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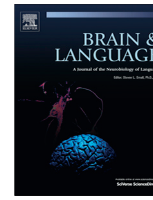

Review

Novel word learning in older adults: A role for sleep?

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ABSTRACT

Sleep is an offline period during which newly acquired semantic information is transformed into longer-lasting memories. Language acquisition, which requires new word learning and semantic integration, is preferentially benefitted by a period of sleep in children and young adults. Specific features of sleep (e.g., sleep stage characteristics) have been associated with enhanced language acquisition and generalization. However, with increasing age, even in healthy individuals, sleep quality and quantity decrease. Simultaneously, deficits in word retrieval and new word learning emerge. Yet it is unknown whether age-related alterations in language ability are linked with alterations in sleep. The goal of this review is to examine changes in language learning and sleep across the lifespan. We consider how sleep detriments that occur with aging could affect abilities to learn novel words and semantic generalization and propose hypotheses to motivate future research in this area.

Contents

1. Introduction

Language is the system by which limitless ideas are conveyed through a limited set of spoken or written units. Humans are

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unique in their development of expansive lexicons that continue to evolve throughout the lifespan. Learning new words and incorporating them into the lexicon is a strong determinant of academic achievement in children and adolescents (Marzano, 2004). Importantly, word learning is not unique to development. The learning of new vocabulary into adulthood is imperative for succeeding in a number of areas, such as within the scientific community (Hayes, 1992) and may challenge the ability of older adults to acquire the technical terminology in evolving occupations. Additionally, new language learning has been associated with structural and functional changes within the brain in both younger and older adults (see review: Li, Legault, & Litcofsky, 2014). As such, a better understanding of the ways in which new words are learned can benefit individuals across a range of ages and disciplines.

Novel word learning and language acquisition are benefited by sleep in young adults and children. The complementary learning systems framework is often cited as the process through which new words are learned (Davis & Gaskell, 2009). In this model, the hippocampal system encodes novel words rapidly, while the neocortical system is involved in the more gradual integration of the novel words into the existing lexicon (Frankland & Bontempi, 2005; O'Reilly & Norman, 2002). During an 'offline' period of disengagement, such as during a period of sleep, information is transferred from hippocampal to neocortical storage, protecting the information from interference, and gradually becoming independent of hippocampal activation (Diekelmann & Born, 2010; Spencer, 2013).

However, sleep (Ohayon, Carskadon, Guilleminault, & Vitiello, 2004), language learning (Nyberg, Bäckman, Erngrund, Olofsson, & Nilsson, 1996), and sleep-dependent consolidation of newly learned information (Wilson, Baran, Pace-Schott, Ivry, & Spencer, 2012) all change across the lifespan, and each are decremented by aging. As such, it is likely that the role of sleep in novel word learning is affected by aging. The aim of this review is to examine the role of sleep in language acquisition across the lifespan and how this might change in older adulthood.

2. Sleep and language

2.1. Sleep and language acquisition

Sleep benefits memory (see review: see Stickgold, 2005), particularly for declarative information (Gais & Born, 2004). For example, when sleep follows learning of either semantically related (Plihal & Born, 1997) or unrelated (Wilson et al., 2012) word-pairs, memory retention across a delay containing sleep is greater than when compared to retention across an equivalent period of wake.

The majority of research examining the relationship between sleep and novel word acquisition has been conducted in developmental and young adult populations. For example, napping improves novel word retention and generalization in infants aged 9 and 16 months of age (Friedrich, Wilhelm, Born, & Friederici, 2015; Horváth, Myers, Foster, & Plunkett, 2015). Similarly, fifteen-month old children exposed to an artificial language were better able to abstract and generalize language rules to novel stimuli following a nap compared to performance following an equivalent interval of wake. Interestingly, however, there were no significant nap-related differences on veridical recall (Gómez, Bootzin, & Nadel, 2006; Hupbach, Gomez, Bootzin, & Nadel, 2009). In 3-year-old children, napping led to an increased ability to identify novel objects with nonsense word names in a children's book. This design mimicked the way in which children are often naturally exposed to new words. Importantly, this nap-related improvement in word retention was long-lasting, still present seven days later (Williams & Horst, 2014). Likewise, a sleep benefit can be seen in foreign language learning in late adolescence, a time in which many students are exposed to new language learning through their education. English-speaking high school students (17 years of age) were better able to remember English-German vocabulary word pairs when nocturnal sleep followed learning compared to when daytime wake separated learning and recall (Gais, Lucas, & Born, 2006).

