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Developmental Differences in the Learning and Consolidation of Linguistic Regularities

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Abstract

Relative to adults, children have a well-known advantage for learning linguistic regularities, which could be partially driven by their deeper sleep. To examine the relationship between consolidation and language learning across development, children and adults learned a novel article system with an implicit grammatical rule. Participants performed a judgment task on phrases containing the novel articles before and after a night of EEG-monitored sleep. We found that rule sensitivity emerged rapidly in children, whereas it did not emerge until the second session in adults. Children demonstrated better generalization of the rule than adults. Consolidation effects showed a developmental double dissociation, with children showing gains in explicit knowledge and adults showing gains in implicit knowledge after consolidation. Sleep physiology was not associated with any between-session changes. Our results suggest that children's language learning advantage is more related to their enhanced sensitivity to implicit structures during initial learning, than to subsequent consolidation.

Keywords: sleep, development, language, EEG, implicit learning, explicit learning, linguistic regularities, consolidation

Summary for Lay Audience

Humans spend much of their lives asleep, and one of sleep's crucial functions is aiding in the consolidation of newly learned information. The structure of sleep changes dramatically over the course of development, with children exhibiting much deeper sleep than adults. This type of deep sleep is thought to be particularly important for memory consolidation. In addition, children have an advantage over adults for learning new languages, particularly in terms of grammar and ultimate linguistic proficiency. It is unclear if children's deeper sleep may play a role in the consolidation of grammar, thus partially driving children's language learning advantage. This thesis investigated the role of sleep in language learning across development by having children (8-10 years) and adults learn a novel miniature language with a hidden grammatical rule before and after a night of sleep, during which their sleep stages were recorded. The grammatical rule was learned implicitly through repeated exposure. Children were able to implicitly and rapidly learn this hidden linguistic rule, whereas adults did not show evidence of implicit learning until the next morning, after a period of consolidation containing sleep. Children also improved in their explicit knowledge of the novel language after this period, whereas adults did not. Finally, children were able to generalize the grammatical rule to new contexts better than adults, although this advantage was not directly supported by consolidation. Our results suggest that children's advantage for language learning is more related to their enhanced sensitivity to implicit linguistic structures, which occurs during initial learning, than to subsequent sleep-dependent consolidation mechanisms. This research can help inform theories of language learning and sleep-dependent consolidation across development.

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Table of Contents

List of Tables

List of Figures

List of Appendices

Chapter 1

1 Introduction

Over the past century, numerous studies have demonstrated the importance of sleep, particularly slow-wave sleep (SWS), in the consolidation of learning and memory (Jenkins & Dallenbach, 1924; Rasch & Born, 2013). A benefit for sleep in memory consolidation has been shown across many diverse domains, including gaining insight (Wagner et al., 2004), spatial memory (Peigneux et al., 2004), word pair learning (van Schalkwijk et al., 2019), and statistical learning (Durrant et al., 2011; for reviews see Rasch & Born, 2013; Diekelmann & Born, 2010). Sleep has also been shown to play an important role in language learning and consolidation (Rasch, 2017).

Sleep patterns change throughout development, with the relative percentage of SWS declining significantly after childhood (Ohayon et al., 2004). In this thesis, I investigated whether developmental changes in sleep may contribute to children's advantage in the domain of language learning. It has long been noted that children learn languages better than adults, attaining higher levels of ultimate proficiency (Johnson & Newport, 1989). Language learning thus represents a developmental reversal, contrasting with most other aspects of cognition in which adults have the upper hand. Although the mechanisms behind children's language learning advantages are still not clearly understood, developmental changes in sleep could represent one factor that contributes to differences in language learning – in particular rule generalization and associated consolidation. The goal of this thesis was to test the hypothesis that richer SWS in children might support the effective consolidation of linguistic regularities, partially accounting for children's language learning advantage.

1.1 Sleep architecture

Sleep progresses through four different stages that occur within approximately 90-minute cycles. Sleep stages are determined using electroencephalography (EEG) waveform recordings, conducted on 30 second epochs of EEG data (Iber et al., 2007). These four stages include three non-rapid eye movement stages (NREM1, NREM2, NREM3) and a rapid eye movement (REM) stage. During initial wake, alpha activity in the range of 8-13 Hz is the dominant cortical rhythm (Malhotra & Avidan, 2013). Wake is then followed by Stage 1 NREM (NREM1) sleep, a stage of light sleep. NREM1 sleep is characterized by a reduction in the amount of alpha activity to below 50% of the epoch, and an increasing amount of theta activity in the range of 4-7 Hz. This stage also includes slow rolling eye movements, and is typically very short in duration, lasting only 1-7 minutes (Malhotra & Avidan, 2013).

Stage 2 NREM (NREM2) sleep typically occurs next, and includes K complexes and sleep spindles. A K complex consists of a negative sharp wave followed immediately by a positive component that stands out from background EEG and lasts at least 0.5 seconds (Malhotra & Avidan, 2013). Sleep spindles are bursts of fast activity that have a frequency of 11-16 Hz (most commonly 12-14 Hz), and typically last 0.5-3 seconds. Spindles are generated in the thalamus, and are associated with memory reactivation (Antony et al., 2019). NREM2 sleep is typically followed by Stage 3 NREM (NREM3) sleep, also called deep sleep or slow-wave sleep (SWS). NREM3 is defined by high amplitude slow waves, which have a frequency of 0.5-2 Hz and peak-to-peak amplitudes > 75 microvolts (Malhotra & Avidan, 2013). Finally, REM sleep is characterized by low amplitude, mixed frequency EEG waves, and rapid eye movements under closed eyelids (Malhotra & Avidan, 2013). REM sleep is associated with more vivid or memorable dreams relative to the other sleep stages (Aserinsky & Kleitman, 1953). Over a night of sleep, we cycle through these stages, with a typical 90 minute sleep cycle consisting of NREM stages followed by REM. Across the night, bouts of REM tend to increase in duration, while bouts of SWS decrease in duration (Malhotra & Avidan, 2013).

1.1.1 Sleep architecture and development

Sleep changes dramatically throughout development. Newborns sleep up to 16 hours per day, one-year-old infants sleep an average of 14 hours per day, and total sleep duration then generally decreases linearly to an average of 8 hours per day by age 16 (Iglowstein et al., 2003). Not only does duration change, but sleep architecture is also quite different in children compared to adults. Young children have significantly more SWS than adults, with the proportion of SWS declining rapidly after age 10 (Ohayon et al., 2004). Stage 3 sleep is reduced by approximately 40% from childhood to adolescence (from around age 6 to age 15), and during adulthood it further declines approximately 2% per decade up to around 60 years old. Sleep in older adulthood tends to be of lower quality, and is marked by frequent arousals and reduced slow-wave sleep (D’Ambrosio & Redline, 2014).

Specific physiological features also change across development. Sleep spindles are not initially observed in newborns but emerge in infants as young as 3 months old (Scholle et al., 2007). Spindle density peaks in late adolescence/early adulthood and declines in late adulthood, whereas spindle duration and amplitude peak earlier in childhood (Clawson et al., 2016). Slow wave amplitude and slow wave activity (EEG spectral power in the band of 0.5-4 Hz) increase until late childhood and then decrease throughout adolescence and adulthood (Kurth et al., 2010). Another feature of sleep that exhibits changes across development is the temporal coupling of slow oscillations and spindles. A recent study found that slow oscillation-spindle coupling became more precisely coupled from childhood to late adolescence, and coupling precision predicted enhancements in declarative word-pair memory consolidation (Hahn et al., 2020). This recent finding suggests that changes in sleep may partially mediate many of the other cognitive changes that occur during childhood.

1.2 The role of sleep in memory consolidation

The function of sleep has been widely debated (Benington, 2000), but aside from general restorative functions, there is strong evidence of a role for sleep in memory consolidation. Initially, theories of sleep and memory consolidation suggested that sleep might benefit memory passively, by acting as a state that shields memories from retroactive interference (Ellenbogen et al., 2006). However, evidence from studies of memory reactivation during sleep (Rudoy et al., 2009), and the specific contributions of the sleep stages and physiological sleep features (Schoen & Badia, 1984) contradict this account, suggesting a more active role of sleep in consolidation.

One influential theory, known as the active system consolidation theory, proposes that sleep supports memory consolidation by repeatedly reactivating newly formed memories during slow-wave sleep (Diekelmann & Born, 2010). Through this reactivation, memories that are located in short-term storage within the hippocampus become redistributed throughout the neocortex. The proposed neural mechanism for this reactivation consists of nested neural oscillations—namely, neocortical slow oscillations, thalamocortical spindles, and hippocampal sharp-wave ripples. The depolarizing up phase of neocortical slow oscillations governs the timing of spindles that are generated in the thalamus, which in turn direct hippocampal sharp wave ripples. This synchronous action is thought to support communication between different brain regions and underlie the integration of memories from the hippocampus into the neocortex, making sleep an active process in consolidation. Importantly, this process is driven by slow oscillations, meaning slow-wave, or deep sleep, is crucial for memory consolidation.

Evidence for this theory comes from a large body of studies that show that post-learning sleep, and its specific physiological features, benefits both declarative and nondeclarative memories (Rasch & Born, 2013). Additional strong neural evidence for memory reactivation during sleep comes from animal work. Wilson and McNaughton (1994) had rats explore a spatial environment while they recorded neuronal activity from hippocampal cells. The same spatio-temporal pattern of firing while the animals were in the environment was subsequently observed during SWS, providing evidence of neuronal memory replay during sleep, rather than just a passive period of rest. A causal role of reactivation in memory consolidation has also been demonstrated in humans, using a method known as targeted memory reactivation (Rasch et al., 2007). In this study, card locations were paired with an odour, and if that odour was presented again during SWS, memory for that card location was enhanced. Targeted memory reactivation has been shown to enhance memory consolidation in multiple contexts (see Hu et al., 2020 for a review), supporting the notion that an active form of consolidation is occurring during sleep, rather than just protection from interference.

