigate whether the degree of processing allocated to the phonological form of novel words during initial acquisition is a pre-requisite for successful lexicalization. In particular, it was proposed that the delayed time-course of semantic-associated relative to form-only novel words (Dumay et al., 2004; Takashima et al., 2014) was due to an emphasis on semantic rather than phonological acquisition during learning. Consistent with this proposal, in Study 4 participants learnt novel words with and without picture associations in a phoneme monitoring task, with instructions to learn the novel word forms, and an equivalent one week lexicalization time-course was observed for both picture-associated and form-only words. Further, whilst participants with stronger new word representations at the immediate test showed larger lexical competition effects one week later, the strength of new word representations immediately after learning was tied to higher phoneme monitoring accuracy. Together, these results suggest that phonological processing during learning may support novel form representations, which in turn engage in the spoken word recognition system. The lack of a robust semantic benefit on declarative word memory further suggests that recruiting phonological rather than semantic processing during initial acquisition may impact upon the content and retrieval of new word representations. A central question for future work, however, is what aspects of learning are critical for lexicalization independently of the test task used.

Chapter 8: Thesis summary and conclusions

8.1 Thesis summary

The studies reported in this thesis sought to investigate the impact of semantics on the learning and consolidation of new spoken words in adults. The research question driving this work was: how are new lexical representations acquired? This broad question was made tractable by considering two themes concerning i) how the knowledge acquired during novel word learning impacts upon both fast and slow aspects of word memory formation, and ii) the way in which the encoding and acquisition of new words impacts upon their offline consolidation, and lexicalization in particular. To investigate these two themes, each study in this thesis manipulated the provision of semantic information during learning, and different aspects of word learning were measured across studies. The first two studies (Study 1 and Study 2) assessed the impact of semantic information on immediate, low-level phonological form learning using ERPs, whilst the second set of studies (Study 3 and Study 4) investigated the semantic influence on the more gradual lexicalization process using behavioural measures of learning.

8.1.1 Thesis motivation

The introduction established three lines of evidence which converged to support the research questions addressed in this thesis. Firstly, adding a new unit to the language system could be conceptualised in terms of establishing a new phonological representation (*phonological form learning*), and the formation of inhibitory links between this new phonological representation and existing language units (*lexical representations*), with the process of establishing these links being *lexicalization*. Recourse to models of spoken word recognition supported such a distinction, in which establishing a new word required the formation of mutually inhibitory connections with other lexical-level units (TRACE; McClelland & Elman, 1986) or a specific pattern of activation across a distributed set of units (Distributed Cohort Model; Gaskell & Marslen-Wilson, 1997) which could reduce the ease of recognition for phonologically similar words (Chapter 1). Second, it was established in Chapter 2 that explicit knowledge about the form and meaning of new words could be rapidly acquired and accessed (e.g. Breitenstein & Knecht, 2002; Church & Schacter, 1994; Forster, 1985; Gupta, 2003; Saffran et al., 1996). Interestingly, however, the influence of semantic exposure on the acquisition of new word forms was inconsistent. The explicit recognition and recall of newly-learnt words was frequently benefited by the provision of semantic information during training (e.g. Forster, 1985; Rueckl & Dror, 1994), consistent with the levels of processing theory of learning and memory positing that greater processing depth at encoding contributes to subsequent gains in memory at later test (Craik & Tulving, 1975). However, these findings did not align with those from implicit, online measures of lexical processing such as naming, in which such a semantic benefit was elusive (Gronholm et al., 2007; Hultén et al., 2009; Sandak et al., 2004). Based on these mixed findings one proposal was that semantic information may also impact upon implicit aspects of word learning, but more time was required for such effects to emerge. Finally, Chapter 3 showed that memory consolidation was a process which promoted enduring memory changes (e.g. Gais et al., 2007). Such memory changes were expressed behaviourally in terms of protection against forgetting (Karni et al., 1994), enhanced declarative memory access (Takashima et al., 2006), and the suggestion of a qualitative shift from episodic to an abstract representations (e.g. Tamminen et al. 2012). Further, it was established that newly-learnt words often required a night of sleep to enter into lexical competition with existing words (e.g. Dumay & Gaskell, 2007, 2012; Henderson, Weighall, et al., 2013). However, the provision of semantic information during learning appeared to delay lexicalization in adults (Dumay et al., 2004; Takashima et al., 2014). The literature thus presented a striking dissociation: whilst semantic information could enhance access to new *phonological forms*, indexed by a recognition and recall benefit, it served to slow the *lexicalization* of these new forms within existing lexical networks. It was thus concluded that the impact of semantics on the learning and consolidation time-course of new words was relatively undefined, and the following experimental chapters set out to bridge this gap.

8.1.2 Chapter 4

In the first experimental chapter, Study 1 investigated the presence of any semantic effect on the online acquisition of new phonological forms. This question was motivated by two complementary themes. The first was from observations of a semantic benefit on known word recognition when discrimination was challenging (Tyler et al., 2000; Zhuang et al., 2011), but with no clear evidence regarding such a semantic benefit on novel word recognition (e.g. Hultén et al., 2009; Sandak et al., 2004), with reports of a semantic influence during novel word processing being in terms of post-recognition measures (e.g. Borovksy et al., 2012; Mestres-Missé et al., 2007). Second, it was of theoretical importance whether semantic information impacted upon the form-based processing of novel words during acquisition, as such form-based processing may be central to subsequent lexical competition.

To address the issue of a semantic impact on the online acquisition of new phonological forms, a new learning paradigm was developed to align semantic and non-semantic learning. Novel spoken pseudowords were always presented with two pictures, where in the *correlated* condition there was a frequent co-occurrence between a novel word and its visual referent. In the *uncorrelated* condition there was no co-occurrence between a novel word and visual referent. This manipulation was intended to allow participants to acquire knowledge of a systematic referent across trials for *correlated* novel words, whilst equating exposure, learning goals and information load for the *uncorrelated* novel words for which no semantic referent could be acquired. Event-related potentials were used to measure phonological form recognition during learning, whereby the convergence of the novel word ERPs with known word ERPs was measured at the average recognition point in the speech signal. It was predicted that if the provision of semantic information could also facilitate spoken word recognition during learning, the convergence of the correlated and known-word ERP amplitude in the form-recognition time window should occur earlier in learning than the convergence of the uncorrelated and known-word ERPs. Conversely, if semantics did not impact upon the recognition of new spoken words during learning, an equivalent time-course of convergence was expected for both novel word categories.

In both the form-recognition and post-recognition ERP time windows the correlated words evoked equivalent ERPs to the known words within the first block of the learning task, whilst the uncorrelated words evoked equivalent responses to the known words by the second block of learning. The faster convergence of the correlated and known word ERPs suggested that the acquisition of a semantic referent could facilitate the recognition of novel words during learning, as measured by the convergence of ERP amplitudes with known words at the average recognition point in the speech signal (e.g. Borovsky et al., 2012; Mestres-Missé et al., 2007). These findings were interpreted with respect to models of spoken word recognition. However, the interpretation of Study 1 was constrained by the temporally smeared recognition window, and the lack of a clearly defined ERP component associated with word recognition. This study was therefore argued to be suggestive of a semantic advantage for the recognition of new phonological forms during acquisition, but convergent evidence was needed.

8.1.3 Chapter 5

The study reported in Chapter 5 extended the previous study by using a defined ERP component, the mismatch negativity (MMN), to measure phonological form discrimination immediately after learning. Study 2 further extended the previous study by assessing phonological form discrimination following 24 hours of offline consolidation. The measurement of phonological form representations before and after consolidation was driven by the observation that the unclear impact of semantic information on the lexical integration of new phonological forms (e.g. Dumay et al., 2004; Takashima et al., 2014) could be partially addressed by investigating whether any semantic benefit on learning new phonological form representations remained stable after 24 hours. Study 2 thus provided the opportunity to corroborate the findings of Study 1, and to establish a footing on the impact of consolidation on low-level phonological form representations.

Study 2 employed the same learning paradigm as Study 1, with a critical improvement: the spoken word stimuli were all minimal pair place contrasts, and cross-spliced such that there was a temporally precise point in the speech signal when each item could be recognised. The MMN was then time-locked to this recognition point to measure the discrimination of new phonological forms from existing words, immediately after training and following 24 hours. A more negative MMN amplitude was elicited for correlated than uncorrelated novel words both immediately after training and following offline consolidation, indicating that a semantic benefit on phonological form learning was present and stable over one day-night cycle of consolidation. Further, as the MMN was elicited automatically in the absence of task demands, and extant reports suggested that the amplitude of the MMN is sensitive to psycholinguistic variables such as word frequency (e.g. Alexandrov et al., 2011; Shtyrov et al., 2011), these data suggested that the MMN indexed the discrimination of the new phonological forms. On the basis of the consolidation literature, however, I speculated that different sources of knowledge may have underpinned the discrimination of the correlated words before and after consolidation. Strikingly, a greater magnitude of the correlated-word MMN was related to better semantic learning performance on the learning task prior to consolidation, but not after 24 hours, despite participants retaining memory of these associations (as measured by an association recall task).

The semantic advantage for phonological form learning extended previous reports of a semantic benefit on recognition memory and recall, by suggesting that semantic exposure could impact upon the discrimination of new phonological forms. The absence of a relationship between correlated-word discrimination and semantic learning after offline consolidation was suggestive of the abstraction of the new correlated forms from the episodic knowledge which supported their discrimination immediately after learning, and was consistent with the memory consolidation literature. As the *correlated-uncorrelated* learning paradigm promoted a semantic advantage for learning relatively low-level phonological form representations, the critical question raised by these findings was thus the consequences of this learning advantage for the integration of new phonological forms with existing lexical knowledge.

8.1.4 Chapter 6

Chapter 6 capitalized on the learning paradigm used in the previous two chapters to address the consequences of the observed semantic advantage for lexical integration. As the learning paradigm had demonstrably supported phonological form representations for semantic-associated words, which were stable over 24 hours, Study 3 thus addressed if new phonological forms acquired from this paradigm subsequently entered into lexical competition. Addressing this question also allowed a window onto the extent to which phonological form representations were a pre-condition for lexicalization. From the consideration that established phonological form representations may be an important pre-cursor to lexicalization, I predicted that semantic-associated (correlated) novel words acquired in this learning paradigm should show lexical competition effects following consolidation, compared to the non-semantic (uncorrelated) novel words.