Recently, work from our lab demonstrated that overnight sleep also benefits the veridical memory involved in novel word learning in young adults (Kurdziel & Spencer, 2015). In this study, college students (18–30 years of age) were asked to learn rarely used word-definition pairs from their native English language. This paradigm allowed us to probe the way in which new vocabulary is typically added to the lexicon in higher education. Using novel English words for native English speakers also allows for pre-existing language rules to be used during encoding. Following 12 h that contained sleep or 12 h of daytime waking, students were shown the definitions of the encoded items and were asked to recall the correct word. Sleep protected memory for the novel words, whereas waking led to significant forgetting, thus supporting the role of sleep on veridical memory for novel words in young adults.

2.2. Sleep and lexical integration

In addition to being critical for language acquisition, sleep has also been shown to be important for integrating new words into the lexicon. In one such study, children between the ages of 5 and 12 years encoded novel words that shared syllables with known English words, and were tested on a lexical competition task following a delay. In the lexical competition task, if the new words (e.g. *biscal*) became part of the lexicon, they should compete with, and slow the recognition of, the existing phonological counterparts (e.g. *biscuit*). Lexical competition was only observed in the condition in which sleep followed encoding of the novel words, suggesting that sleep is necessary to integrate novel words into the existing lexicon (e.g. Henderson, Weighall, Brown, & Gareth Gaskell, 2012). Similar sleep-dependent lexical integration in young children has been observed across a number of different paradigms. For instance, when real novel words were used in place of artificial language (e.g. the novel *hippocampus* competing with the existing *hippopotamus;* (Henderson, Weighall, & Gaskell, 2013), sleep is, again, essential for competition effects. Likewise, when novel artificial words (e.g. *daffodat* competing with *daffodil*) were learned as part of a storybook, and were thus encoded through a more naturalistic incidental exposure, lexical competition was greatest following sleep (Henderson, Devine, Weighall, & Gaskell, 2015).

The role of sleep in lexical development is also supported by studies in young adults. Dumay and Gaskell (2007) demonstrated that overnight sleep benefited both veridical recall of newly learned artificial words, as well as the incorporation of those words into the existing lexicon. It is important to note, however, that novel word integration can be achieved in the absence of sleep, but only with repeated additional exposures across the day to both the novel words and the associated existing lexical counterparts (Lindsay & Gaskell, 2013).

Language acquisition and integration is complex, and multiple processes are necessary for successful learning. As such, the role of sleep in language learning must be examined from all perspectives. Generalization of newly acquired language rules is one such aspect of language acquisition. Fenn, Nusbaum, and Margoliash (2003) assessed the role of sleep in the generalization of phonological categories across varying acoustic patterns. A naturalistic spoken language learning task was used such that training on a subset of artificial monosyllabic consonant-vowel-consonant words improved performance on a new set of words that contained the same phonemes. However, this improvement occurred only when the 12-h delay included overnight sleep. As the words were unique in each session, improvements cannot be due to a sleep benefit on veridical memory. Rather, sleep must also serve an additional role in perceptual generalization common in language learning. Similarly, Tamminen, Davis, Merkx, and Rastle (2012) trained individuals on words with novel affixes (e.g. *climbnule* = someone who climbs mountains with dangerous peaks), and then observed generalization to novel stems (e.g. *sailnule*). Generalization was not observed directly following learning, but only after a 2-day delay. While this study did not specifically test for the function of sleep on this task, the authors ascribe the delayed generalization to consolidation, likely across the intervening sleep bouts.

2.3. Neural basis of sleep's role in language

Sleep has been shown to play a role in brain plasticity. Neurophysiological and neuroimaging studies have implicated sleep in the consolidation of memory traces through both thalamocortical and hippocampocortical networks (see review: Dang-Vu, Desseilles, Peigneux, & Maquet, 2006). For example, Peigneux et al. (2004) used positron emission tomography (PET) to observe activation of specific areas of the hippocampus during a spatial navigation task. During subsequent sleep, and specifically slow wave sleep (SWS), a sleep stage characterized by large amplitude, slow EEG waves, those same areas of the hippocampus were reactivated. Importantly, greater reactivation of the hippocampus during sleep was associated with improved performance following the sleep bout. The authors concluded that processing of recent memory traces during sleep promotes plastic changes to stabilize and strengthen the memory.