Building on the active systems consolidation model, Lewis and Durrant (2011) proposed that the process of reactivation supports rule abstraction, integration and generalization, via the selective strengthening of shared elements. Sleep preferentially supports extraction of the "gist" of an idea (Payne et al., 2009), pointing towards the functional reorganization of a memory trace. According to their theory, when two neural traces are reactivated simultaneously by the hippocampus, there are some neocortical neurons that are unique to the memory and some that are shared across memories. The shared neurons become potentiated more strongly and develop stronger connections. After a process of synaptic downscaling, only the shared connections remain intact, such that information that is replayed more frequently and/or has greater overlap will be represented more strongly (Lewis & Durrant, 2011). This represents a mechanism for the integration and abstraction of new memories. For example, a child may visit two different playgrounds, each with their own unique features. However, if both of these playgrounds have a swingset, the concept of a swingset would be reactivated across both memories during sleep, and eventually come to be represented in the child's "gist" representation of a playground. While the specific, idiosyncratic details of each individual playground may fall away, the shared elements (e.g., the swingset) remain intact.

Although the active system consolidation theory is influential and well-supported, there are other competing accounts of the mechanisms of memory consolidation during sleep, such as the synaptic homeostasis hypothesis (Tononi & Cirelli, 2014). This hypothesis suggests that synaptic downscaling during SWS reduces the metabolic energy demands of synaptic strengthening from learning and prepares the neural network for encoding new information during the following day. The theory argues that decreased neuronal connections after synaptic downscaling enhances signal-to-noise ratios of synaptic connections, leading to enhanced consolidation after sleep. Evidence for this theory comes from electrophysiological evidence in rats that slow oscillations <1Hz have a tendency to facilitate synaptic downscaling through long term depression of neural connections (Massey & Bashir, 2007). Further computational models have predicted slow wave activity decreases with decreased synaptic strength, leading to the decline of SWS by the end of the night (Esser et al., 2007). However, this theory fails to address the role of memory reactivation and the qualitative reorganization of memory traces that occurs during sleep. Additionally, the process of synaptic downscaling should preferentially preserve stronger connections, but there is evidence showing that weaker memory traces benefit more from sleep than strongly encoded memories (Drosopoulos et al., 2007).

1.3 Developmental changes in sleep-dependent memory consolidation

The importance of SWS in memory consolidation, along with architectural changes in SWS across development raise the possibility that there are key differences in memory consolidation between children and adults. Consistent with this idea, several studies have shown benefits for hippocampal-dependent declarative memory after sleep in children relative to adults. One such study asked children (8-11 years) and adults to press a repeating sequence of cued buttons that followed a repeating, hidden sequence (Wilhelm et al., 2013). Participants then either slept overnight, or stayed awake throughout the day. Twelve hours later, participants attempted to explicitly recall the implicitly learned motor sequence. Both children and adults were able to recall the sequence better after sleep than wake, but children demonstrated greater sleep-dependent gains in explicit sequence knowledge than adults. The authors also found a strong positive correlation between the power of slow wave activity during sleep and explicit sequence knowledge after sleep in both children and adults. These findings suggest that children may have an advantage in extracting explicit knowledge from implicitly learned information, and that this advantage is related to slow-wave activity during sleep. Similar findings were reported in a study of 3- to 6- year old children who were read stories either prior to a nap or an equivalent period awake (Lokhandwala & Spencer, 2021). A nap immediately after learning led to greater improvements in episodic memory for the stories, and change in performance was positively correlated with time in SWS. Another study investigating declarative memory consolidation in 7-12 year old children and adults aimed to minimize any pre-existing knowledge adults may have of the stimuli by assigning novel creatures with a “magical” function (Peiffer et al., 2020). They found that after a night of sleep, children showed an increase in retrieval performance for the magical functions of the objects, whereas adults showed a decrease. Both children and adults also showed a decrease in memory performance after a period of wake. These results demonstrate an interaction between age and sleep on declarative memory consolidation.

While sleep appears to benefit declarative memory in children, it may not have the same beneficial effects on procedural memory. A study by Wilhelm and colleagues (2008) found that sleep in both 6- to 8-year old children and adults led to an improvement in performance on a declarative, hippocampal dependent task, but on a procedural implicit memory key press task, children who stayed awake actually performed better. This is in contrast to adults who showed better performance on the procedural task after sleep compared to wake. Converging evidence from a study of 10-13 year old children demonstrated that recognition accuracy for emotional declarative stimuli improved after a night of sleep compared to wake, whereas performance on a procedural mirror tracing task was not enhanced after sleep (Prehn-Kristensen et al., 2009). This dissociation between declarative and procedural memory consolidation was also observed by Fischer and colleagues (2007), who had 7-11 year old children and adults complete a serial reaction time task and then either sleep or stay awake before completing the task again. On this task, participants were cued to press target buttons that followed a probabilistic pattern on grammatical blocks, and that occurred randomly on ungrammatical blocks. The difference in reaction times between grammatical and ungrammatical blocks was greater after sleep in adults, reflecting a gain in implicit knowledge. In contrast, this difference was reduced after sleep in children, reflecting a *reduction* in implicit knowledge. Although the authors did not directly assess explicit memory in this study, they speculate this reduction in implicit knowledge may be due to explicit task elements interfering with implicit performance gains. This theory relates to the hypothesis that hippocampal-dependent memories are being preferentially strengthened by reactivation during slow-wave sleep (Rasch & Born, 2013), such that explicit memories are more likely to become strengthened in children, and thus interfere with implicit knowledge.

However, children typically perform worse on procedural motor tasks than adults, which represents a potential confound when examining age-related differences in procedural memory consolidation. To address this issue, Wilhelm and colleagues (2012) provided one group of 4- to 6-year-old children with extra training on a finger tapping task, and compared their performance to adults who had received low and moderate levels of training. They found that children with extra training and adults with minimal training showed a performance gain after sleep, but children with minimal training and adults with moderate training did not benefit more from sleep than a period of wake. This suggests that sleep-dependent consolidation benefits may only emerge if the pre-sleep performance is at an intermediate level. Taken together, results from procedural motor skill learning studies suggest that while sleep typically benefits implicit or procedural memories in adults, the same benefits may not be observed in children, possibly due to prioritization of hippocampal-dependent consolidation over procedural learning, or differences in initial learning.

1.4 Role of sleep in language learning and generalization

As mentioned previously, language learning is one of the few exceptional domains where children outperform adults in terms of cognitive abilities. In an influential study by Johnson & Newport (1989), it was shown that as age of exposure to a second language increases, performance on tests of grammatical knowledge decreases. Another more recent study compared the time course of learning phonotactic constraints (the rules that govern where phonemes can be placed within a language), and found that children are much faster at implicitly learning these rules than adults (Smalle et al., 2017). While there is still ongoing debate over whether a defined “critical period” for language learning exists, it is clear that the ability to acquire key aspects of language, such as grammatical and phonotactic regularities, declines after childhood (Hartshorne et al., 2018).

1.4.1 Sleep and linguistic rule generalization in adulthood

A key component of language learning involves the extraction of grammatical regularities and the generalization of those structures to new items. For example, adding “–ed” to the end of a word (e.g., “worked”) indicates that the action occurred in the past. Once extracted, this rule can be generalized and applied to unfamiliar verbs (e.g., “ricked”; Berko, 1958). Generalization is necessary for components of language such as phonotactic constraints (e.g., English words cannot begin with the letters “nt”), syntactic rules, morphology, and other regularly occurring features of a language. The generalizations of these rules to new contexts may be promoted by sleep, particularly by the structural reorganization of memories that occurs during SWS (Lewis & Durrant, 2011).

The effects of sleep on learning linguistic regularities in adults have also been explored in a small body of literature. Batterink and colleagues (2014) investigated the role of an afternoon nap in learning a hidden linguistic rule. This study exposed adults to two-word phrases that included one of four novel words (gi, ro, ul, ne), composed of a novel article (acting similarly to the word “the”), and a subsequent noun (e.g. ro table). Participants were explicitly instructed that two of the novel words meant the accompanying noun was near, and the other two meant it was far. However, there was also a hidden rule that participants were not told, which was that the novel article also predicted whether the accompanying noun was animate or inanimate. Participants were presented with a word pair, and had to make a response indicating whether the item was living or nonliving and then near or far. Throughout the experiment, occasional violation trials occurred where the article was paired with objects that did not match the hidden animacy rule. Participants then had a nap while their EEG was measured, before being tested again. Batterink and colleagues found that participants became sensitive to this hidden rule over time, exhibiting slower reaction times to trials that violated the hidden rule. This implicit learning effect emerged at the end of the pre-nap block, and became even stronger after the nap. Importantly, this effect was modulated by sleep, such that participants who had greater amounts of SWS and REM showed increased sensitivity to the hidden rule after sleep. These results suggest that sleep plays a role in the extraction of linguistic regularities.

Sleep has also been shown to have an impact on learning phonotactic constraints (Gaskell et al., 2014). Phonotactic constraints are the rules in a language that govern where phonemes can be placed or combined within words. For example, in English, the phoneme “ng” can be placed at the end of a word, but not at the beginning (e.g., “ping” vs. “*ngip”). Gaskell and colleagues had adult participants recite syllable sequences that had specific constraints in terms of where individual phonemes could be placed within a word. After initial training, participants either had a nap or stayed awake, and were then retested. Only the participants who slept showed evidence of implicit phonotactic learning, making speech errors consistent with the phonotactic constraints they had recently learned. Participants in the sleep group also generalized the constraints better than participants in the wake group, as demonstrated by the ability to distinguish between two untrained syllable sequences that either violated or adhered to the experimental constraints. Furthermore, the speech error effect was positively correlated with time in SWS, providing clear support for the role of slow wave sleep in language learning and generalization.