Study 3 used bi and tri-syllabic novel words (compared to Study 1 and Study 2) to critically test the shift in the uniqueness point of existing words as a consequence of acquiring a new novel neighbour. Pause detection was used as the test of lexicalization, which has been demonstrated to be sensitive to the magnitude of lexical activity from the parallel activation of multiple lexical candidates (Gaskell & Dumay, 2003; Mattys & Clark, 2002; Mattys et al., 2005). Two additional tests of new word knowledge were used: recognition memory, to probe declarative knowledge of the new words, and shadowing, to measure the speed of online access to the new phonological forms.

Study 3 revealed no evidence for the lexical integration of either correlated or uncorrelated novel words after 24 hours. However, an intriguing dissociation was observed between the absence of lexical integration and the presence of consolidation for recognition memory and shadowing, where novel words with a 24 hour period of consolidation prior to testing showed faster shadowing and recognition speed than unconsolidated words, and greater recognition accuracy. There was a further recognition memory benefit for the correlated novel words, suggesting that the provision of semantic information supported declarative word memory. These data corroborated extant reports suggesting that enhancement of declarative memory and lexicalization reflect distinct memory processes (e.g. Dumay & Gaskell, 2012; Henderson et al., 2014; Tamminen et al., 2010). The lack of lexicalization for either novel word category, despite intact consolidation of explicit word knowledge and online access, led to the suggestion that a longer period of time was required for lexicalization. This suggestion was driven by i) the semantic nature of the learning paradigm, and thus the possibility of a slower lexicalization time-course (e.g. McClelland, 2013; Wincour & Moscovitch, 2011), and ii) the mismatch between the semantic training and phonological test task (pause detection) viably necessitating a longer period of consolidation for lexical competition effects to emerge (e.g. Bakker et al., 2014).

These considerations led to a follow-up study, in which participants returned to the lab for re-testing after several months of consolidation (cf. Tamminen & Gaskell, 2008), and completed the same test tasks as those used at the initial test. Again, no lexical competition was observed on the pause detection task. However, the data yielded interesting evidence for the long-term impact of semantic acquisition and day of training on declarative memory: recognition accuracy was greater for correlated words than uncorrelated words overall, and for words learnt on Day 1 (with 24 hours of consolidation before testing) in training compared to words learnt on Day 2 overall. Novel words learnt on Day 1 were additionally responded to faster than Day 2 words in the recognition memory task. The shadowing task showed a learning effect, in which the trained novel words were repeated more quickly than untrained novel words, but no effect of semantic exposure or day of training was present in reaction times.

Overall, the follow-up data thus aligned with Study 3 to suggest that lexicalization and declarative memory consolidation reflected distinct aspects of memory formation. I further put forward the suggestion that the presence of associated pictures in the learning paradigm, alongside a learning goal of acquiring these novel word-picture associations, could have contributed to increased contextual knowledge acquired with the new words and a decreased level of phonological processing during learning, which could have subsequently debilitated lexicalization.

8.1.5 Chapter 7

Finally, Chapter 7 tackled the issue of whether the degree of processing allocated to phonology during learning was a central factor in the success and time-course of lexicalization. Study 4 was motivated by the consideration that a slower lexicalization time course for semantically-associated words in two previous studies (Dumay et al., 2004; Takashima et al., 2014) and Chapter 6 could have partially stemmed from a reduced degree of phonological processing during encoding, due to a task focus on learning word-meaning mappings (Ruz & Nobre, 2008; Yoncheva et al., 2010). Study 4 thus extended a learning task used by Takashima et al. (2014), in which novel words were acquired via phoneme monitoring. Half of the novel words had a consistent picture association (picture-associated), and half were phonological forms in isolation (form-only). Critically, participants were instructed to learn the novel word forms, with no explicit instructions to learn the word-picture associations. Further, the learning and consolidation of the new words was tested immediately after training (Day 1), after 24 hours of consolidation (Day 2), and after one week of consolidation (Day 8). It was predicted that a more substantial degree of processing allocated to the phonology than meaning of the novel words during acquisition would equate the lexicalization time-course of picture-associated and form-only words.

Consistent with this prediction, both the picture-associated and form-only words showed lexical competition following one week of consolidation. Two convergent further analyses attributed the lexical competition effect at least partially to the degree of phonological processing novel words underwent during training. Firstly, accuracy during the phoneme monitoring task (as a measure of phonological processing) was positively correlated with recognition memory for the novel words immediately after training. Second, participants with stronger recognition memory immediately after training showed larger lexical competition effects one week later. These findings suggested that the lexicalization of the novel words was constrained by declarative memory, which was in turn supported by attending to the phonological forms of the novel words during training. The instructions for participants to learn the novel word forms, with no goal of learning the word-picture associations, also diminished the semantic benefit on declarative memory: no robust semantic advantage was present in the recognition memory or free recall tasks, despite performance on an association memory task indicating good knowledge of the word-picture associations immediately after learning. These data supported the contention that the nature of processing subserving learning may mediate both the lexicalization time-course and the establishment of declarative memory.

A key consideration in interpreting the findings, however, was the compatibility between the training and lexicalization test task, given the strong empirical basis for enhanced memory when the nature of encoding and retrieval are compatible (Craik & Lockhart, 1972; Lockhart, 2002; Morris et al., 1977; Rajaram et al., 1998). The measure of lexicalization used in this thesis was pause detection, a phonological task, and lexicalization was observed following phonological training (via phoneme monitoring) but not after semantically-oriented training (via learning word-picture associations, in Chapter 6). Understanding the relationship between novel word acquisition and the nature of the lexicalization test was thus suggested to be a crucial addition to building a full picture of the impact of semantic information on the success and time-course of lexicalization.

8.2 Meaning and memory consolidation in novel word learning

The main aim of this thesis was to establish what contributes to the development of new lexical representations, by elucidating the impact of semantic information and consolidation across measures of phonological form learning (Study 1 and Study 2), explicit knowledge of new word forms, speeded online access, and lexical competition (Study 3 and Study 4). The below sections thus provide an overview of the commonalities between these findings, and limitations on their interpretation.

8.2.1 Semantic impact on novel word learning

Two key findings emerged from the provision of semantic information during learning: i) the broadly beneficial impact of semantic information on the phonological form learning and recognition of new words (Studies 1-3), with no semantic benefit for the engagement of these new forms in lexical competition (Study 3 and Study 4), and ii) this semantic advantage being observed only in the studies in which the learning goal

Table 11. Summary of semantic effects across the word-learning measures, at each consolidation time point.

Measure of word learning	Consolidation time			
	0 hours	24 hours	1 week	Long term
Phonological form learning	Semantic advantage *Studies 1 and 2*	Semantic advantage *Study 2*		
Recognition memory accuracy	Semantic advantage *Study 3*[1]	Semantic advantage *Studies 2 and 3*		Semantic advantage *Study 3*
	No semantic advantage *Study 4*	No semantic advantage *Study 4*	No semantic advantage *Study 4*	
Free recall	No semantic advantage *Study 4*[2]	No semantic advantage *Study 4*	No semantic advantage *Study 4*	
Shadowing speed	Semantic advantage *Study 3*	Semantic advantage *Study 3*		No semantic advantage *Study 3*
	No semantic advantage *Study 4*	No semantic advantage *Study 4*	No semantic advantage *Study 4*	
Lexical competition	No semantic advantage *Studies 3 and 4*	No semantic advantage *Studies 3 and 4*	No semantic advantage *Study 4*	No semantic advantage *Study 3*
Explicit knowledge of semantic associations	Study 1: ~70% Study 2: ~70% Study 3: ~80% Study 4: ~70%	Study 2[3]: ~65% Study 4: ~60%	Study 4: ~50%	

Notes. 1. This semantic advantage for unconsolidated words in Study 3 was interpreted from a main effect of Condition, but note that the Condition x Day interaction was marginal. 2. In the free recall task (Study 4), there was an advantage for picture-associated words which was significant by-items only, and thus interpreted as no robust semantic advantage. 3. Study 2 tested semantic association knowledge at 24 hours by participants matching each novel word to a picture from an array, and the task was thus more challenging than the learning measure used at 0 hours.

was to acquire new word-meaning associations (Studies 1-3 vs. Study 4). Table 11 presents a summary of the impact of semantics across the different measures of word learning, at each consolidation delay tested.

Table 11 indicates that in Studies 1-3, which used the correlated-uncorrelated learning paradigm with explicit instructions for participants to learn the word-meaning associations, there was a semantic advantage for phonological form learning, recognition accuracy, and shadowing both immediately and after 24 hours of consolidation. Further, the semantic advantage on recognition accuracy remained after a delay of several months. However, no semantic benefit on lexical competition (nor any lexical competition) was observed in Study 3. A particularly interesting aspect of the data was the dissociation between such semantic support for phonological form learning (Study 2) and explicit memory (Study 3), with no evidence of lexicalization. The possible reasons for this lack of semantic benefit on lexicalization were discussed extensively in Chapters 6 and 7, and further suggest a distinction between the explicit word knowledge which is available immediately after learning, and the slower lexicalization time-course. In contrast, using picture associations versus form-only exposure in Study 4, with no goal of acquiring word-meaning associations, led to no robust semantic advantage on these measures. This pattern aligns firstly with the idea of a separable semantic effect on aspects of word knowledge which are accessible immediately (phonological form representations and declarative knowledge) and those which require longer to emerge (lexical competition). Secondly, the distinction between Study 3 and Study 4 is suggestive that learning goals may impact upon the extent to which semantic information is recruited during learning (this was discussed in more detail in Chapter 7, section 7.3.2) and its subsequent support for declarative memory of new words[33]. Finally, a suggestion raised earlier in this thesis (Chapter 2, section 2.4) was that semantic gains in implicit measures of processing may require a longer period of consolidation to emerge. No evidence to this effect was found in this thesis, whereby no semantic advantage on shadowing was observed several months after training (Study 3 follow-up), nor after one week (Study 4), or across any lexical competition measures.