This work is also consistent with studies examining the neural basis of sleep dependent language learning. Based on the complementary learning systems framework (McClelland, McNaughton, & O'Reilly, 1995; O'Reilly, Bhattacharyya, Howard, & Ketz, 2014), novel words are encoded in the hippocampus and transferred gradually to neocortical stores during offline periods. Using functional magnetic resonance imaging (fMRI), the cortical underpinnings of the lexical integration of novel words was assessed with a lexical competition task (Davis, Di Betta, Macdonald, & Gaskell, 2008). Post-learning retention of the artificial words was correlated with hippocampal activation during learning. Following overnight sleep, cortical activation was similar for both the novel fictitious word (e.g. *cathedruke*) and the associated English word currently in the lexicon (e.g. *cathedtral*). Sleep was critical, as additional exposure in the absence of sleep did not affect cortical activation generated by the new word presentations. This work further supports the two-process complementary learning systems framework, and that this shift from hippocampal to neocortical storage is specifically enhanced during periods of sleep.

2.4. Sleep physiology and language learning

A number of studies have assessed sleep physiology in order to further support the active role of sleep in language acquisition. Most commonly, SWS (Gaskell et al., 2014), and sleep spindles (Tamminen, Payne, Stickgold, Wamsley, & Gaskell, 2010), high frequency theta bursts indicative of thalamocortical, or hippocampocortical interaction (see review: De Gennaro & Ferrara, 2003), are implicated in consolidation of newly learned words and integration into the lexicon. For example, nocturnal SWS was associated with veridical novel word memory recognition, whereas sleep spindles were positively associated with lexical integration of novel words into the existing lexicon (Tamminen et al., 2010).

Additionally, both sleep spindles and Slow Wave Activity (SWA), the spectral power in the delta frequency band (0.5–4 Hz), have been shown to be involved in integrating new information into pre-existing knowledge (Tamminen, Ralph, & Lewis, 2013). Tham, Lindsay, and Gaskell (2015) assessed whether SWS or spindles would integrate novel words into the lexicon within the context of their meanings. Following training on English-Malay translations, performance benefits following sleep were observed for both a size congruency and a semantic distance task, two paradigms that have been used previously to measure access to word meanings. In the size congruency task, when asked to select either the physically larger font size, or the larger referent, judgments are faster if these two size dimensions are congruent (e.g. BEE-COW), than if they are incongruent (e.g. BEE-COW). Comparatively, in the semantic distance task, faster judgments are made when referent size distance is greater (e.g. BEE-COW) than when they are more similar (e.g. BEE-CAT). Performance on the semantic distance task was positively associated with SWS, whereas size congruency was associated with sleep spindles.

Previous work has demonstrated a role of REM sleep in both the abstraction of relevant information and the integration of new memories into existing schemas (see reviews: Spencer, 2013; Walker & Stickgold, 2010). As such, REM is a potential candidate for aiding in the abstraction of linguistic rules as well as semantic integration during sleep. A recent study has implicated REM sleep in language processing, but only in combination with SWS (Batterink, Oudiette, Reber, & Paller, 2014). Batterink and colleagues compared an integrated measure of REM and SWS to sleep-related performance benefits on a hidden linguistic rule task. In this task, individuals had to learn an underlying rule about how novel word articles predicted the subsequent noun categories (e.g. *gli* rhino). They report increased sensitivity to the hidden linguistic rule following sleep (an afternoon nap). The authors suggest that the combination of both SWS and REM sleep may synergistically lead to abstraction of the underlying rules when learning a new language. Previous studies have suggested that these sleep stages work in succession on the stabilization and integration of memories (Ficca, Lombardo, Rossi, & Salzarulo, 2000; Sonni & Spencer, 2015). It is possible that SWS was necessary for the veridical consolidation of the newly learned words, whereas REM sleep was then necessary for extracting the underlying rule in which these new words were used. However, the role of REM sleep in language integration requires further examination.