Another element of language learning is statistical learning, or the ability to pick up on statistical regularities in the environment, which is thought to be particularly important for infant language learning (Saffran et al., 1996). To examine the effect of sleep-dependent memory consolidation on this ability, Durrant and colleagues (2011) presented tone sequences that followed a sequential structure, and then compared consolidation after 12hrs of sleep or wake, and over 4 hours with either a nap or no nap. Relative to the wake conditions, both the overnight sleep and nap conditions yielded greater improvements in participants' ability to discriminate between structured and random sequences as assessed through behavioural tests. Importantly, the amount of improvement was also correlated with the percentage of time spent in SWS (Durrant et al., 2011). Although this study was not linguistic in nature, it provides a strong demonstration of the benefit of sleep in abstraction of underlying patterns, which may in turn be important for language learning. Overall, these findings suggest that sleep plays a role in the integration of linguistic rules.

1.4.2 Sleep and linguistic rule generalization in childhood

A number of studies have also shown that sleep plays a beneficial role for linguistic rule generalization in children. Sleep has been shown to promote the abstraction of grammar structures in infants as young as 15 months old (Gomez et al., 2006). Gomez and colleagues had infants learn an artificial language that required them to track sequential dependencies between the first and the third word in a sentence (e.g., phrases beginning with *pel* ended in *jic*). Using a head-turn preference paradigm, they found that infants who napped showed greater abstraction of the rule to new sentences, with increased looking time to new sentences that were consistent with the rule. Infants who didn't nap showed better veridical memory for the identical phrases, demonstrated by increased looking time to sentences that were heard before, but no differences for the new sentences. Another study using the head-turn preference paradigm exposed 6.5-month-old infants to an artificial language speech stream before either a nap or an equivalent period of wake (Simon et al., 2017). The authors found that sleep was related to statistical language learning, where absolute SWA, theta and alpha activity during NREM correlated with retention in the first testing block. Both of these studies support the idea that sleep aids with the consolidation and abstraction of grammatical structures from a very young age.

Sleep in children has also been shown to contribute to lexical integration, defined as the integration of new spoken word forms with existing lexical knowledge (Henderson et al., 2012). In this study, 7-12-year-old children learned novel words that were similar sounding to existing English words (e.g., "banara") either in the morning before a period of wake or in the evening before a period of sleep. The children then completed a pause detection task, in which they were asked to detect pauses that occurred in the middle of words. Retesting occurred 12 hours, 24 hours, and 1 week after initial learning. The authors found that children who had slept (i.e., 12 hours for the evening group, 24 hours for the morning group) were significantly slower to respond to items that were similar to the novel words they had learned (e.g., "banana") compared to control words. This delay in response times reflects a competition between similar items in the lexicon and is indicative of lexical integration. Thus, these results suggest that children's integration of novel words depends on sleep. Another study directly compared lexical integration in children (7-8 years) and adults by using eye-tracking to measure fixations to images of newly learned words and existing competitors (e.g., biscal versus biscuit; Weighall et al., 2017). Children displayed a greater competition effect than adults for words that had the opportunity to be consolidated (i.e., were learned the previous day) compared to newly learned words. In addition, children showed a larger benefit from sleep for explicit recall of newly learned words than adults. These studies show a clear effect of sleep for the integration of words, with children perhaps benefiting more from consolidation across sleep than adults.

As mentioned previously, children have also been shown to implicitly learn phonotactic constraints more rapidly than adults (Smalle et al., 2017). Smalle and colleagues had young adults and 9-year-old children complete a phonotactic constraint recitation task (similar to the task described earlier, used by Gaskell et al., 2014). They found that children showed reliable evidence of learning during the first session, after exposure to only 24 sequences. In contrast, adults did not show evidence of learning until the second day, after a period of consolidation that contained sleep. While this study didn't directly measure or manipulate sleep, it does demonstrate children's ability to pick up on elements of linguistic rule learning quickly and implicitly.

Taken together with adult studies of language learning, and studies of sleep and memory consolidation, there is strong support for an effect of sleep on the consolidation and generalization of linguistic regularities. Children also show evidence of an advantage over adults in certain key areas of language learning that critically involve generalization processes, such as phonotactic learning. However, it is unclear whether children's unique sleep architecture may partially support this advantage in language learning, as few studies have directly investigated the role of sleep in linguistic rule learning in adults compared to children.

1.5 The present study

The goal of the current study was to investigate and compare the role of sleep in the consolidation of linguistic regularities in children and adults. I used the same novel article system used by Batterink and colleagues (2014), but adapted the paradigm to be child-friendly and to include an additional test of generalization. Children (8-10 years) and adults both completed a learning session in the evening and the next morning, with overnight sleep being recorded by a portable EEG headband in the participants' homes. They learned the four novel article system (gi, ro, ul, ne) that contained the same explicitly instructed distance rule and hidden animacy rule as Batterink and colleagues (2014). On each trial, participants were required to physically sort items described with the article system (e.g., gi lion; ne table) into the designated correct location on a computer screen (e.g., a near zoo, a far shop, respectively). Reaction times and accuracy for each trial were measured. A small number of trials violated the hidden animacy rule (e.g., gi lamp, rather than gi lion), and were used to assess participants' implicit knowledge of the rule (i.e., as reflected by a slowing of reaction times and decreased accuracy). In addition, a subset of generalization trials, consisting of a novel article with a nonsense word (e.g., gi badupi), were used to assess generalization of the hidden rule. At the end of the second session, we also assessed participants' explicit knowledge of the hidden rule through a structured interview.

Based on previous findings, I predicted the following: First, children's implicit rule learning will occur more rapidly than adults, similar to the findings from Smalle and colleagues (2017), and in line with the idea that children have an advantage for language learning. Second, a period of time containing sleep will benefit implicit learning to a greater extent in adults than in children – i.e., adults will show an improvement in implicit learning after sleep whereas children's implicit learning effect may be stable from session 1 to session 2, or even deteriorate as in Fischer and colleagues (2007). Finally, a period of time containing sleep will benefit explicit knowledge to a greater extent in children than adults, such that children will show a larger increase in explicit knowledge after sleep. This could be reflected by an improvement on generalization trials from session 1 to session 2, as well as increased likelihood to be aware of the hidden animacy rule at session 2. An improvement in explicit knowledge may also correlate with measures of SWS, such as percent of time spent in SWS and slow wave activity power.

Chapter 2

2 Methods

2.1 Participants

Participants were comprised of 31 children (16 female; age range 8-10 years old; M= 9.19, SD = 0.99) and 30 adults (21 female; age range 18-35; M= 24.65, SD = 4.17). Participants were recruited from the London, Ontario community through the Western University *OurBrainsCAN* participant database and Facebook postings. The inclusion criteria required that participants be native English speakers, have normal or corrected-to-normal vision and normal hearing, have no history of neurological or sleep disorders, and not be taking medication that may affect brain functioning. Informed consent was obtained from participants and parents, and assent was obtained from children. Participants were compensated for their time. The study was approved by the Research Ethics Board at Western University (REB #118676; see Appendix B and C).

2.2 Stimuli

The task was adapted from Batterink and colleagues (2014), which used an artificial article system originally developed by Williams (2005). As in these previous studies, the article system consisted of four novel articles (“gi”, “ro”, “ul” and “ne”; see Table 1). Participants were instructed that these novel words functioned similarly to the word “the”, with *gi* and *ro* indicating that the accompanying noun was near, and *ul* and *ne* indicating that the accompanying noun was far. Unbeknownst to participants, in addition to this explicit distance rule, there was a second “hidden” animacy rule: *gi* and *ul* typically preceded animals, while *ro* and *ne* typically preceded objects. Because Williams (2005) previously demonstrated that the specific assignment of animacy to each article did not affect learning, we kept animacy-article mappings consistent across participants.

Each trial contained a novel article paired with a unique noun (e.g., *gi shirt* = “the near shirt”). The nouns in this study consisted of 240 unique animal names and 240 unique object names (Appendix D). Selection of nouns was partially guided by the nouns that were used by Batterink and colleagues (2014) and age of acquisition ratings (Kuperman et al., 2012), with words generally associated with earlier age of acquisition selected for inclusion to ensure that children would be familiar with them. Cartoon images of the objects and animals were sourced through Google Images, and edited to remove the background. Nonwords were created using the ARC Nonword Database (Rastle et al., 2002), with settings selected to generate words that included only orthographically existing onsets, only orthographically existing bodies, only legal bigrams, and a range of 4-10 letters. All words (both articles and nouns) were recorded using a text-to-speech program (http://www.naturalreaders.com/) with speaker “Graham” at 0 speed. The audio was recorded and edited with Audacity software. All stimuli were presented auditorily, rather than through text, in order to eliminate any confound in reading ability between children and adults.

Table 1
The novel article system

	Participants are *not* told	
	Animate	Inanimate
Participants are told		
Near	gi	ro
Far	ul	ne

2.3 Procedure

An overview of the procedure is shown in Figure 1. Before beginning the experiment, participants received a physical kit to take home, which contained the ZMax EEG headband, a laptop computer with the associated ZMax software, a Fitbit Sense and an Android phone to control the Fitbit. The experimental protocol consisted of an evening testing session, an overnight in-home sleep session with portable EEG recording, and a morning session. All experimental tasks were completed online, on participants' home computers.

Participants were instructed to begin the first session ~1.5 hours before their usual bedtime. Before starting the main experimental task, participants completed a questionnaire that included items relating to demographic information, language background, neurological history, vision and hearing, and current state/sleepiness (Appendix E). For adults, the links to the questionnaire and the online experiment were shared via email, and they completed the task on their own. For children, the parents received the questionnaire link via email, and the children completed the questionnaire with the assistance of a parent. Next, a Zoom call with the experimenter was initiated by the parent at an agreed-upon time. The children shared their screen and sound with the experimenter, and the experimenter remained on the Zoom call throughout the session to encourage the child to complete the experiment task properly. Questionnaires were administered via Qualtrics and the main experimental task was created on PsychoPy software (Peirce et al., 2019) and administered through Pavlovia.org. The first session lasted approximately 1 hour.