There are two main limitations concerning the interpretation of these findings as a semantic benefit on the early stages of word memory formation, however. The first

[33] It is noteworthy that an alternative interpretation of this difference between Study 3 and Study 4 is of active versus passive learning of the word-meaning mappings, whereby the active process of referent selection in Study 3 may have provided greater support for word learning (e.g. McMurray, Horst, & Samuelson, 2012) than simply the goal to learn these associations. However, the key comparison here is between Study 4 and the report of Takashima et al. (2014), in which participants were instructed to learn the word-picture associations. In the report of Takashima et al. a consolidation advantage was observed for recognition accuracy of picture-associated words, alongside a by-participants free-recall advantage for picture-associated words. It is thus important to emphasise that the contention that learning goals contribute to semantic recruitment during training requires more explicit testing, but the observed contrast between Study 4 and Takashima et al. (2014) are consistent with such a proposal.

is the fact that in Studies 1-3, the comparison between the correlated and uncorrelated words was not one of 'semantics' and 'no semantics', but between consistent semantic referents and inconsistent semantic referents. A critical consideration is thus whether the observed findings reflect a relative disadvantage for the uncorrelated words, rather than an advantage for correlated words. This issue was discussed previously (Chapter 5, section 5.3.1; Chapter 6, section 6.4.1) but there are two further points in the data which deserve consideration here. First, in Study 2 there was a relationship between greater semantic association learning and greater phonological form discrimination immediately after training. Second, in Study 3 there was a further positive correlation between semantic association learning and recognition memory accuracy. These relationships between word learning measures and the degree of semantic association learning during training are difficult to explain in terms of simply a disadvantage for the uncorrelated words: if this was the case it would be unlikely for the picture-association learning to support correlated-word learning at an individual level. Nonetheless, the current data cannot rule out the possibility that the difference between the correlated and uncorrelated words in Studies 1-3 was enhanced by the inconsistency in the uncorrelated learning condition, especially with respect to the learning goal of these studies.

The second limitation is relevant to each study, and poses a critical constraint on interpretation in this thesis: the use of an associated novel picture for semantic learning, rather than a richer semantic meaning. The key issue here is whether the observed findings are representative of semantic effects as they may occur in natural word learning. Indeed, in the adult word learning literature there are suggestions of contradictory effects between training participants on novel objects with meaningful features and observing no semantic benefit on naming (Cornelissen et al., 2004; Whiting et al., 2007), but a semantic benefit on word recognition (e.g. Breitenstein et al., 2005; Takashima et al., 2014) from training participants on novel word-picture associations, compared to reports of a semantic benefit for the acquisition of richer new meanings from sentences and definitions (e.g. Henderson, Weighall, & Gaskell, 2013; Rabovsky et al., 2012; see also Rodd et al., 2013). These discrepancies imply that the way in which semantic information is recruited during training may at least partially mediate its influence, rather than whether that semantic information involves picture associations or richer sentential definitions. Two findings in the literature align with this idea. Firstly, when Leach and Samuel (2007) trained participants on novel words with picture associations, the novel words affected the perception of existing phoneme categories immediately after training; however, this effect was diminished when participants repeated the novel words during learning, with a semantic referent still present. Second, Rodd et al. (2012) observed that the relatedness of new and existing word meanings only facilitated lexical decision reaction times when participants explicitly focused on learning word-meaning mappings during training (similar findings were obtained by Forster, 1985). These findings suggest that the processing supporting novel word learning, rather than the availability of meaning per se, may critically mediate its impact on subsequent measures of learning. However, it is important to emphasise that the multiple stages involved in word learning, and the memory systems drawn upon (Chapter 1, section 1.5), viably make the influence of semantics more nuanced across different memory subsystems, test tasks, and the type of semantic information acquired.

With respect to the data reported in this thesis, there are two considerations regarding how the findings may have differed by associating novel words with richer semantic meanings, such as sentential definitions (e.g. Dumay et al., 2004; Tamminen & Gaskell, 2013). The first concerns the semantic advantage for phonological form learning and declarative memory (Studies 1-3). One mechanism suggested for this semantic benefit (Chapter 6, section 6.3.3) was of the integration of new semantically-associated words into existing semantic networks, and thus supporting their later retrieval. It follows that this retrieval benefit may be greater for words with a higher number of semantic features (e.g. Pexman, Hargreaves, Siakaluk, Bodner, & Pope, 2008; Rabovsky et al., 2012; cf. James & Gauthier, 2004), and thus that novel words learnt from sentences, with a greater number of semantic features, may show stronger benefit than observed here from novel pictures with very few semantic features (although, as noted previously, the observation of this benefit may critically depend on the 'non-semantic' counterpart). It is also notable that the current data therefore cannot address whether the semantic advantage observed in Studies 1-3 reflected an advantage based on semantic properties of the language system, or a more low-level effect such as the picture associations providing an additional episodic cue or tagging these words as particularly relevant for memory purposes (e.g. Craik & Tulving, 1975; Rauchs et al., 2011; van Dongen et al., 2012; discussed in depth in Chapter 6, section 6.3.3). The extent to which a semantic benefit in acquiring explicit word knowledge draws on the language system, versus general properties of the memory system, is a question for future work to address.

The second consideration concerns the influence of richer semantic associations on the lexicalization of new word forms. The data of Tamminen et al. (2013) best speak to this issue: following training on novel words with meanings which fell into dense or sparse semantic neighbourhoods, novel words with sparse semantic neighbourhoods showed greater spindle density and slow-wave activity in the night of sleep following learning. One interpretation of this effect was of novel words falling into sparse semantic neighbourhoods having a reduced possibility for interference with existing knowledge, consistent with a recent proposal by McClelland (2013) of consolidation being *prior knowledge dependent* rather than *slow.* It is thus possible that novel words trained with a richer semantic meaning in Study 4 may have continued to show a slower consolidation time-course than form-only words, with more semantic features (relative to the picture associations) posing a greater possibility of interference with existing semantic knowledge[34]. It remains an avenue for future investigations to test the impact of prior semantic knowledge on the lexicalization time-course, and a means of addressing this will be discussed at the end of this chapter.

Alongside how richer semantic meanings may have impacted upon the observed findings, a final relevant point pertains to the nature of the word stimuli used across experiments in this thesis. Study 1 and Study 2, which tested the impact of semantic information on phonological form learning, used minimal pair items (e.g. *boap-boak-boat*), which had a degree of overlap with many existing words. Conversely, Study 3 and Study 4 used *cathedruke-cathedral* items to test the consequence of semantic learning for lexical competition effects on existing words, which had a high degree of phonological overlap with only one existing word. It may be the case that semantics operates differently upon the learning of each of these item sets (these differences were also discussed in Chapter 7, section 7.1.1). First, recall that a semantic benefit in known word processing has been observed for items in high competition cohorts specifically (e.g. Tyler et al., 2000), and the semantic advantage for the phonological discrimination of new words in Study 2 was obtained with the *boap-boat* items, with relatively large phonological neighbourhoods. Accordingly, it is difficult to assess whether such a benefit for phonological discrimination was present for the *cathedruke-cathedral* items used in Studies 3 and 4, and whether the phonological representations of the *boap* items reflect

[34] Note, however, that *faster* lexicalization has been observed when richer semantic meanings can be rapidly integrated into an existing schema (e.g. Coutanche & Thompson-Schill, 2014; see also Tse et al., 2007).

the same processes involved in learning the *cathedruke* items. Second, the *cathedruke* items have a high degree of phonological overlap with existing words, and it is thus possible that these items carry some inherited meaning of the base word (Davis et al., 2009; Tamminen, 2010). Whilst a parsimonious prediction is that this inherited meaning may have masked a semantic advantage for the *cathedruke* items, this was not the case (Study 3; see also Henderson, Weighall, & Gaskell, 2013). The important consideration is thus that the encoding of novel words between Studies 1-2 and Studies 3-4 may not have been directly comparable, and future investigations should thus also address the contribution of low-level phonological form learning to subsequent lexicalization within the same set of novel words.

8.2.2 Consolidation and lexical integration

The work reported in this thesis tested novel word learning across a range of consolidation delays, from which two main findings emerged. First, consolidation could benefit the aspects of word knowledge available immediately (phonological form representations, declarative memory, and speeded access to the novel words), without concurrently enabling lexicalization. Second, the contrast between Study 3, Study 4, and Takashima et al. (2014) interestingly suggested that lexicalization may not be necessarily tied to the strength of new word representations, but the nature of processing subserving learning. Table 12 presents the consolidation effects observed across Studies 2-4, in terms of whether each word learning measure was benefited by consolidation.

Chapter 1 put forward a framework distinguishing between the learning of a new phonological form, and the engagement of this new phonological form in lexical competition (see also Leach & Samuel, 2007) in terms of models of spoken word recognition. Chapters 2 and 3 then raised the possibility that different cognitive mechanisms may underpin the learning of these representations, given the different time-courses involved in fast access to declarative knowledge about a new word form and meaning, and the slower embedding of this new knowledge within the existing lexical system. This proposal aligned with the Complementary Learning Systems account of word learning (Davis & Gaskell, 2009), in which the twin demands of acquiring new words whilst retaining existing lexical items are met by the initial storage of new words in a fast-learning hippocampal system, with a gradual transfer to lexical representations in a slow-learning neocortical system. The data obtained in Study 2, Study 3 and Study 4 are broadly consistent with this framework. The CLS account (Davis & Gaskell, 2009)

Table 12. Summary of the consolidation advantage across each measure of word learning and consolidation delay.

	Consolidation delay		
	0 → 24 hours	24 hours → 1 week	24 hours → Months
Phonological form learning			
Study 2	No enhancement; possible abstraction from semantic associations		
Recognition memory accuracy and speed			
Study 3	Yes	Yes	Advantage for Day 1 trained words, and correlated novel words
Study 4	Yes	Yes	
Free recall			
Study 4	Yes	Yes	
Shadowing			
Study 3	Yes		Measures not comparable
Study 4	No	No	
Lexical competition			
Study 3	No	No	No
Study 4	No	Yes	

proposes that consolidation facilitates recognition of novel words by their incorporation into the neocortical route, which may operate more quickly during word recognition than the hippocampal route (to avoid effects akin to catastrophic interference during spoken word recognition). Intriguingly, however, the consolidation of declarative memory and speeded access did not co-occur with the emergence of lexical competition. Whilst the distinction between immediately accessible and slower aspects of word learning aligns with the CLS framework, what is particularly interesting is the conditions which may support lexicalization. It seems that lexicalization may be tied to a more specific set of factors pertaining to the type of novel word processing subserving learning, and, possibly, its relationship to the later test (Study 3-Study 4). To evaluate this proposal, Appendix 14 presents a review of lexicalization studies to date in terms of the training task used, the declarative memory consolidation for new words, and the lexicalization time-course. From this review it is evident that the emergence of lexicalization is not tied to declarative memory per se, but rather may be associated with the way in which novel words are acquired.