These studies support the role of sleep in the acquisition of novel words and their meanings, and the incorporation of these words into the lexicon. Specifically, the synchrony of neuronal firing (Marshall, Helgadóttir, Mölle, & Born, 2006) and the reactivation of hippocampal networks (Gais & Born, 2004) during SWS are thought to be critical for the plastic changes underlying the stabilization and strengthening of newly acquired declarative memories. Whereas the integration of novel words into the existing lexicon has been most consistently associated with sleep spindles, possibly due to the hippocampal-neocortical interaction that underlies these physiological markers (Andrade et al., 2011; Fig. 1). However, REM sleep is also a potential candidate for lexical integration and language rule abstraction. Sleep has been demonstrated to be critical for language acquisition throughout development and into young adulthood. Yet the question remains whether this relationship remains stable throughout the aging process.

3. Language and aging

Investigations into age-related changes in language ability reveal the intricacies of the language system. Subjective reports of language difficulty in older adults do not match objectively-measured

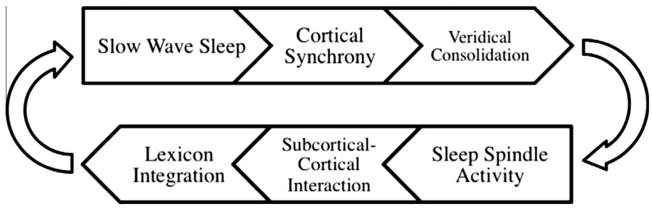

Fig. 1. A model for how sleep-dependent processes facilitate language learning. Slow Wave Sleep is necessary for strengthening and stabilization of newly learned words, contributing to veridical recall. Sleep spindles are indicative of thalamocortical and hippocampocortical interaction, thus possibly fostering the integration of newly learned words into the existing lexicon.

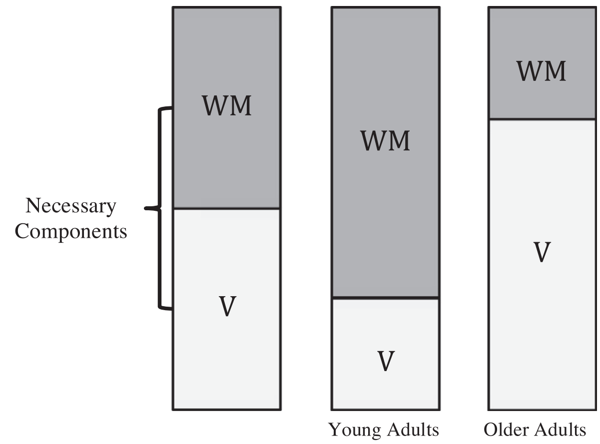

Fig. 2. Age-related differences in lexical integration components. WM = working memory; V = vocabulary. Older adults may overcome working-memory deficits by drawing upon their existing vocabulary to achieve lexical integration as well as young adults.

language ability. For instance, a prevalent memory complaint in older adults is a frequent inability to recall words. However, relative to young adults, older adults have a superior raw vocabulary lexicon, even when being compared to young adults who are more educated (Nyberg et al., 1996). Moreover, the slope of the age-related decline in language ability is far more gradual than that for global memory decline. These contradictory findings suggest there is a specific cognitive element within the language domain that is vulnerable to aging while other components of language ability remain intact (Marshall, 1984).

Indeed, when examining two key elements necessary for language production, 'input' and 'output', the input-related mechanisms remain unchanged throughout aging, while output is reduced (Burke & Mackay, 1997). Interestingly, early investigations failed to capture this deficit: In Studies in which older adults were given a word and asked to recall its definition, older adults performed as well or superior to young adults (Kramer & Jarvik, 1979). Similarly, when shown an incomplete or incorrect version of a word, older adults had no difficulty identifying which word was represented while young adults were more inaccurate (Howard, 1983). However, when the presentation of stimuli was reversed (i.e., participants were given a definition and asked to identify its corresponding word), age-related deficits emerged. Older adults were unable to recall the corresponding word as quickly or accurately as young adults (Bowles & Poon, 1985), suggesting that the word-definition pair may exist within the lexicon but older adults are unable to retrieve the target word without the proper cuing. Supporting this notion, others have found that older adults, relative to young adults, experience more 'tip-of-the-tongue' errors in which they feel certain that they have knowledge of the sought word, yet they are unable to identify it (Burke, MacKay, Worthley, & Wade, 1991). During some of these instances, an individual may be able to identify the first letter of the word, yet not the world itself. Taken together, these findings indicate that age-related language deficits are primarily rooted in retrieval.