Once they were ready for bed, participants (or their parents, in the case of child participants) initiated a zoom call with the experimenter, allowing the experimenter to lead the participant through the setup of the EEG recording equipment (described in greater detail in

Section 2.3.3). After starting the recording, participants were instructed to go to sleep as usual, and the Zoom call was terminated. The next morning upon waking, participants stopped the sleep recordings, and removed the devices. They then completed a sleep questionnaire designed to assess the duration and subjective quality of their sleep, administered via Qualtrics (Appendix F).

The second session began approximately 12 hours after the first session started. Once again, the children's parents initiated a Zoom call with the experimenter when they were ready to begin, while adult participants completed the session on their own. After finishing the experimental task, adult participants then initiated a Zoom call with the experimenter. The experimenter then conducted a structured interview with participants (both children and adults) over Zoom (described in greater detail in Section 2.3.4). The second testing session lasted approximately 1 hour.

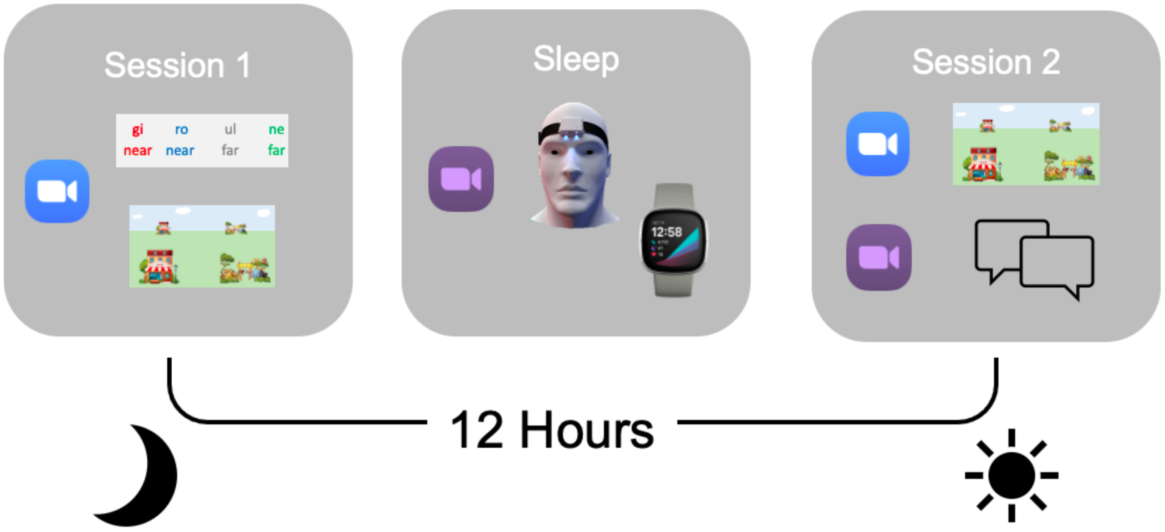
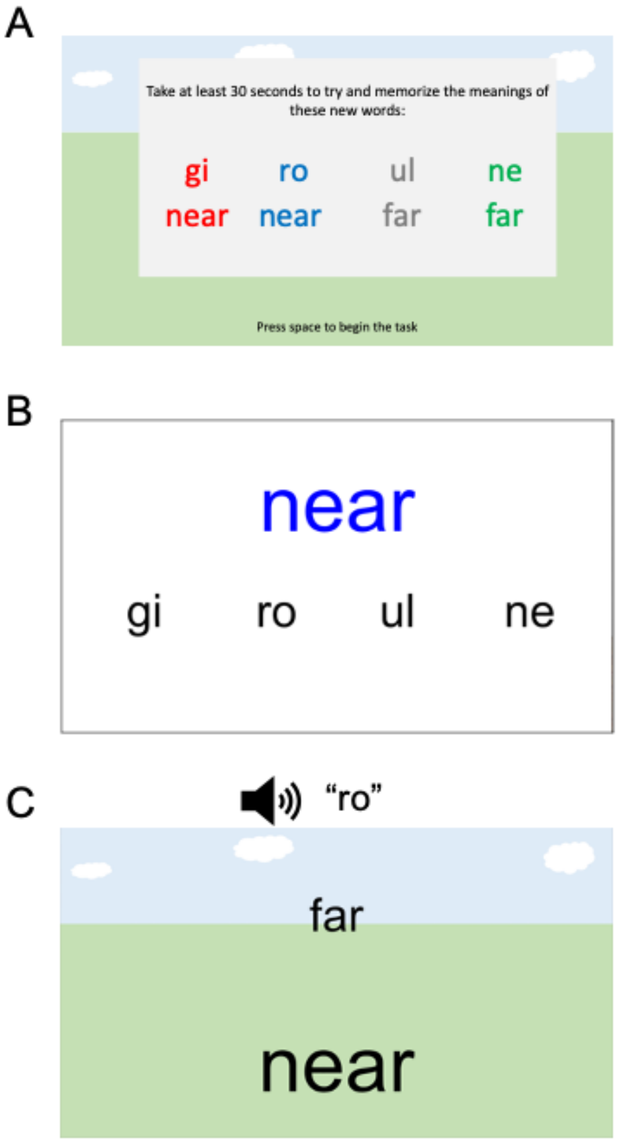


Figure 1. Overview of the experimental paradigm. Blue Zoom icons represent only children on Zoom with the experimenter; purple Zoom icons represent both children and adults on Zoom with the experimenter.

2.3.1 Pre-Training on Novel Article System

Prior to beginning the main experimental task in session 1, participants completed several pre-training tasks designed to encourage explicit encoding of the four new words and their distance meanings (i.e., *gi* and *ro* for near; *ul* and *ne* for far). As participants progressed through the pre-training tasks, all instructions were presented in both written and audio format. First, in an initial memorization phase, participants were presented with the novel articles and their meanings, each shown in a different colour, for at least 30 seconds (i.e., *gi* means near and is red, *ro* means near and is blue, etc.; Figure 2A). Participants were asked to memorize the meaning of each novel word and its unique colour during this time. The different colours were used in the subsequent pre-training phase as a way to distinguish between two words that had the same distance meaning. Next, participants completed a translation task, in which they viewed the word “near” or “far” presented in a certain colour, and selected the novel article that was a match in terms of both meaning and colour (i.e., if “near” was presented in blue, they would click on *ro*; Figure 2B). Participants were given feedback to show if they clicked the correct or incorrect word. This task was performed until participants got at least 11/12 correct in a row, or until they completed a maximum of 60 total trials. Finally, participants completed a second training task, in which one of the four novel articles was presented auditorily and participants were asked to select the word “near” (placed at the front of the screen) or the word “far” (placed at the back of the screen; Figure 2C). They received feedback on whether their response was correct or incorrect. The spatial layout of the words “near” and “far” on the screen were designed to prepare participants for the main experimental task to come. This training task contained 48 trials, with the four novel articles presented 12 times each.



Take at least 30 seconds to try and memorize the meanings of these new words:

Press space to begin the task

Figure 2. Training tasks. (a) Memorization phase in which participants had to take at least 30 seconds to memorize the novel articles and their distance meanings and corresponding colours. (b) Example of the translation task where participants had to select the correct novel article based on the distance and colour. c) Example of the listening task where participants were auditorily presented with one of the novel articles and selected if it meant near or far.

2.3.2 Main Experimental Task

Participants were first presented with a child-friendly cover story, in which objects and animals had “escaped” and the participant’s help was needed to return each object and animal back to where it belonged. It was explained that the animals belonged in the zoo and the objects belonged in the shop. The main experimental trials then began. As depicted in Figure 3, each trial began with an image of two shops and two zoos, one of each which were “near” the participant (located at the front of the screen) and the other which were “far” (located farther back on the screen). One of the four novel articles, followed by a noun, was then presented auditorily (e.g., “ro shirt”). The participant was asked to respond by clicking on the correct location for the item (i.e., the near or far shop or zoo), based on the distance of the novel article as well the animacy of the noun. If the participant clicked on the correct location, an image of the item would appear in the correct place. The participant would then click to continue to the next trial. If the participant clicked on the wrong location, the phrase would be presented again. A correct response was required in order to move on to the next trial.

Each session (Session 1 and Session 2) included 280 trials. Of those, 200 were canonical trials, in which the animacy of the noun corresponded to the hidden animacy rule (e.g., “ro shirt”). In addition, there were 40 violation trials (10 of each novel article) in which the animacy of the noun violated the hidden rule (e.g., “ro lion”). Finally, there were 40 generalization trials, in which the novel article was paired with a nonword (e.g., “ro badupi”). Before these trials, a screen was presented to inform the participant that the next trial would contain a word that they had not heard before. Participants were instructed to sort these trials based on what they felt was best. Participants did not receive feedback on the generalization trials, and an image of a question mark would appear wherever they clicked (Figure 3). Trial order was pseudorandomized, such that violation trials, generalization trials and trials of the same article were distributed roughly evenly throughout the session. Specifically, 24 different preset pseudorandomized orders were created, and participants were assigned to a given order according to their participant ID. The objects and animals assigned to each session were counterbalanced, such that a given noun would be presented in session 1 for half the participants and in session 2 for the other half. Breaks were given every 40 trials, and length of the break was determined by the participant. The task lasted approximately 45 minutes.