This proposal be can conceptualized with recourse to the standard consolidation model (Squire & Alvarez, 1995). As reviewed in Chapter 3, the central tenet of this model is the strengthening of new cortical representations through the reactivation of cortical-hippocampal links during offline consolidation, which subsequently serves to strengthen new cortical representations. It follows that for close phonological links between new and existing lexical items (as required for lexical competition in spoken word recognition), the hippocampal representations of new words from encoding must be supported by a sufficient degree of phonological detail for these links with existing words to be strengthened by offline consolidation. This would mean that in a test of lexical competition, such as pause detection, phonological processing of the existing word would activate the newly-learnt word via these intra-cortical links, and thus lead to lexical competition. It could similarly be conceived that following the encoding of novel words with a semantic referent, activation between these novel words and existing words benefit from a test promoting the semantic processing of existing words (e.g. Coutanche & Thompson-Schill, 2014). It may therefore be the case that a relatively specialized set of processes are involved in lexicalization, whereby these processes may particularly tied to the nature of encoding during training, and possibly the relationship of this encoding to the subsequent test. The work reported in this thesis thus complements the existing lexicalization literature, but from the complex pattern of emerging findings it is evident that many avenues of investigation remain.

However, a recent report appears to be inconsistent with the proposal of lexicalization as a distinguishable mechanism from other aspects of word learning. Kapnoula et al. (2015) trained participants on novel words through repetition and stem completion, or phoneme monitoring. In an immediate lexicalization test using the visual world paradigm, in which lexical competition was measured by the proportion of fixations to a target picture, the newly-trained words showed greater competition than untrained novel words. From this immediate emergence of lexical competition, Kapnoula et al. (2015) proposed that the establishment of new phonological representations and their engagement in lexical competition were governed by the same mechanisms. An alternative explanation is that lexicalization is not a dichotomous state, but may rather involve the gradual strengthening and re-organisation of neocortical connections, whereby this process begins immediately after encoding. It may thus be the case that eye-tracking provides a more sensitive measure to tap into the early stages of this process, in which intra-cortical links between new and existing representations are weak (as predicted by CLS accounts; McClelland et al., 1995). It is then through the strengthening of these cortical links, either over offline consolidation (e.g. Dumay & Gaskell, 2007; Tamminen et al., 2010) or specific online states such as interleaving (Lindsay & Gaskell, 2013; see also Coutanche & Thompson-Schill, 2014; Fernandes et al., 2009; Szmalec et al., 2012), that they can be expressed behaviourally in tests of pause detection and lexical decision.

The central limitation on interpreting the current findings stems from alternative explanations of consolidation effects. The most important of these were discussed in the experimental chapters: proactive interference (Chapter 6), repeated testing (Chapter 7), and the consolidation of episodic traces rather than lexical integration (Chapter 7). One further consideration is of predictive coding as an alternative account of lexical competition effects. Gagnepain et al. (2012) trained participants on novel *cathedruke* words and measured the MEG response in the superior temporal gyrus, a region involved in speech perception, during a pause detection task on existing phonological neighbours following overnight consolidation. The difference between the MEG response for the neighbours of consolidated and unconsolidated new words following the uniqueness point (e.g. *cathedra*-) indexed greater prediction error for neighbours of consolidated relative to unconsolidated new words. These findings suggested that the spoken word recognition system utilised prediction error for efficient word recognition. Predictive coding thus provides an alternative account of the mechanism of lexical competition, but it does not seem that this alternative mechanism alters the interpretation of lexical competition between new and existing words in the literature.

8.3 Limitations of this thesis

The limitations of each specific study have been discussed extensively within the experimental chapters, with general constraints on interpreting these results considered above. There is, however, a broader limitation to the work in this thesis as a whole: the assumption of participants treating the novel words as functional additions to their native language (L1), rather than a separate language encapsulated from the native language (L2). The degree to which participants implicitly treat new words as belonging to L1 or L2 may depend substantially on the nature of the learning task and stimuli used;

for example, in Forster (1985) repetition priming effects for new words only emerged when participants were told that the new words were meaningful. This finding suggests that when new words are thought not to be relevant to the existing language, they may be less likely to affect behaviour in a similar way to existing words. This proposal is also consistent with findings in the general memory literature, whereby items cued as relevant during learning are more likely to be recalled at later test (e.g. Rauchs et al., 2011). In the studies reported in this thesis, if it was the case that the novel words were treated as relevant only in the context of the experiment, this limits the extent to which the observed findings are reflective of L1 learning. Two points in the data mitigate this concern, however: the suggested abstraction of phonological form representations following consolidation (Study 2), and the emergence of lexical competition (Study 4). These findings are align with the idea of the novel words being integrated with existing linguistic knowledge, rather than encapsulated from the lexicon.

It is also notable, however, that the bilingual literature as a whole has converged on the notion of an integrated lexicon (Brysbaert & Duyck, 2010). For example, lexical competition effects can occur across languages in the case of word recognition in isolation (e.g. Hoshino & Thierry, 2011; Marian & Spivey, 2003). Furthermore, similar cognitive mechanisms for L1 and L2 learning have supported an explanation of L2 leaning within a CLS framework (Lindsay & Gaskell, 2010), implying that the pattern of data observed in the current studies could also be explained by L2 learning mechanisms (but cf. Witzel & Forster, 2012, for an episodic account of L2 learning). As such, whilst the assumption of L1 learning and the degree to which this impacts upon learning and consolidation remains important to verify, the issue of whether participants approached learning from a native or second language perspective may not pose a significant constraint on interpreting the current work.

A final limitation of note is that the effect of sleep was not explicitly examined. For effects emerging within a 24 hour time-frame the current data is thus unable to disentangle the influence of offline sleep-based consolidation from the passage of time (e.g. Szmalec et al., 2012). However, effects emerging over a longer time-course – lexical competition, and the long-term declarative memory effects after 8 months in Study 3 – suggest that an offline consolidation mechanism, including sleep, contributed to these effects (Squire & Alvarez, 1995; Davis & Gaskell, 2009; McClelland et al., 1995). The specific contribution of sleep on the impact of semantic versus non-semantic learning on word memory formation thus remains to be addressed in future work.

8.4 Conclusions and future work

The work presented in this thesis converges on two complementary ideas. When recruited during training, the provision of semantic information can benefit the aspects of word knowledge that are available immediately (phonological form representations and declarative memory) but confers no advantage on the emergence of lexical competition. In terms of consolidation, it appears that offline consolidation may frequently benefit these aspects of word knowledge that are immediately available (in terms of strengthening declarative memory, and facilitating speeded access to newly-learnt words) with no concurrent emergence of lexical competition. The time-course of word learning from the data in this thesis is presented in Figure 39.

The central question driving this thesis was: how are new lexical representations established? The answer to this question thus seems to be that the lexicalization of newly-learnt words may be contingent on a more specific set of factors than the consolidation of other aspects of word knowledge. These factors may include the type of encoding subserving learning and its relationship to the type of representations drawn upon in the later test, and the subsequent ease of linking new and existing lexical items. The comparison between Study 3 and Study 4 in particular suggests that the strength of declarative memory may not be important for lexicalization per se, but rather that the

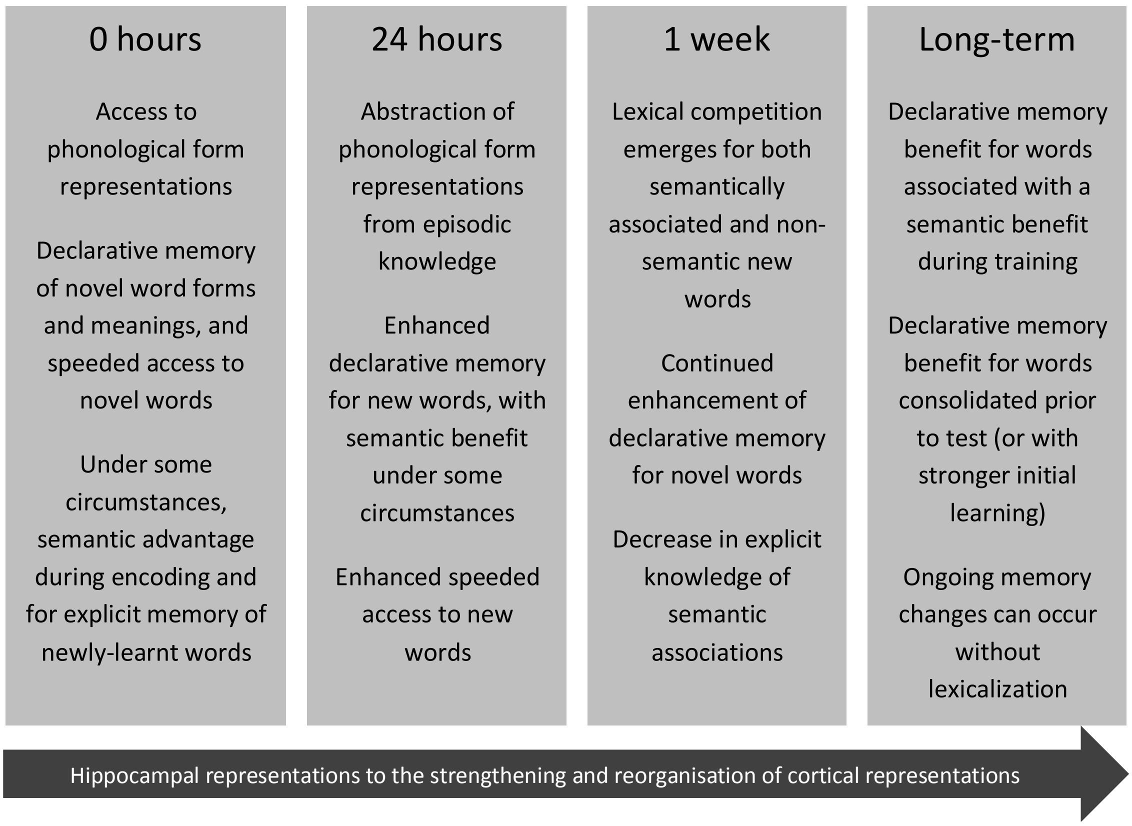

Figure 39. The time-course of word learning from the data reported in this thesis.

knowledge from encoding which underpins declarative memory may critically support lexicalization.