In general, retrieval-related difficulties fit within several proposed frameworks of aging that are not specific to language learning but are indeed applicable. It has been posited that crystalized intelligence (e.g., breadth of knowledge, wisdom) remains intact with aging, but 'access' to and 'control' of these thoughts and ideas is diminished with age (Craik & Bialystok, 2006). Similarly, fluid intelligence (e.g., identifying patterns and relationships) has been posited to diminish while crystalized intelligence is preserved. In the case of language learning, it is possible that previously or newly acquired words are encoded and stored as crystalized intelligence, but access to this knowledge is limited.

3.1. Aging and language acquisition

Novel word learning is thought to depend on two elements that differ between young and older adults: Working memory capacity/efficiency and previously-acquired vocabulary (Craik & Jennings, 1992). Older adults have reduced working memory capacity, as has been shown using behavioral testing (Long & Shaw, 2000) and neuroimaging studies (Cabeza, Anderson, Locantore, & McIntosh, 2002). Given these deficits, it could be hypothesized that older adult novel word learning efficiency is reduced with advancing age. However, as previously stated, older adults have a larger lexicon relative to young adults (Howard & Howard, 1989). Therefore, a larger established vocabulary may be sufficient to support novel word learning in older adults.

An early series of studies (discussed below) suggests that increased reliance on this lexicon may provide a means of compensation that restores novel word learning abilities in older individuals. In the first investigation, both young and older adults were asked to memorize pairs of words, one being a familiar English word and the other being a pseudo-English word (either phonologically similar to English words or not) or a Finnish word (Service & Craik, 1993). Separately, working memory and vocabulary ability were gauged. During the recall phase, which was performed immediately after stimuli presentation, young adults recalled more items than older adults, especially when pseudo-English or Finnish words were phonologically similar to common English words. In both groups, working memory performance was positively correlated with task performance, but only in the older adult group was vocabulary ability related to performance. The authors concluded that while young adults store phonological word features in the working memory to enhance performance, older adults rely on both working memory and the existing semantic vocabulary network (Fig. 2).

Long and Shaw (2000) attempted to replicate this finding using a task considered to be more representative of a real-world learning scenario (Gupta, 2003). Given that novel words are typically learned within a sentence that includes contextual significance, it was posited that a task mirroring realistic learning might yield dissimilar results from previous studies (Service et al., 1993). To test this, young and older participants read passages in which a novel word (e.g., qualtagh) was presented in a sentence that included contextual clues. During the subsequent recall, older adults unexpectedly outperformed young adults and recalled more words and their corresponding definitions. Further analyses revealed participants' available lexicon was the greatest predictor of learning success. The authors posited that laboratory-based experimental designs (e.g., paired-associates memorization; (Service et al., 1993) engage working memory abilities, whereas more naturalistic learning paradigms utilize established cognitive abilities (e.g., the

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lexicon). Consequently, older adults are able to perform these tasks more efficiently.

Although the latter study suggests that richer existing semantic representations, be it vocabulary or information of some other type, aid in learning novel words, this hypothesis had not been directly tested. A recent study aimed to perform a more direct examination (Whiting, Chenery, & Copland, 2011). In this study, the acquisition of a novel label for a familiar object (e.g., "flole" paired with a cup drawing) was compared with the acquisition of a novel label for an unfamiliar object (e.g., "flole" paired with an unknown object drawing). This task differed from those previously discussed, as recall was performed immediately and also over 5 subsequent days. As predicted, the older adult group performed similarly to young adults but only when novel labels were paired with familiar objects (i.e., existing semantic representations). Yet performance was only equivalent between age groups at immediate recall; older adult recall on subsequent days was reduced compared to young adults.