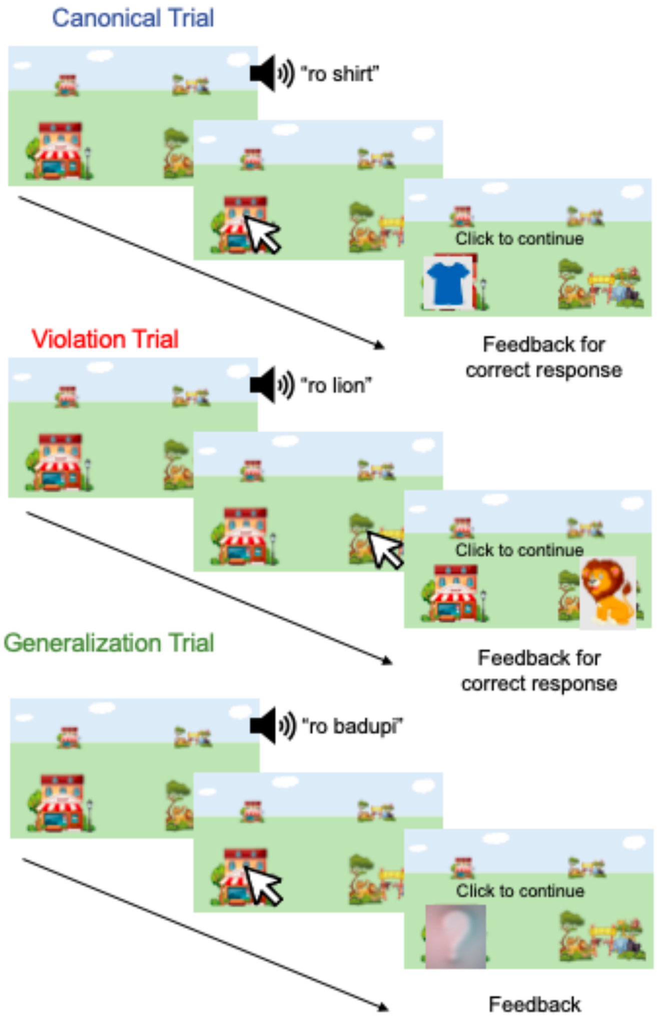


Figure 3. Example trials. On each trial, participants heard a novel article paired with a noun, and were then required to click on one of four locations (near/far shop or near/far zoo) based on both

the animacy of the noun and the distance indicated by the novel article. For canonical trials, the animacy of the noun corresponded to the probabilistic hidden animacy rule (i.e., “ro” typically predicts inanimate). For violation trials, the animacy of the noun did not correspond to the hidden rule. If the response on a canonical or violation trial was incorrect, the phrase was re-presented, and participants were required to make another selection. Once the participant selected the correct response, positive feedback was shown in the form of a corresponding image over the correct location. On generalization trials, a nonword was presented along with the novel article. Once participants selected a location, a question mark icon was presented where they clicked.

2.3.3 Sleep Recording

The Hypnodyne ZMax system, a portable EEG device designed for in-home sleep recordings, was used to record participants’ EEG data while they slept in their own homes (see Figure 4). The Hypnodyne ZMax headband was placed on the participant’s forehead, and used to collect EEG and eye movement data from two frontal electrode channels (F7-FPZ and F8-FPZ), with a reference electrode at FPZ. Heart rate, noise levels, head position, and ambient light were also recorded by the Zmax, though not analyzed in the current study. EEG data were sampled at 256 Hz. In addition to the ZMax headband, participants wore a smartwatch equipped with actigraphy, the Fitbit Sense.

As mentioned previously, the experimenter led the participant (and/or their parent) through the set-up via Zoom. First, an alcohol wipe was used to clean participants' forehead, and hair was tucked out of the way. Participants then attached a new electrode patch to the headband and removed the plastic coverings to reveal the hydrogel electrodes and an adhesive along the forehead. They applied the headband to the center of the forehead, with the electrodes connecting to the forehead around the temple area. Participants then fastened the straps to cover the electrode patch and connect at the nape of the neck with velcro adhesive. The adjustable nature of the straps allowed for a close fit for both children and adults.

Participants then started the ZMax software called *HDRecorder*, which uses a receiver connection to wirelessly transmit the data from the headband to the computer in real time. The experimenter was shown the recording screen to verify the transmission was working and the electrodes were connected properly. On one occasion, the wireless transmission failed, so an SD card was inserted into the headband and used to record the data instead; in this case, visual inspection of the signal could not be performed. Participants then put on the Fitbit and started recording from the Fitbit app and a custom app.

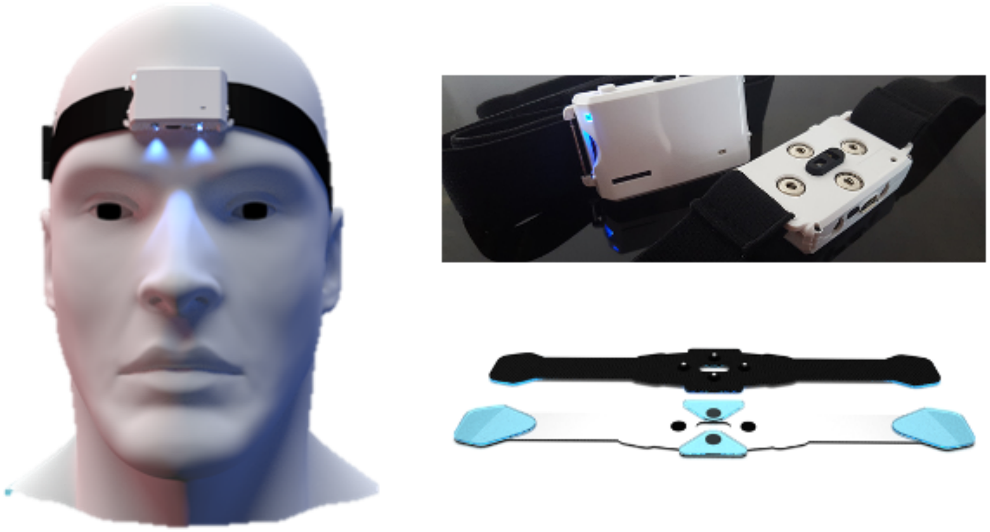


Figure 4. The ZMax device and electrodes used for sleep recording. Images from *hypnodynecorp.com*

2.3.4 Awareness Assessment

The awareness assessment consisted of a verbal interview that probed participants' explicit knowledge of the hidden animacy rule (Appendix G). It was conducted at the end of the second session over zoom. The experimenter asked a series of questions and immediately transcribed participants' responses. The questions became more specific as the interview went on. Participant responses were later coded as aware or unaware. Using a liberal awareness criterion (and thus a conservative "unaware" criterion), we coded participants as aware if they correctly indicated the relevance of animacy for at least one of the four novel articles (e.g., "ul was for animals" or "ro was for objects").

2.5 Behavioural Data Analyses

All analyses of behavioural data were conducted with R software (R Core Team, 2020), mixed effects models were conducted using the *lme4* package (Bates et al., 2015), and interactions were interpreted using the *emmeans* package (Lenth et al., 2022). As a first step, canonical trial accuracy was calculated for each participant over both sessions. Participants who performed below chance overall on the canonical trials (i.e., < 25% accuracy for first responses) were excluded due to failure to perform the explicitly instructed task (n = 5 children). This resulted in a final sample of 26 children and 30 adults for all behavioural analyses. All trials with a reaction time (RT) greater than 8 seconds were removed (5.21% of all trials; 8.61% for children and 2.04% for adults).

As a measure of sensitivity to the hidden animacy rule, we conducted two main analyses, directly comparing (1) RTs and (2) accuracy for canonical versus violation trials. For the RT analysis, because children's RTs were slower than adults, RTs for correct trials were within-subject Z-scored to allow for more direct RT comparisons between groups. A linear mixed effects model was conducted on z-normalized RTs, with condition (canonical vs. violation), trial number (1-560), and session (1,2) as within-subject factors, age group as a between-subjects factor, and participant intercept modeled as a random effect. We expected RT to decrease overall across sessions and across trials, reflecting improved general fluency with the task with greater practice. More critically, we expected slower RTs for violation trials compared to canonical trials as time went on, reflecting learning of the hidden animacy rule.

For the accuracy analysis, a mixed effects logistic regression was conducted on accuracy for each trial (1= correct, 0 = incorrect) with age group as a between-subjects factor, condition (canonical vs. violation), trial number (1-560), and session (1,2) as within-subject factors, and participant intercept modeled as a random effect. Similarly to RT, we expected that accuracy should increase overall across sessions and trials, while at the same time decreasing for violation trials relative to canonical trials over time. Additionally, to examine the relationship between implicit rule learning and sleep measures, a composite measure called a rule learning index (RLI; used previously by Batterink et al., 2014) was calculated as the overall difference in accuracy between canonical and violation trials from the last half of the first session to the first half of the second session.

Next, a combined measure of speed and accuracy called the Balanced Integration Score (BIS) was calculated to examine implicit rule sensitivity while controlling for potential speed accuracy trade-offs (Liesefeld et al., 2014). BIS has been shown to incorporate RT and percent correct in equal amounts, effectively controlling for speed-accuracy trade-offs (Liesefeld & Janczyk, 2019). This measure is calculated by z-scoring reaction times and the percentage of correct trials, then subtracting the standardized RTs from the standardized percent correct (Liesefeld & Janczyk, 2019). Because the BIS is a composite measure that cannot be modelled at the trial level, for this analysis, each session was separated into 4 mini-blocks, resulting in 8 total mini-blocks. The values were z-scored separately for each age group and the BIS was calculated by condition, participant, and mini-block. We first ran a linear mixed effects model on BIS scores, with condition (violation vs. canonical), mini-block and age group as fixed effects and participant modeled as a random effect. We expected to see higher BIS scores for canonical trials than violation trials, indicating relatively facilitated performance. In addition, a cumulative trial measure of the BIS was used to determine the earliest time point at which a significant condition effect emerged in each age group. Paired samples t-tests were calculated at each cumulative mini-block (i.e., the BIS for mini-block 1, then the BIS for mini-blocks 1 and 2 combined, etc.) between the canonical and violation conditions. We expected a difference in conditions to emerge earlier in children than in adults.