8.4.1 Contributions of this thesis

The contributions of this thesis can be summarised in four main points:

1. The provision of a systematic semantic association can benefit the learning of new phonological form representations, which remain stable following 24 hours of consolidation (Study 2).

2. The enhancement of explicit word knowledge and lexicalization may reflect separable aspects of word memory formation and consolidation (Study 3).

3. Whilst explicit word knowledge can constrain lexicalization (Study 4), good explicit knowledge is not a sufficient pre-requisite for lexicalization to occur (Study 3). The relationship between declarative memory and lexicalization may be influenced by the type of knowledge which supports declarative memory.

4. Acquiring well-specified phonological representations may be an important factor for lexicalization (Study 4), suggesting that the nature of encoding subserving learning may critically mediate how a new lexical representation is established.

8.4.2 Future questions

It is clear that fully-formed lexical representations in the real world require semantic information, and meaning is therefore a natural and crucial part of word learning. An important point to draw from the above conclusions is thus that an apparent meaning disadvantage (or lack of advantage) in lexicalization may be driven by how lexicalization is measured, and what the encoding of new words focuses on. One central question for future work thus concerns how the relationship between encoding and test impact upon the observed time-course of lexicalization for both meaningful and meaningless new words. This question could be tackled by incorporating multiple measures of lexical competition into a single experiment, such as pause detection and semantic categorisation. If it is the case that the observed lexicalization time-course is in part determined by the relationship between novel word encoding, and the way in which known word representations are drawn upon at later test, it would be predicted that from semantic training (such as in Study 3) lexical competition on a semantic categorization task may be evident before such competition effects on a pause detection task.

The second issue then concerns how the relationship between newly-acquired meanings and existing semantic knowledge may influence the lexicalization time-course of new word forms. For example, this could be addressed by training participants on novel words with meanings falling into dense or sparse semantic neighbourhoods (e.g. Tamminen et al., 2013) and subsequently testing the engagement of these novel words in lexical competition 24 hours, one week, and two weeks following learning. The prediction here would be that, if the engagement of semantically associated new words in lexical competition is constrained by existing semantic knowledge, the novel words acquired in sparse semantic neighbourhoods should show form-based lexical competition effects earlier compared to those with dense semantic neighbourhoods. Such a finding would align with the proposal of McClelland (2013) of the rate of neocortical learning being contingent on prior knowledge, and intriguingly suggest that the emergence of phonological lexical competition may be governed by the concurrent rate of semantic integration.

Finally, a future endeavour is to understand the relationship between declarative memory and lexicalization. From the above discussion it is clear that good explicit word knowledge alone is not sufficient for lexicalization, but under some circumstances such declarative knowledge may constrain the entry of new words into lexical competition. Investigating how the encoding of new knowledge influences the subsequent offline consolidation process it undergoes can thus continue to provide a window onto the cognitive mechanisms underpinning our ability to learn.

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Appendices

Appendix 1

Table of the lexical variables controlled for in Study 1.

	Known words	**Novel words (set 1)**	**Novel words (set 2)**
Orthographic neighbourhood size	7.13 (3.48)	7.88 (4.49)	7.5 (4.34)
N-hood frequency mean	107.44 (128.59)	133.18 (229.81)	99.09 (152.93)
Number of positions in word at which neighbours can be generated	2.63 (.74)	2.50 (1.07)	2.88 (1.13)

Note. Each value is the mean across the 8 items in each word category, and standard deviations are shown in brackets.

Appendix 2

Table of the auditory profile of the spoken items in Study 1.

Word	Vowel onset	Vowel offset	Fricative onset	Closure duration	Aspiration onset	Word length
bife	5	214	211			500
bike	5	201		203	384	479
chufe	100	265	262			518
chuke	133	267		279	420	592
daf	25	200	212			572
dak	25	190		186	375	541
kipe	92	279		149	428	622
kite	96	280		165	447	537
knop	137	279		206	494	601
knot	117	276		188	464	582
loaf	89	256	267			557
loak	101	285		288	450	566
lup	127	238		192	430	580
lut	98	208		390	390	500
pipe	76	243		146	390	524
pite	86	265		145	415	501
rafe	100	319	294			610
rake	101	294		153	448	635
roof	114	315	312			601
ruke	105	290		143	434	556
soap	205	395		129	525	560
soat	248	435		144	579	700
vape	108	306		166	472	645
vate	110	306		129	435	549

Note. Each measure is in milliseconds from word onset. The recognition point in Study 1 was defined as the earliest point of vowel offset within each word pair, at which the items could be disambiguated. The mean known and novel word lengths did not significantly differ (known M = 559ms, SD = 48; novel M = 572ms, SD = 56).

Appendix 3

The picture stimulus set used in Study 1. The top set of pictures shows the 8 known word referents, and the bottom set of pictures shows the 40 novel object pictures.

Appendix 4

The full set of spoken items used in Study 2.

Known Words	Novel Words	
boat	**boap**	**boak**
kite	**kipe**	**kike**
jet	**jep**	**jek**
stick	**stip**	**stit**
pipe	pite	
bike	bipe	
	vake	*clek*
	vape	*clep*
	vate	*clet*

Note. The left-hand column shows the known words (in bold). The two columns under the 'Novel Words' heading show the minimal pairs with these known words (also in bold) along each row. The top four rows show the minimal triplets, two of which were used in each learning task and subsequent MMN oddball session (one on Day 1, and the one on Day 2). Under the words in bold, there are two known-novel word minimal pairs (in plain font), whereby one of the novel items was assigned to the correlated condition and one to the uncorrelated condition. Finally, there are two minimal triplets of novel words (in italics), one shown in each 'Novel Words' column. One minimal pair from each of these triplets would be used in the learning task, with one item of the pair in the correlated learning condition and one in the uncorrelated learning condition. Table 2 in Chapter 5 shows the allocation of these stimuli to learning conditions.

Appendix 5

The auditory profile of the cross-spliced spoken items used in Study 2.

Word	Recognition point (ms)	Length (ms)
bike	344	402
bipe	344	402
boak	369	420
boap	369	420
boat	369	420
jek	316	375
jep	316	375
jet	316	375
kike	369	428
kipe	369	428
kite	369	428
pipe	390	449
pite	390	449
stick	482	542
stip	482	542
stit	482	542
vake	460	521
vape	460	521
vate	460	521
clep	372	430
clek	372	430
clet	372	430

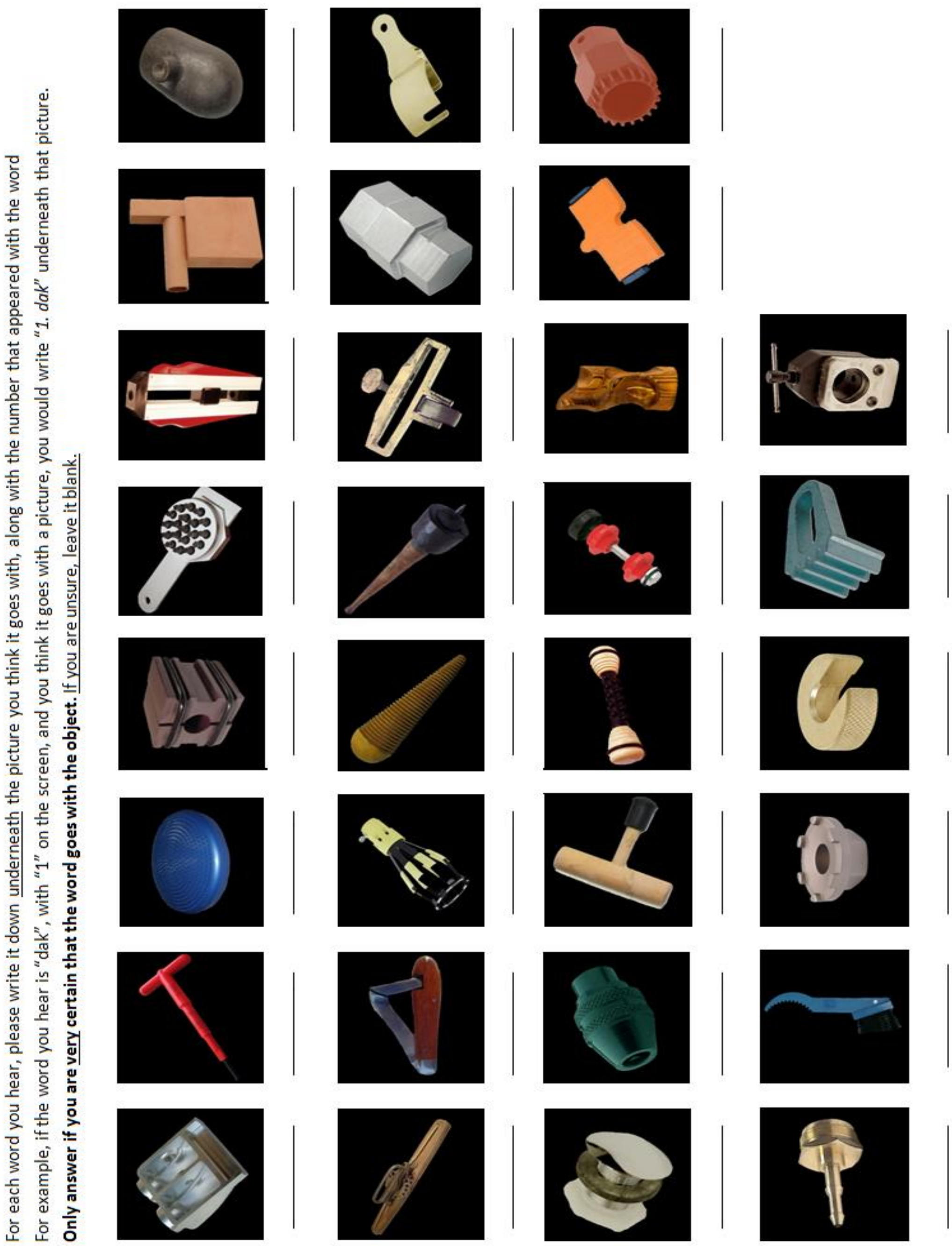
Note. The recognition point and item length is measured in milliseconds from word onset.