Taken together, these findings suggest that older adults can efficiently learn novel words, but the acquisition of these words depends on the context within which the words are presented. Whiting et al. (2011) demonstrated that initial learning is not reduced in older adults, but subsequent retention and retrieval is. This suggests a necessary addition to the investigation of older adult novel word learning: consolidation. As discussed previously, consolidation of novel word learning in young adults is enhanced over sleep (Dumay & Gaskell, 2007; Gaskell et al., 2014; Tamminen et al., 2010; Kurdziel & Spencer, 2015; Tham et al., 2015). However, whether or not older adults exhibit sleep-dependent consolidation for newly learned words to a similar degree as young adults is unknown. Therefore, an investigation directly probing sleep (i.e., controlling for circadian factors and daytime interference) is warranted.

3.2. Aging and lexical integration

Of note, the above reviewed investigations probed language use and acquisition within the existing lexicon/semantic network but did not gauge age-related differences in lexical integration. This is an important distinction, as it has been proposed that these domains may be physiologically separate: The use of existing neural connections within the lexicon remains intact with advancing age while the formation of new connections may become increasingly difficult (Burke & Mackay, 1997). Therefore, it is unknown whether retrieval-related deficits in older adults are generalizable to novel lexical integration or whether they occur only for information in the existing lexicon.

3.3. Aging and general learning deficits

Although work focusing on age-related changes in language learning is limited, much applicable information can be extrapolated from investigations in neighboring fields. For example, it is well-established that older adults have a limited ability to form associative memories even when memory for distinct units remains intact. That is to say, both young and older adults are able to retain newly-learned single words, yet only young adults are able to efficiently recall fabricated connections between these words (Naveh-Benjamin, 2000). Given this, it could be conjectured that deficits in novel word learning (i.e., forming a connection between a word and a definition) are rooted in a lack of ability to build or retain associations. However, it is important to note that although encoding of associations is reduced in older adults, sleep-dependent consolidation of such associations is preserved with age (Wilson et al., 2012).

Older individuals, relative to young adults, also have a greater incidence of improper source identification, or information about the circumstances or context within which learning occurred (Dodson, Bawa, & Slotnick, 2007). Improper source identification is thought to reduce the ability to prevent false memories and misinformation from impeding veridical information (Dodson, Koutstaal, & Schacter, 2000; Wilson, Gallagher, Eichenbaum, & Tanila, 2006). Thus, learning and recall are impacted by this fault. In parallel, memory 'calibration,' or the ability to gauge one's own correctness, is altered with aging, such that older adults are more likely to identify responses as correct when they are not (Shing, Werkle-Bergner, Li, & Lindenberger, 2009). The latter phenomenon is suggested to be due to mis-combinations of information: When memory traces from different events are combined into one memory, incorrect details are recalled but confidence about those details remains. When attempting to learn novel words or definitions, this blunder may impact correctness of recall. Thus, both source misidentification and poor calibration may hinder novel word learning in this population.

4. Age-related changes in sleep

Sleep changes in quantity and quality with age (see: Pace-Schott & Spencer, 2011; Fig. 3). Overall, older adults have fewer minutes of sleep during the night, possibly because sleep need is reduced (Duffy, Willson, Wang, & Czeisler, 2009) or sleep is more difficult to maintain (Landolt & Borbély, 2001). Typically, reduced sleep time is not due to less time spent in bed, but instead due to an increase in awakenings during the night (Bliwise, 1993; Buysse, Monk, Carrier, & Begley, 2005). Importantly, these awakenings tend to be in nREM stages of sleep, while awakenings during REM seem to decrease with age (Dijk, Duffy, & Czeisler, 2001; Salzarulo et al., 1999; although it is notable that REM disruption does not seem to impair older adult declarative consolidation: Hornung, Regen, Danker-Hopfe, Schredl, & Heuser, 2007). Sleep stage proportion and distribution are also altered with increasing age. Time in the deepest stage, SWS, is reduced and is more distributed across the night (Lombardo et al., 1998), while time in lighter stages (nREM1 and nREM2) increases (Ohayon et al., 2004). Despite these changes, time in REM decreases only slightly and stabilizes around age 70 (Floyd, Janisse, Jenuwine, & Ager, 2007; Ohayon et al., 2004).