We then conducted a more fine-grained analysis of the types of errors that participants made to distinguish implicit versus explicit rule knowledge. The difference in proportion of *animacy* errors on violation trials compared to canonical trials (violation animacy error % - canonical animacy error %) serves as an index of implicit rule knowledge, and the overall proportion of *distance* errors serves as a (reverse) index of explicit rule knowledge. For each block (2 blocks per session, 4 total blocks), and participant, we calculated the percentage of trials in which the participant selected (1) the incorrect animacy and (2) the incorrect distance. Trials where participants committed a simultaneous animacy and distance error were not considered for this analysis. For the percentage of explicit distance rule errors, we ran a linear mixed effects model with block (1-4) and age group as fixed effects and participant as a random effect. Condition was not included in this analysis because we would not expect performance on the explicit distance rule to differ between conditions. To examine the effect of overnight consolidation, we ran the same model with just block 2 and 3 (the blocks directly before and after sleep). Here, we expected explicit distance errors to decrease after a period of consolidation. Next, we examined hidden animacy rule errors by conducting a linear mixed effects model with age group, block and condition modeled as fixed effects and participant modeled as a random effect. We then ran the same model with just block 2 and 3 to investigate effects of overnight consolidation. We would expect there to be a greater proportion of errors on violation trials as compared to canonical trials in the 3rd block than the 2nd block, indicating overnight consolidation of the implicit rule.

Accuracy for generalization trials was analyzed separately. A mixed effects logistic regression was conducted on generalization accuracy for each trial (1= correct, 0 = incorrect) with age group as a between-subjects factor, trial number and session (1,2) as within-subject factors, and participants as a random effect. In a second analysis, as a way to isolate generalization of the hidden animacy rule specifically, we excluded all trials that involved making a distance error, as these more general errors were not of specific interest. One sample t-tests were then conducted to test whether participants' animacy rule generalization performance was above chance (50%). An independent two-sample t-test was also conducted to determine whether there were overall age-related differences in generalization ability. Finally, the difference in hidden rule generalization (excluding trials with a distance error) between session 1 and session 2 was calculated for each participant to examine the relationship between generalization improvement and sleep measures.

Finally, to assess if adults and children became aware of the rule at different rates, a chi-square test was conducted.

2.6 EEG Analyses

Due to the unsupervised nature of the in-home sleep recording, a variety of technical issues arose. For 10 participants (6 adults; 4 children), the electrodes disconnected for a majority of the night, resulting in unusable EEG data. For a further 10 adult participants there were technical issues with the ZMax hardware, resulting in no connection or a poor connection being established with the recording software. Additionally, the child participants who were removed for poor behavioural performance (see criteria in section 2.5) were not included in the sleep analysis. These exclusions resulted in a total of 22 children and 14 adults with usable sleep data (though many of these participants still experienced some brief periods of data loss).

Sleep staging was performed manually using the ZMax software HDScorer in 30 second epochs according to standard sleep staging criteria established by the American Academy of Sleep Medicine (Iber et al., 2007). The percentage of time in each sleep stage was calculated for each participant, excluding periods of time where the data could not be scored.

More fine-grained physiological analyses of the EEG data were conducted with an open-source, Python-based sleep analysis toolbox called YASA (Yet Another Spindle Algorithm; Vallat & Walker, 2021). We specifically extracted the following physiological sleep features from both data channels, all of which have been previously associated with memory consolidation: spindles, slow oscillations, spectral bandpower and the strength of spindle-slow oscillation coupling (Tamminen et al., 2010; Wei et al., 2016; Holz et al., 2012; Hahn et al., 2020).

Spindles. First, A bandpass finite impulse response (FIR) filter of 1 to 30 Hz was applied to the data from both channels during NREM sleep. Then power in the sigma frequency range of 11-16 Hz was calculated using a Short-Term Fourier Transform, on consecutive epochs of 2 seconds with a 200ms overlap. There were 3 thresholds to be met for inclusion as a spindle event. The first threshold required 20% of the signal's relative power to be within the sigma band. For the second threshold, Pearson correlation coefficients were calculated between the raw EEG signal and the signal filtered to the sigma band with a moving sliding window of 300 ms and steps of 100 ms. The threshold was set at a correlation value $r > .65$. This was done so only spindles that were visible on the raw signal were detected. The final threshold was based on the root mean square (RMS) calculated from the EEG signal in the sigma band with a sliding window of 300ms and steps of 100ms. The RMS threshold was a constant value set as the mean of all the RMS values plus 1.5 times the RMS standard deviation. The spindle threshold was met at any time point where the RMS exceeded the RMS threshold value. This detected increases in energy in the sigma EEG signal. Data that passes all 3 thresholds was then put through a decision vector that computed the beginning and end of the spindle event, by determining the point at which 2 out of 3 of the thresholds were crossed. Spindles that were too close to each other (less than 500ms) were merged together, and spindles that are <0.5 seconds or >2s were removed. For spindles that overlapped in both channels, only one was counted. Spindle density was then calculated as the number of spindles per minute of stage 2 sleep.

Slow Oscillations. First, a bandpass FIR filter from 0.3-1.5 Hz with a transition band of 0.2 Hz was applied to the data. Next, negative peaks with an amplitude between -40 and -200 µV, and positive peaks with an amplitude between 10 and 150 µV were detected. To be counted as a slow oscillation, the peak-to-peak amplitude had to be within 75-350 µV, and complete a zero-crossing. The duration of the negative phase had to be between 0.3 and 1.5 seconds, and the duration of the positive phase had to be between 0.1 and 1 second. For slow oscillations that overlapped in both channels, only one was counted. The density of slow oscillations was then calculated as the number of slow oscillations per minute of stage 3 sleep.

Spectral bandpower. First, a bandpass filter from 0.5-45 Hz was applied to NREM data. Welch's sliding periodogram, a method of the Fourier transform that reduces noise by averaging periodograms of short segments, was applied. A sliding window of 4 seconds was used to calculate the power of the signal at different frequencies, and produce the power spectral density for each channel and stage (NREM2 and NREM3). The power (μV^2/ Hz) in the delta band (0.5-4 Hz), theta band (4-8 Hz), alpha band (8-12 Hz), sigma band (12-16 Hz), beta band (16-30 Hz) and gamma band (30-40 Hz) were calculated and averaged within each sleep stage for each channel.

Slow Oscillation- Spindle Coupling. Finally, cross frequency analysis of slow oscillation-spindle coupling was calculated using the YASA algorithm. For each slow oscillation detected using the method described above, the Hilbert transform was used to extract the instantaneous phase of the slow oscillation from the 0.3-1.5Hz filtered data. Then the same data were filtered in the sigma range (12-16 Hz), and the instantaneous amplitude was extracted using the Hilbert transform. This was calculated within a 4 second epoch centered around the negative peak of the slow wave (i.e., 2 seconds before and after the negative peak). The phase of the slow wave corresponding to the maximum amplitude of the associated spindle was then extracted. Across all slow oscillation events in stage 3 sleep, the circular mean and the vector length of the slow oscillation phase at the peak spindle amplitude was then calculated and averaged across both channels. The mean phase provides a measure in radians of when in the slow oscillation cycle spindles tend to occur, and the vector length provides a measure of phase variability across SO-spindle events, with a longer vector length indicating less variability and stronger coupling.

Group Comparisons. Independent samples t-tests were conducted to compare the percentage of SWS, spindle density, slow oscillation density, and delta bandpower between children and adults. The goal of these analyses was to determine if there were differences in sleep characteristics between children and adults, particularly related to slow-wave sleep and associated physiological signatures.

Correlational Analyses. Our sample size was likely underpowered to detect correlations between sleep signatures and behavioural measures of linguistic rule learning. Nonetheless, as an exploratory analysis for future research, Pearson r correlations were conducted to determine the relationship between sleep measures (percentage of time in SWS, spindle density, slow wave density, delta bandpower, strength of slow oscillation-spindle coupling) and session 1 to session 2 change in generalization performance, separately for children and adults. Another set of correlations was conducted between the sleep measures and change in the RLI from the last half of session 1 to the first half of session 2.

Finally, exploratory analyses of the Fitbit data yielded low correspondence between the EEG data and the sleep estimates produced by actigraphy. We thus opted to focus primarily on the EEG data for the purposes of the current thesis.

Chapter 3

3 Results

3.1 Behavioural Results

3.1.1 Reaction Time

We first sought to examine how condition (canonical vs. violation), trial number (1-560), session, and age group influenced normalized reaction times (Figure 5A). The model yielded significant main effects of trial number, age group, and session (see Table 2 for full model results). As trial number increased, reaction times got faster, and reaction times during session 2 were faster than session 1. As a by-product of our z-score normalization procedure, children had faster normalized RTs at the intercept than adults, since adults became faster over time. Overall, there was no significant main effect of condition. However, in a simpler model with only condition and age group as fixed effects and participant as a random effect, there was a main effect of condition, $t(20401)=2.217$, $p= .027$, where violation trials had slower RTs than canonical trials, but no main effect of age group ($t(20401)=-0.188$, $p= .851$), or interaction between the two ($t(20401)=0.542$, $p= .588$). This indicates that both age groups do show an overall sensitivity to the hidden rule.

Returning to the main model, across both age groups, there was a significant interaction between condition and trial, characterized by a greater speed-up for canonical trials versus violation trials as trials progressed. This interaction suggests gradually greater difficulty in processing violation trials, indicative of learning the hidden animacy rule. Additionally, there was a significant three-way interaction of condition, trial and age group, indicating that the two age groups showed differences in the progression of the violation effect over the course of the task.