Appendix 6

The known word referent pictures used in Study 2. The novel object pictures were the same as those used in Study 1.

Appendix 7

An example of the association recall task used in Study 2.



Appendix 8

The word triplets used in Study 3.

Item	Base word	Novel word 1	Novel word 2	Base word, with pause inserted
1	blossom	blossail	blossain	bloss_om
2	pulpit	pulpen	pulpek	pulp_it
3	lantern	lantobe	lantoke	lant_ern
4	partridge	partred	partren	partr_idge
5	parsnip	parsneg	parsnes	parsn_ip
6	molecule	molekyen	molekyek	molec_ule
7	biscuit	biscal	biscan	bisc_uit
8	capsule	capsyod	capsyoff	caps_ule
9	tulip	tulode	tulome	tul_ip
10	cataract	catarist	catarill	catar_act
11	pelican	pelikiyve	pelikibe	pelic_an
12	skeleton	skeletobe	skeletope	skelet_on
13	apricot	aprickel	apricken	apric_ot
14	clarinet	clarinern	clarinerl	clarin_et
15	ornament	ornameast	ornameab	ornam_ent
16	badminton	badmintel	badmintet	badmint_on
17	anecdote	anecdel	anecden	anecd_ote
18	decibel	decibit	decibice	decib_el
19	spasm	spaset	spasel	spas_m
20	bayonet	bayoniss	bayonil	bayon_et
21	tycoon	tycol	tycoff	tyc_oon
22	crocodile	crocodiss	crocodin	crocod_ile
23	yoghourt	yogem	yogell	yog_hourt
24	moped	mopall	mopass	mop_ed
25	bramble	brambooce	bramboof	bram_ble
26	octopus	octopoth	octopol	octop_us
27	pyramid	pyramon	pyramotch	pyram_id
28	fountain	fountel	founted	fount_ain
29	hyacinth	hyasel	hyased	hyac_inth
30	assassin	assassool	assassood	assass_in
31	napkin	napkem	napkess	napk_in
32	parachute	parasheff	parashen	parach_ute
33	onslaught	onsleete	onsleeth	onsl_aught
34	baboon	babeel	babeen	bab_oon
35	siren	siridge	sirit	sir_en
36	amulet	amulos	amulok	amul_et
37	canyon	canyel	canyes	cany_on
38	cartridge	cartroce	cartrole	cartr_idge
39	daffodil	daffadat	daffadan	daffod_il
40	cardigan	cardigite	cardigile	cardig_an

Appendix 8 continued

41	ravine	ravooce	ravoole	rav_ine
42	caravan	caravoth	caravol	carav_an
43	culprit	culpren	culpred	culpr_it
44	profile	profon	profod	prof_ile
45	mucus	muckip	muckin	muc_us
46	canvas	canvick	canvit	canv_as
47	cathedral	cathedruke	cathedruce	cathedr_al
48	mandarin	mandarook	mandarool	mandar_in
49	squirrel	squirrome	squirrope	squirr_el
50	dolphin	dolpheg	dolphess	dolph_in
51	alcohol	alcohin	alcohid	alcoh_ol
52	dungeon	dungeill	dungeic	dung_eon
53	hurricane	hurricarb	hurricarth	hurric_ane
54	lectern	lectas	lectack	lect_ern
55	artichoke	artiched	artichen	artich_oke
56	gimmick	gimmon	gimmod	gimm_ick
57	slogan	slowgiss	slowgith	slog_an
58	grimace	grimin	grimib	grim_ace
59	mistress	mistrool	mistrooke	mistr_ess
60	methanol	methanack	methanat	methan_ol
61	pedestal	pedestoke	pedestode	pedest_al
62	specimen	specimal	specimav	specim_en
63	consensus	consensom	consensog	consens_us
64	utensil	utensont	utensop	utens_il
65	aubergine	aubergore	aubergette	auberg_ine
66	diplomat	diplomul	diplomig	diplom_at
67	veranda	verandab	verandaf	verand_a
68	metronome	metronash	metronip	metron_ome
69	revenue	revenyol	revenyem	reven_ue
70	albatross	albatrum	albatrit	albatr_oss
71	anvil	anvik	anvit	anv_il
72	cactus	cactul	cactuk	cact_us
73	magenta	magentald	magentaft	magent_a
74	flotsam	flotsaise	flotsote	flots_am
75	barnacle	barnaci	barnacu	barnac_le
76	tissue	tissuge	tissup	tissu_e
77	tavern	tavite	tavile	tav_ern
78	haddock	haddale	haddan	hadd_ock
79	gelatine	gelatord	gelatorl	gelat_ine
80	hormone	hormice	hormike	horm_one

Appendix 9

The filler items used in the pause detection task in Study 3.

Filler items	Pause inserted	Filler items	Pause inserted
abbey	abb_ey	button	b_utton
abdomen	ab_domen	cable	cabl_e
abrasive	abra_sive	camouflage	camoufl_age
ache	a_che	carol	c_arol
acrobat	acrob_at	casserole	casser_ole
acrylic	ac_rylic	cedar	ced_ar
address	a_ddress	cellar	cella_r
adrift	adrif_t	cement	cem_ent
aerial	ae_rial	chocolate	chocolat_e
aggregate	aggreg_ate	chrome	chr_ome
albino	alb_ino	cinnamon	cinn_amon
alien	al_ien	circuit	circ_uit
aloof	aloo_f	clique	cli_que
amalgam	a_malgam	cloak	c_loak
anchor	anch_or	cloud	cl_oud
antenna	antenn_a	composite	comp_osite
arena	aren_a	compound	comp_ound
aroma	arom_a	compromise	co_mpromise
aside	as_ide	conjecture	con_jecture
atlas	at_las	console	consol_e
avenue	a_venue	cortex	cort_ex
bachelor	bachel_or	costume	co_stume
balance	balan_ce	crank	cran_k
balcony	balc_ony	crate	cr_ate
ballad	ball_ad	crook	cr_ook
banana	b_anana	crossroads	crossroad_s
bankrupt	b_ankrupt	cubicle	cubicl_e
barbecue	barbec_ue	debate	deb_ate
bargain	barg_ain	decree	decr_ee
basket	b_asket	delinquent	delinqu_ent
bench	ben_ch	diamond	diam_ond
bible	bib_le	dilute	di_lute
bikini	bik_ini	diploma	di_ploma
bishop	bish_op	discipline	discipl_ine
blackmail	black_mail	discredit	discred_it
bourgeois	bour_geois	disregard	disre_gard
brat	b_rat	domain	dom_ain
broom	broo_m	domestic	d_omestic
brush	b_rush	draft	draf_t
buffalo	bu_ffalo	duplicate	d_uplicate
earnest	ea_rnest	mirror	m_irror