There are also age-related changes in more discreet sleep characteristics. Globally, spectral EEG power is reduced during sleep in

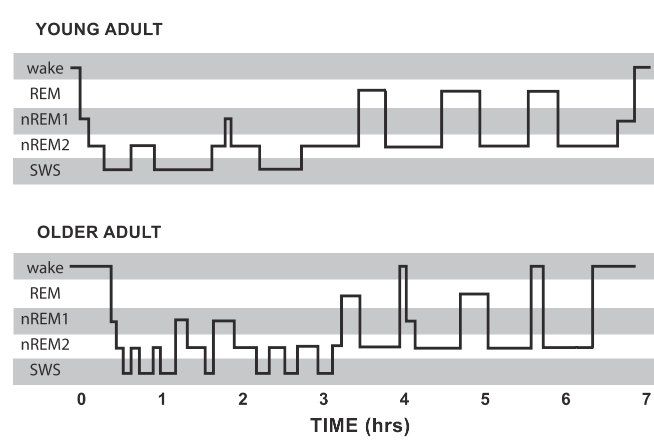

Fig. 3. Typical nocturnal hypnograms demonstrating sleep stage proportion and distribution for a young and older adult. Relative to young adults, older adults have less SWS, more nREM2 sleep, and sleep stages are more fragmented. Differences in sleep architecture may hinder sleep-dependent lexical integration in older adults.

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older adults (Landolt & Borbély, 2001), possibly due to age-related changes in brain morphology (Dubé et al., 2015; Mander et al., 2013). This reduction is especially profound during sleep stages nREM2 and SWS: Older adults have reduced EEG sigma power (a surrogate of spindles) during nREM2 (Mander et al., 2013) and reduced SWA during SWS (Dubé et al., 2015). Given that SWA is influenced by both the number of underlying firing neurons and the synchronicity between these neurons (see review: Greene & Frank, 2010), a reduction in SWA represents the breakdown of these processes. It has also been suggested that SWA is reduced with increased β-amyloid burden (Mander et al., 2015), which occurs with both normal and disordered aging (Rodrigue et al., 2012). As mentioned, increased power of SWA has been linked with enhanced language acquisition (Tamminen et al., 2013), it has therefore been posited that these sleep alterations are detrimental for sleep-dependent consolidation (Pace-Schott & Spencer, 2014).

Similarly, sleep spindle integrity is diminishes with increasing age. Spindle density (i.e., the number of spindles per minute), frequency, and duration are reduced with aging (Crowley, Trinder, Kim, Carrington, & Colrain, 2002; Guazzelli et al., 1986) potentially due to age-related atrophy of networks associated with spindle generation along the thalamo-cortial pathway (Nordahl et al., 2006). Similar to SWA, sleep spindle reduction has been suggested to causally impact sleep-dependent consolidation learning in the associative domain (Mander et al., 2013). Spindles have been associated with lexical integration (Tamminen et al., 2010), and a reduction of such could impact consolidation.

5. Inter-relationships between aging, sleep, and memory consolidation

In addition to sleep, age also affects the underlying neural structures involved in sleep-dependent consolidation of novel words. Throughout aging, the hippocampus deteriorates structurally while also undergoing biochemical changes (Driscoll et al., 2003). These changes, overall, lead to a reduction of hippocampal effectiveness. Further, several studies have demonstrated that as a consequence of hippocampal deterioration, the prefrontal cortex takes on a compensatory role whereby prefrontal neural activation is increased beyond typical levels during declarative memory retrieval (e.g. Lighthall, Huettel, & Cabeza, 2014; McDonough, Wong, & Gallo, 2013). Overall, given that proper hippocampal functioning and proper hippocampal-prefrontal connectivity are critical for the stabilization of newly learned declarative items, this research suggests that there would be an age-related change in sleep-dependent novel word learning.