To follow up on this condition x trial x age group interaction, we examined the separate linear trends of trial number by condition within each age group for RT. In adults, there was a marginally significant difference in slopes between canonical and violation trials across time (*t*(20401) =-2.541, *p*= .053), reflecting relatively greater facilitation over time for canonical trials. In contrast, children showed no difference in slopes between canonical and violation trials over time (*t*(20401)= -0.388, *p*= .98). These results suggest the adults became increasingly sensitive to violations of the animacy rule as the task progressed, whereas in children the violation effect was present from very early on in learning, remaining stable thereafter (illustrated in Figure 5A).

3.1.2 Accuracy

In line with learning of the hidden rule, there was an overall significant main effect of condition, with better accuracy for canonical (M = 73%) than violation trials (M = 65%). Unsurprisingly, there was also a significant main effect of age group, reflecting that children showed significantly poorer accuracy (M = 63%) than adults (M = 80%).

Here we describe only the interactions that include condition, the factor of interest (see Table 2 for a report of the full results from the model). Similar to RT, we expected to see a decrease in accuracy for violation trials as compared to canonical trials over time, reflecting gradual learning of the hidden animacy rule. Critically, supporting this prediction, there was a significant condition by trial interaction across both age groups. Relative to canonical trials, violation trials show a decline in accuracy as trials progressed (see Figure 5B for accuracy averaged over each block). This interaction effect did not differ significantly between children and adults, suggesting that both groups showed a similar pattern.

Table 2
Summary of reaction time and accuracy model results

	RT model				Accuracy model			
Parameter	estimate	SE	*t*	*p*	estimate	SE	*z*	*p*
intercept	.250	.002	8.93	**<.001**	1.35	.149	9.12	**<.001**
Condition	-.006	.070	-0.96	.33	-.352	.142	-2.47	**.013**
Trial	-.001	.0001	-6.81	**<.001**	.0006	.0003	1.60	.109
Session	-.248	.079	-3.13	**.002**	.066	.181	0.37	.715
Age Group	-.155	.044	-3.54	**<.001**	-.894	.215	-4.16	**<.001**
Condition *Trial	.001	.0004	2.31	**.021**	.002	.0009	2.07	**.039**
Condition *Session	-.126	.195	-0.64	.52	.582	.414	1.41	.160
Condition * Age Group	.199	.110	1.81	.071	-.082	.192	-.430	.667
Condition *Trial* Session	-.0004	.0006	-0.75	.45	-.003	.001	-2.54	**.011**
Condition *Trial* Age Group	-.001	.0006	-2.04	**.041**	-.001	.001	-1.26	.210
Condition *Session* Age Group	-.185	.307	-0.60	.54	.495	.568	.872	.382
Condition * Trial* Session* Age Group	.001	.0009	1.60	.109	.0008	.002	.436	.663

Note: The reference level for condition is canonical. The reference level for age group is adult. Bolded values are significant at p <.05.

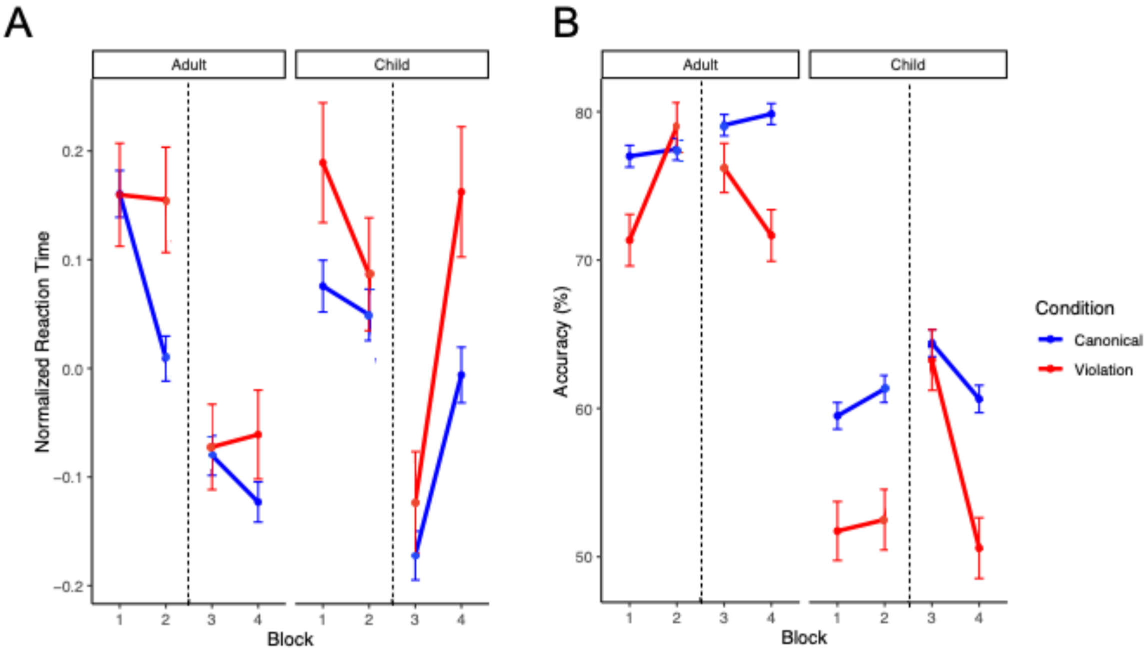


Figure 5. Mean (a) normalized reaction time and (b) accuracy percentage, averaged by blocks here for visualization purposes. Block 1 includes the first half of session 1 (i.e. 140 trials), block 2 includes the half of session 1. The dotted line represents the overnight break in which sleep occurred. Blocks 3 and 4 include trials in the first and second halves of session 2 respectively. Error bars represent standard error.

3.1.3 Time Course of Learning

To summarize the prior section, the RT results suggest that children became sensitive to the rule more quickly than adults, although accuracy results indicated no significant age group difference in the time-course of rule sensitivity. An integrated measure of speed and accuracy called the balanced integration score (BIS) combines both measures of performance into a single metric while controlling for possible speed-accuracy trade-offs, allowing us to adjudicate between these two possibilities. In addition, we used this BIS measure to directly test when children and adults first became reliably sensitive to the hidden rule (see Figure 6). Trials with higher accuracy and/or faster RTs produce a higher BIS value, indicative of relatively facilitated performance.

As described in the Methods, because BIS must be computed across a group of trials rather than on a trial-by-trial basis, we computed the BIS over 8 “mini-blocks” (4 per session). Across age groups, there was a significant effect of mini-block (see Table 3), with increasing BIS across mini-blocks, reflecting overall facilitation in performance over time. Neither condition, age group, or any interactions were significant. In a simpler model with only condition and age group as fixed effects and participant as a random effect (see Table 3), there was a significant effect of condition, with higher BIS for the canonical condition than the violation condition. Neither age group nor the interaction with condition and age group was significant. This indicates an overall sensitivity to the hidden rule using the BIS measure.

Table 3

Summary of BIS model results

	Full BIS model				Simpler BIS model			
Model	BIS ~ Condition * Mini Block * Age Group + (1 | participant)				BIS ~ Condition * Age Group + (1 | participant)			
Parameter	estimate	SE	*t*	*p*	estimate	SE	*t*	*p*
intercept	- .302	.254	-1.19	0.238	.099	.222	.0446	.657
Condition	-.035	.197	-.179	0.858	-.198	.090	-2.20	**.028**
Mini Block	.089	.028	3.24	**.001**				
Age Group	.329	.373	.884	.379	.118	.326	.363	.718
Condition* Mini Block	-.036	.039	-.930	.353				
Condition* Age Group	-.338	.289	-1.17	.242	-.237	.132	-1.80	.073
Condition* Mini Block*	.022	.057	.393	.695				

Age Group

Note: The reference level for condition is canonical. The reference level for age group is adult. Bolded values are significant at p <.05.

We next utilized a cumulative block measure of BIS to determine the earliest reliable time point of rule sensitivity for each age group (see Figure 6B). Children first showed a significant difference in BIS between canonical and violation trials by cumulative mini-block 2, which remained significant throughout the remaining mini-blocks. In contrast, adults first showed a significant difference by cumulative mini-block 7, continuing until mini-block 8. This indicates that children became sensitive to the hidden rule at an earlier timepoint than adults, and that rule sensitivity did not emerge in adults until midway through the second session. These results converge with the findings from the RT analysis, supporting the hypothesis that children became sensitive to the hidden rule more quickly than adults.

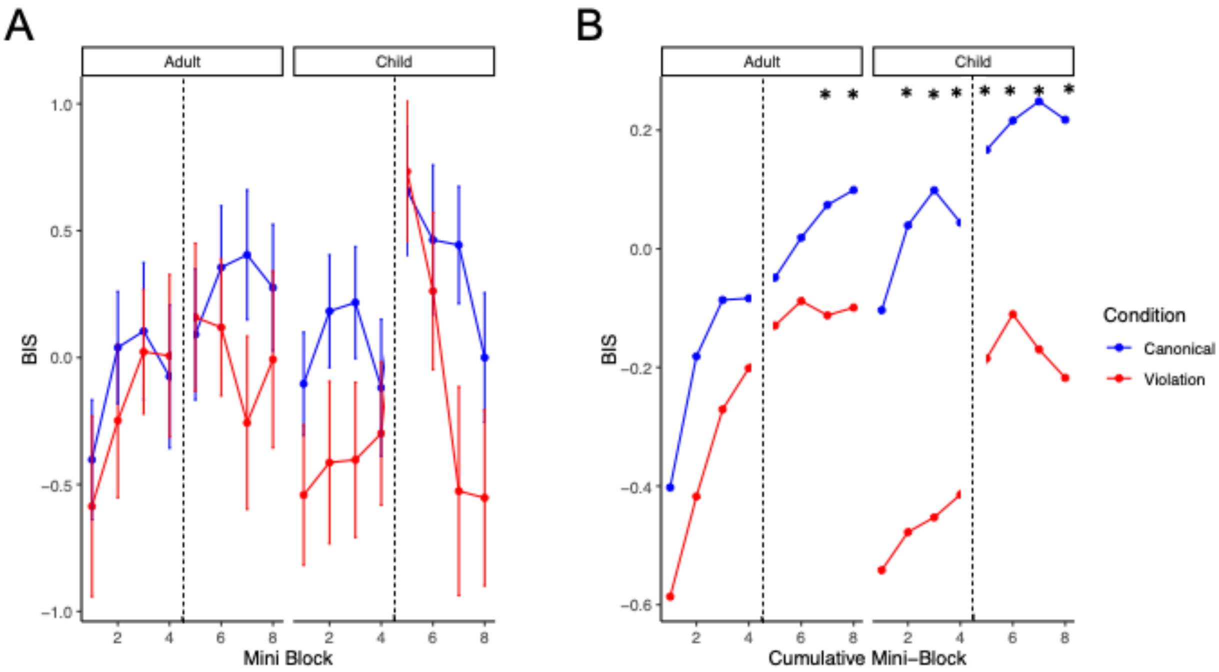


Figure 6. Speed-accuracy tradeoff. Note that the values on the y-axis are different between the two figures. (a) Balanced integration score (BIS), an integrated measure of speed-accuracy, at

each mini-block. Error bars represent standard error. (b) The cumulative score indicating the mean BIS of all blocks up to and including that point. Asterisks represent paired sample t-tests between canonical and violation BIS where $p < .05$.