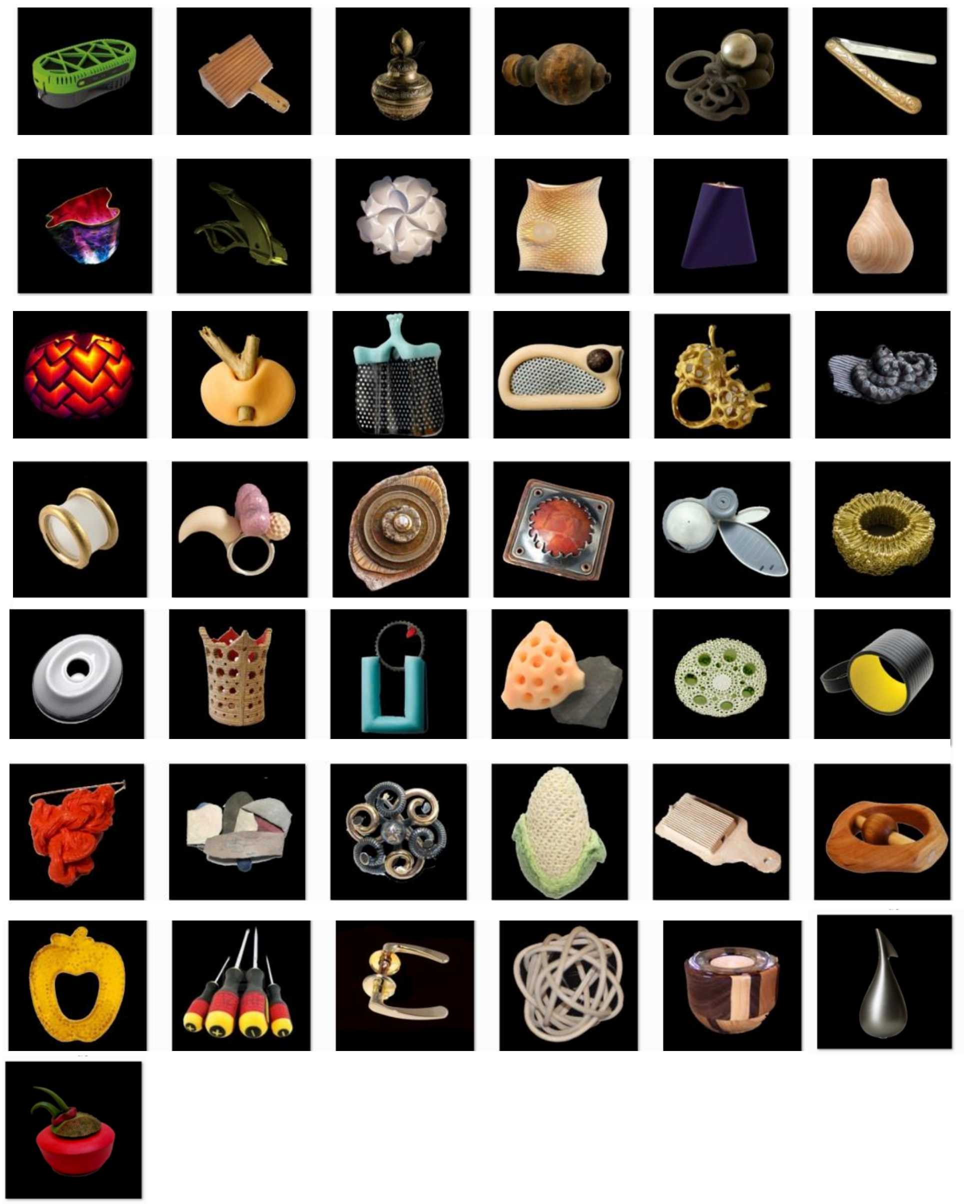
Appendix 9 continued

echo	ech_o	mortgage	m_ortgage
elder	e_lder	mushroom	mush_room
embryo	embr_yo	nationwide	nationwi_de
empire	em_pire	oblong	ob_long
enamel	en_amel	occult	occul_t
evening	even_ing	octagon	octag_on
exhaust	exh_aust	octave	octav_e
fault	faul_t	opera	o_pera
fiesta	fi_esta	optimum	op_timum
fist	fi_st	oracle	oracl_e
flint	flin_t	pagoda	pag_oda
formula	formul_a	paradise	pa_radise
gent	g_ent	parallel	parall_el
ghost	ghos_t	parasite	paras_ite
goliath	goli_ath	parasol	p_arasol
goodnight	goodnigh_t	pedigree	pedi_gree
gorilla	gorill_a	physique	physi_que
gossip	go_ssip	picnic	pi_cnic
graffiti	graff_iti	pinpoint	pin_point
grammar	gram_mar	pint	pi_nt
grease	greas_e	pirate	pira_te
griffin	griff_in	plain	p_lain
groom	gr_oom	plot	plo_t
grotesque	grotesqu_e	plum	plu_m
habitat	habita_t	plume	plum_e
hammer	hamm_er	prayer	pray_er
harlequin	harl_equin	premier	pr_emier
harness	harn_ess	primary	prim_ary
harvest	harv_est	prose	pr_ose
hemp	he_mp	protestant	protest_ant
holiness	holine_ss	protocol	pro_tocol
hook	h_ook	province	prov_ince
intellect	intell_ect	pumpkin	pumpk_in
invalid	inval_id	puzzle	puzz_le
jargon	j_argon	quid	q_uid
kiln	kil_n	quote	q_uote
lamp	l_amp	regulate	reg_ulate
lavender	lav_ender	relinquish	re_linquish
lettuce	lettuc_e	rents	rent_s
locust	l_ocust	reptile	r_eptile
maggot	magg_ot	restaurant	restaur_ant
martyr	mart_yr	riverside	ri_verside
mascara	mascar_a	salad	sa_lad
massacre	massa_cre	sandal	s_andal
matron	m_atron	sapphire	sapph_ire

merit	m_erit	testament	testa_ment
metaphor	met_aphor	tomato	t_omato
scout	sc_out	treasure	tr_easure
scaffold	scaff_old	trauma	trau_ma
scorpion	sc_orpion	tribe	tr_ibe
scrap	scra_p	tribune	tribun_e
screw	scr_ew	trifle	t_rifle
sect	se_ct	trinity	tr_inity
self	se_lf	trough	trou_gh
semester	se_mester	turquoise	turqu_oise
seminar	semin_ar	twentieth	twen_tieth
shanghai	shan_ghai	umbrella	umbrell_a
shower	sh_ower	vaccine	v_accine
shrub	shr_ub	vanilla	vanill_a
sinus	sin_us	venom	ven_om
skirt	skir_t	vertigo	ve_rtigo
slang	sl_ang	vigil	vig_il
slave	sl_ave	vitamin	vitam_in
snack	sn_ack	warrant	w_arrant
snag	s_nag	whistle	whistl_e
soldier	sol_dier	worship	worsh_ip
spike	sp_ike	wrench	wren_ch
spire	spir_e	zeppelin	zeppel_in
spruce	sp_ruce		
squad	squ_ad		
squire	s_quire		
stamina	stamin_a		
statistic	st_atistic		
statue	stat_ue		
stem	st_em		
stereo	stere_o		
stream	str_eam		
stress	stre_ss		
stud	stu_d		
stump	stu_mp		
stunt	stun_t		
sublime	subli_me		
succulent	su_cculent		
summons	su_mmons		
sweat	sw_eat		
switch	sw_itch		
symbol	symb_ol		
symptom	sympto_m		
tarmac	tarm_ac		
tennis	ten_nis		

Appendix 10

The novel picture stimulus set used in Study 3. The 43 pictures on this page, along with the 40 object pictures in Appendix 3, constituted the 83 pictures selected via a Google image search used in Study 3.



Appendix 10 continued.

The pictures on this page are the remaining 45 pictures used in Study 3, which were selected from the NOUN database (Horst & Hout, 2014).

Appendix 11

The 80 additional triplets used in Study 4, along with the 80 items presented in Appendix 8.

Item	Base word	Novel word 1	Novel word 2	Base word, with pause inserted
81	umpire	umpiam	umpiack	ump_ire
82	mushroom	mushrood	mushrook	mushroo_m
83	agenda	agenfi	agento	agen_da
84	balcony	balcozo	balcola	balc_ony
85	fanfare	fanfairge	fanfairn	fanfar_e
86	asbestos	asbestash	asbestib	asbest_os
87	cobalt	cobalve	cobalk	coba_lt
88	murder	murdek	murdell	murd_er
89	scaffold	scaffost	scaffont	scaff_old
90	succulent	succulelv	succulumph	succul_ent
91	signature	signatik	signatad	signa_ture
92	tranquil	tranquet	tranquowl	tranqu_il
93	portcullis	portcullate	portculluv	portcull_is
94	kiosk	kiosd	kiosp	kios_k
95	bachelor	bachelil	bacheludge	bachel_or
96	tarpaulin	tarpaulos	tarpaulurb	tarpaul_in
97	somersault	somersaumf	somersausp	somers_ault
98	astute	astum	astul	astu_te
99	thorax	thorant	thoralt	thor_ax
100	impromptu	impromptrow	impromptlai	imprompt_u
101	porcelain	porcelail	porcelais	porcela_in
102	marmoset	marmosum	marmosole	marmos_et
103	costume	costuke	costute	cost_ume
104	peculiar	peculiet	peculiop	pecul_iar
105	spider	spidet	spided	spid_er
106	atlas	atlal	atlap	atla_s
107	graffiti	graffino	graffipaw	graff_iti
108	kangaroo	kangami	kangada	kang_aroo
109	vitamin	vitamek	vitamat	vita_min
110	torment	tormeft	tormeld	torme_nt
111	sesame	sesamo	sesamuy	sesam_e
112	shrapnel	shrapno	shrapnu	shrapn_el
113	athlete	athlove	athlake	athl_ete
114	porcupine	porcupas	porcupot	porcup_ine
115	tandem	tandek	tandell	tand_em
116	sarcasm	sarcasol	sarcaseed	sarcas_m
117	orthodox	orthodolv	orthodont	orthod_ox
118	mayonnaise	mayonnote	mayonneure	mayonn_aise
119	vector	vectom	vectol	vect_or

Appendix 11 continued

120	funeral	funeret	funerine	fune_ral
121	origin	origive	origisse	orig_in
122	paprika	paprilay	paprimo	papri_ka
123	pumpkin	pumpkige	pumpkish	pumpk_in
124	placenta	plassybup	placenfi	plac_enta
125	sovereign	soverot	soverep	sover_eign
126	jargon	jargos	jargol	jarg_on
127	crevasse	creval	crevaf	creva_sse
128	angel	angesh	angev	ange_l
129	nugget	nuggev	nugges	nugg_et
130	turquoise	turquoil	turquoit	turquo_ise
131	mandolin	mandolut	mandolul	mandol_in
132	jasmine	jasmIt	jasmis	jasm_ine
133	chimpanzee	chimpantu	chimpando	chimpan_zee
134	picnic	picnin	picnib	picn_ic
135	chocolate	chocolor	chocolil	choco_late
136	lozenge	lozeld	lozex	loz_enge
137	couscous	couscall	couscette	cousc_ous
138	broccoli	broccaroo	broccato	brocc_oli
139	tempest	tempeld	tempeft	temp_est
140	guitar	guitas	guitat	guit_ar
141	scoundrel	scoundrait	scoundriff	scound_rel
142	vortex	vortent	vortest	vort_ex
143	algebra	algeblu	algebzi	algeb_ra
144	alien	aliet	aliek	alie_n
145	vaccine	vaccik	vaccisse	vacc_ine
146	avalanche	avalaks	avalast	aval_anche
147	mackintosh	mackintith	mackintetch	mackint_osh
148	protocol	protocare	protokit	proto_col
149	soluble	soluba	solubi	solub_le
150	thermostat	thermostoob	thermostiv	thermo_stat
151	kimono	kimota	kimodu	kimo_no
152	caramel	caramen	caramet	caram_el
153	volcano	volcagi	volcashu	volc_ano
154	lament	lamex	lameft	lame_nt
155	mayhem	mayhek	mayhes	mayh_em
156	pamphlet	pamphlell	pamphlove	pamph_let
157	formula	formubo	formuta	form_ula
158	sergeant	sergeast	sergeax	serg_eant
159	ointment	ointmex	ointmeld	ointm_ent
160	penguin	pengwove	pengwal	peng_uin