In support of this notion, we have recently demonstrated that there are age-related changes in the structural reorganization of memories during sleep. Consistent with the complementary systems framework, we found recall of declarative memories in young adults become more independent of the hippocampus following SWS-rich sleep (Baran, Mantua, & Spencer, 2016). However, older individuals retained strong hippocampal activation, and especially strong hippocampal-prefrontal cortical connectivity, during recall of declarative memories following sleep. This indicates a slowing, or a breakdown, in the complimentary systems framework in older adults. Given this, it is plausible that newly learned words may not be incorporated into the lexicon during sleep as easily with advancing age. In addition, the recruitment of additional neural structures, such as the prefrontal cortex, may be necessary in order to maintain newly learned words in the unstable state within the hippocampus. Whether this is a direct result of hippocampal deterioration, or that of changes in sleep physiology (e.g., a reduction in SWS and sleep spindle integrity) has yet to be identified.

6. Implications for future research

Findings on older adult language acquisition, in conjunction with information on age-related changes in neurophysiology, sleep quality and sleep physiology, lead to two overlapping, yet distinct, hypotheses regarding sleep-dependent language learning in older adults.

6.1. Hypothesis 1: Veridical consolidation

The reviewed literature presents the hypothesis that older adults may not consolidate newly learned words to an equivalent extent as young adults (Dumay & Gaskell, 2007; Gaskell et al., 2014; Tamminen et al., 2010; Kurdziel & Spencer, 2015; Tham et al., 2015). Given the known age-related changes in the neural underpinnings governing sleep-dependent consolidation of declarative memory traces (e.g., hippocampal activation and connectivity alterations: Baran et al., 2016), veridical consolidation of novel words could be reduced. As such, post-sleep retrieval would be reduced (Bowles & Poon, 1985; Burke et al., 1991), and performance following a delay including sleep would be poorer in older adults than in young adults. Long and Shaw's (2000) observations are consistent with this hypothesis. During a task in which novel labels were paired with familiar representations, older adults were able to perform as well as young adults, suggesting that encoding of novel words was preserved with aging. However, performance on subsequent days was poorer for older adults than young adults and, thus, sleep-dependent consolidation for these novel words or labels may not have been efficient. A number of age-related cognitive changes, including deficits in forming associations and poor memory calibration, may have contributed to this deficit. Additionally, it could be that age-related reductions SWS time and SWA, in conjunction with increased SWS fragmentation (Pace-Schott & Spencer, 2014), thwarted the veridical consolidation for novel word traces.

6.2. Hypothesis 2: Integration

The reviewed literature also promotes the hypothesis that lexical integration over sleep is reduced in older compared to young adults. Although Long and Shaw (2000) did not probe veridical recall and lexical integration separately, both elements were likely involved. Thus, integration, in addition to veridical consolidation, might have been reduced. This is further supported by the fact hippocampal activation during recall is not reduced following sleep in older adults (Baran et al., 2016), as has been demonstrated to be the case for lexical integration following sleep in young adults (Davis et al., 2008); overall, this suggests a deterioration of the complementary systems framework in older adults. We surmise reduction in spindle integrity (Mander et al., 2013) hinders effective lexical integration of novel words and descriptions. However, given the relative stability of REM sleep with aging, the relationship between sleep physiology and lexical integration warrants further investigation.

7. Conclusions

There is ample research to support the role of sleep in the consolidation and integration of newly learned words and linguistic rules. In support of the complementary learning systems framework, newly learned words are stored hippocampally during encoding, and then are incorporated into the lexicon (transferred to cortical storage) most efficiently over a period of sleep. In particular, SWS seems to drive the veridical processing, whereas sleep spindles have been most associated with lexical integration. REM

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sleep may also play a role in rule abstraction or generalization of newly learned linguistic principles.

In this review, we have examined the current literature and propose two predictions regarding sleep-dependent language learning in older populations. Importantly, past research has focused almost entirely on developmental and young adult populations. Given the evident age-related changes in sleep, specifically in both SWS and sleep spindles, it is probable that novel word learning and language acquisition would differ in older adults. However, to date, the relationship between sleep and language acquisition has not been assessed in older populations.

Successful learning throughout aging is imperative. Older adults who keep mentally and physically active are less likely to suffer from cognitive deficits and depression, but keeping active requires continual learning. For example, older adults continuing their education must learn novel words and concepts, and older adults remaining in or re-entering the work-force will be required to learn new vernacular with time. If sleep-dependent consolidation of language acquisition and integration is intact, this process will be facilitated. If not, interventions, perhaps involving sleep improvement, could be implemented.

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