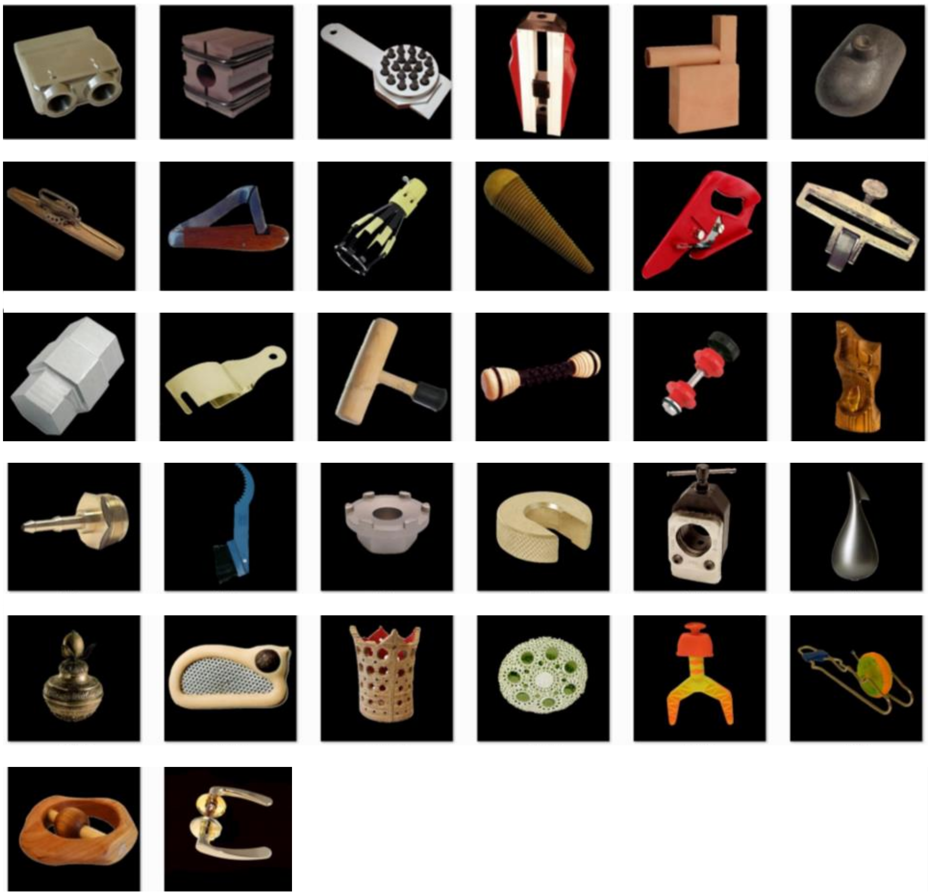
Appendix 12

The 80 additional filler items used in the pause detection task in Study 4, which were used along with 208 of the fillers presented in Appendix 9.

Filler items	Pause inserted	Filler items	Pause inserted
alibi	a_libi	corduroy	cor_duroy
banjo	ban_jo	donkey	don_key
bingo	bing_o	flimsy	flims_y
bungalow	bun_galow	libido	li_bido
cargo	car_go	memento	mem_ento
chassis	chass_is	mildew	mild_ew
coyote	c_oyote	placebo	pla_cebo
cranny	cran_ny	potato	po_tato
curfew	curf_ew	soprano	sopran_o
dainty	d_ainty	tornado	t_ornado
debut	de_but	rescue	res_cue
derby	der_by	viaduct	viadu_ct
embargo	em_bargo	dinosaur	di_nosaur
empty	emp_ty	platform	platf_orm
emu	em_u	tuxedo	tuxe_do
fancy	f_ancy	trombone	tr_ombone
fiasco	fia_sco	fugitive	fug_itive
flamingo	flaming_o	target	targ_et
jackdaw	j_ackdaw	rhythm	rhy_thm
jersey	jer_sey	fortune	fort_une
jiffy	jiff_y	lurid	lur_id
monkey	m_onkey	pelvis	p_elvis
nephew	neph_ew	silhouette	silhoue_tte
parsley	parsl_ey	prohibit	prohib_it
ratio	ra_tio	falcon	fal_con
rodeo	rod_eo	banister	banist_er
rugby	rugb_y	gadget	ga_dget
sinister	s_inister		
slaughter	slaugh_ter		
slender	slend_er		
sonata	so_nata		
stiletto	stil_etto		
swallow	s_wallow		
tattoo	ta_ttoo		
widow	wid_ow		
worry	worr_y		
cabaret	cab_aret		
casino	cas_ino		
chutney	chutn_ey		

Appendix 13

The 32 picture stimuli used in Study 4.



Appendix 14

A review of the lexicalization literature grouped by training task, declarative memory consolidation, and the timecourse of lexicalization.

Paper	Novel word training	Declarative memory consolidation over 24h	Lexicalization timecourse	Lexicalization test
Section 1: Phonological training with no declarative memory improvement over consolidation				
Bakker, Takashima, van Hell, et al. (2014)	Phoneme/letter monitoring	No in 2AFC	Lexicalization after 24 hours *(train-test uni and crossmodal)*	Pause detection and semantic decision
	Letter monitoring	No in 2AFC	No lexicalization until 1 week *(crossmodal)*	Pause detection
Dumay & Gaskell (2007)	Phoneme monitoring	No in 2AFC	Lexicalization after 12 hours, only with sleep	Pause detection
Dumay, Gaskell, & Feng (2004)*	Phoneme monitoring	No until 1 week, in 2AFC	Lexicalization after 24 hours *(Exp.1)*	Lexical decision
	Sentences with meaning	No until 1 week, in 2AFC	ΔNo lexicalization until 1 week *(Exp. 1)*	Lexical decision
Gaskell & Dumay (2003)	Phoneme monitoring	No in 2AFC	Lexicalization after 1 week *(Exp. 3; earliest test)*	Pause detection
Takashima, Bakker, van Hell, et al. (2014)*	Phoneme monitoring	No in recognition memory	Lexicalization after 24 hours	Pause detection
Tamminen & Gaskell (2008)	Phoneme monitoring†	No in 2AFC	Lexicalization after 1 week *(earliest test)*	Lexical decision
Section 2: Phonological training with declarative memory improvement over consolidation				
Brown, Weighall, Henderson, & Gaskell (2012)	Phoneme monitoring†	Yes in 2AFC and free recall	Lexicalization after 24 hours *(suggestive)*	Lexical decision
Davis, Di Betta, Macdonald, & Gaskell (2009)	Phoneme monitoring	Yes in recognition memory	Lexicalization after 24 hours *(Exp. 1)*	Lexical decision
Dumay & Gaskell (2012)	Phoneme monitoring	Yes in 2AFC and free recall	Lexicalization after 24 hours	Pause detection
Henderson, Powell, Gaskell, & Norbury (2014)	Phoneme monitoring†	Yes in recognition and cued recall	Lexicalization after 24 hours *(TD children)*	Pause detection
Henderson, Weighall, & Gaskell (2013)	Phonological tasks† with written forms	Yes in cued recall	Lexicalization after 24 hours	Pause detection
	Phonological tasks† with pictures	Yes in 2AFC and cued recall	Lexicalization after 24 hoursΔ	Pause detection

Appendix 14 continued

Paper	Novel word training	Declarative memory consolidation over 24h	Lexicalization timecourse	Lexicalization test
Henderson, Weighall, Brown, & Gaskell (2013)	Phoneme monitoring†	Yes in 2AFC and cued recall (for children and adults)	Lexicalization after 24 hours (for children and adults)	Pause detection
Dumay, Gaskell, & Feng (2004)*	Phoneme monitoring	Yes in 2AFC and free recall	Lexicalization after 24 hours *(Exp. 2)*	Pause detection
Takashima, Bakker, van Hell, et al (2014)*	Phoneme monitoring with picture associations	Yes in recognition memory	[Δ]No lexicalization after 24 hours	Pause detection
Section 3:Phonological training with lexicalization before sleep-based consolidation				
Brown, Weighall, Henderson, & Gaskell (2012)	Phoneme monitoring†	Yes in 2AFC and free recall	Lexicalization immediately *(12-year-olds)*	Lexical decision
Lindsay & Gaskell (2013)	Phoneme monitoring with spaced learning and interleaving	Yes in 2AFC	Lexicalization before sleep	Lexical decision
Tamminen, Payne, Stickgold, et al. (2010)	Phoneme monitoring	Yes in old-new categorization speed	Lexicalization before sleep	Lexical decision
Kapnoula, Packard, Gupta, & McMurray (2015)	Phoneme monitoring Reptition and stem completion	Not tested	Lexicalization immediately	Eyetracking (visual world paradigm)
Section 4: 'Implicit' training with lexicalization before sleep-based consolidation				
Coutanche & Thompson-Schill (2014)	Fast mapping, explicit encoding, and incidental encoding	No in recognition and recall	[Δ]Lexicalization immediately, for 'fast mapping' words only	Semantic categorisation
Fernandes, Kolinsky, & Ventura (2009)	Statistical learning	No in 2AFC	Lexicalization immediately	Lexical decision
Szmalec, Page, & Duyck (2012)	Hebbian learning (visual)	Not measured	Lexicalization after 12 hours, with or without sleep	Pause detection

Appendix 14 continued

Notes. This table is divided into four sections which organise the literature base on the training task used, any declarative memory enhancement after 24 hours of consolidation, the time-course for lexicalization to emerge, and the lexicalization test used. Section 1: Phonological training (with the exception of Dumay et al., 2004), with no declarative memory improvement over consolidation, and lexicalization after overnight consolidation.
Section 2: Phonological training (with the exception of Henderson, Weighall, & Gaskell, 2013, and Takashima et al., 2014), with declarative memory improvement over consolidation, and lexicalization after overnight consolidation (in all but one case).
Section 3: Phonological training, with lexicalization occurring without sleep-based consolidation.
Section 4: Broadly 'implicit' learning tasks, with lexicalization occurring before sleep.
Declarative memory consolidation is the reported enhancement in declarative memory over the first 24 hours of consolidation, the time window in which lexicalization often emerges. For cases in which improvement was within a day, or between sessions separated by a period of wake, this is flagged.
For simplification, this review only includes studies testing lexical competition between newly-trained words and their existing phonological neighbours (all lexicalization tests are on existing words). Studies testing aspects of consolidation outside lexicalization such as semantic integration, abstraction, and generalisation have thus been excluded for ease of interpretation. *Lexicalization timecourse* reports the earliest test point at which lexicalization was observed. The effect remained at later time points unless otherwise stated.

* These papers have results reported in two sections of the table (due to different relationships between declarative memory and lexicalization across training conditions or experiments).
† 'Phoneme monitoring' refers to phonological-based training tasks including phoneme monitoring, phoneme segmentation, phoneme isolation, and repetition. These training tasks have been grouped under the label 'phoneme monitoring' for ease of interpretation here. The † symbol indicates cases where training involved phonological tasks outside phoneme monitoring.
$^{\Delta}$ This denotes lexicalization effects for semantic training.