3.1.4 Error Type

We next analyzed the types of errors that participants made, by classifying each error according to whether it involved an incorrect distance decision (i.e., incorrect application of the explicit rule) or an incorrect animacy decision (a more direct reflection of the implicit rule; see Figure 7 for averages computed across 2 blocks per session). Trials that included both animacy and distance errors were excluded from this analysis.

For the explicit distance rule, there was a significant effect of age group, with children making more distance errors than adults ($t(149.2)=5.127$, $p<.001$). There was also a significant interaction between block and age group, with children showing a stronger decrease in explicit errors (i.e., greater improvement) across blocks relative to adults (Child contrast between the first and last block error percentages: $t(370) = 7.09$, $p <.001$; Adult contrast between the first and last block error percentages: $t(370)=0.985$, $p=.32$). Turning to the effects of overnight consolidation, planned comparisons of the change in error from blocks 2 to 3 revealed an interaction between block and age group, $t(371)= -4.396$, $p<.001$, suggesting age differences in overnight consolidation. Children showed a significant decrease in overall proportion of distance errors from block 2 (M=6.8%) to block 3 (M=3.3%), suggesting continued improvement of the explicit distance rule after a period of sleep, $t(156)= -5.67$, $p= <.001$. In contrast, adults showed no difference in error rate for the explicit distance rule between block 2 and 3, $t(156)= -0.166$, $p= .87$, potentially because they were already near ceiling on this aspect of performance.

For the hidden, implicit animacy rule there were no significant effects of block, condition, age group, or any interactions (see Supplementary Table 1). However in a simpler model with only condition and age group as fixed effects, there was a significant effect of condition (*t*(390.7)=2.469, *p*=.014), indicating more overall animacy errors on violation trials than canonical trials. Next, we conducted a planned contrast between block 2 and 3 to investigate overnight consolidation. There was a significant interaction between condition, block, and age group, *t*(158.5)= -2.504, *p*= .013. We then compared the difference scores between canonical and violation trial accuracy in block 2 to block 3. Adults had a marginally significant larger condition effect in block 3 than block 2, suggesting overnight consolidation of the hidden animacy rule (*t*(27)=-1.72, *p*=.09). In contrast, children had a *smaller* difference in block 3 than block 2, providing no evidence of overnight consolidation of this rule (*t*(25)=2.13, *p*=.04). This suggests age group differences in the degree of overnight consolidation of the implicit hidden animacy rule.

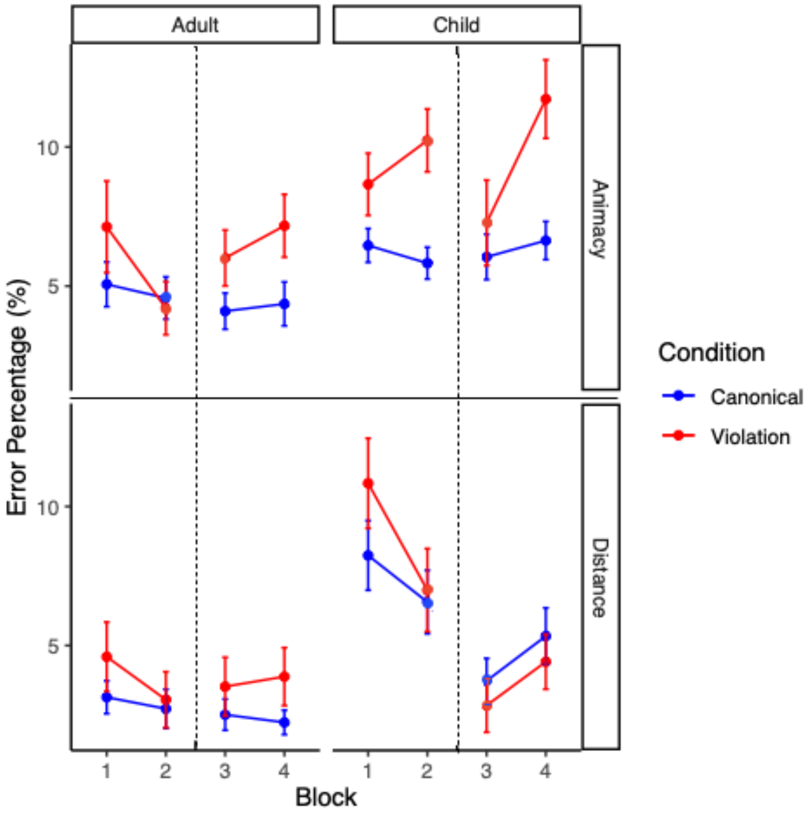


Figure 7. The percentage of animacy (top), or hidden rule errors, and distance (bottom), or explicitly learned rule errors across blocks. Error bars represent standard error.

3.1.5 Generalization

In our initial model that included all trials, none of the predictors (trial number, age group and session) nor their interactions significantly predicted generalization accuracy (see Supplementary Table 2). Our secondary analysis specifically isolated generalization of the hidden animacy rule by including only trials in which participants made a correct explicit distance judgement (i.e., excluding trials in which the explicit distance rule was incorrectly applied). Interestingly, this analysis revealed that across both sessions, children showed overall significantly higher generalization performance than adults, $t(3743)= 3.91$, $p< .001$, indicating that they were better able to apply the hidden animacy rule to novel words when forced to guess.

Children also performed significantly better than chance during block 4 (the second half of the second session), *t*(400)=1.95, *p*= .05. Children were significantly below chance on block 1 (*t*(346)=-2.21, *p*=.02), and not significantly different from chance on blocks 2 and 3 (*p*'s > .05). In contrast, adults' performance on the generalization task was overall below chance, *t*(2203) = -5.10, *p*<.001, and below chance on all blocks except block 4 where it was not different from chance. See Figure 8.

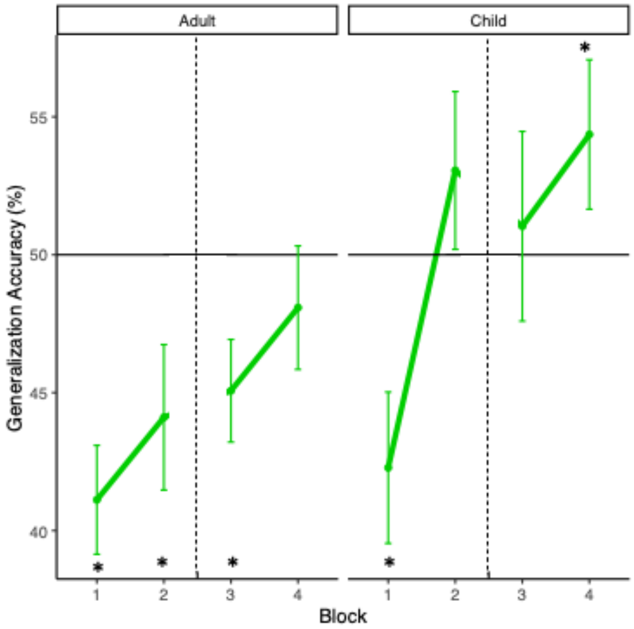


Figure 8. Generalization accuracy for only trials in which participants made a correct explicit distance judgement. Error bars are standard error.

The finding that adults (as well as children during block 1) performed significantly *below* chance on generalization trials was unexpected. To better understand this finding, we examined possible biases in "shop" versus "zoo" selection for each of the four different novel articles. The proportion of "shop" selections (i.e., corresponding to a decision of inanimacy for the article +

nonword pair) as a function of novel article can be seen in Supplemental Figure 1. Despite the fact that novel words were randomly assigned to the four articles, we found that adults showed a significant inanimacy bias for *gi* and *ul*, selecting the shop more frequently than chance levels ($t(1116)=8.29$, $p<.001$), suggestive of possible unintended idiosyncrasies in these items that led to an inanimacy preference. Because these articles actually correspond to animate items, this bias explains adults' below chance performance on generalization trials.

3.1.6 Awareness

Although a numerically greater proportion of children demonstrated awareness of the hidden rule than adults (38% children versus 23% adults; see Table 4), this difference was not significant, X^2 (1, N = 56) =1.51, $p = .219$.

Table 4

The number of participants who reported becoming aware of the hidden animacy rule.

	Child	Adult
Aware	10	7
Unaware	16	23
Proportion Aware	38%	23%

3.2 Sleep Results

For the participants with usable sleep data, the average percentage of time in each sleep stage is reported in Table 5.

Table 5

The percentage of time spent in each sleep stage for each age group, and the results of an independent two sample t-test between children and adults for each stage.

Stage	Child Mean (SD)	Adult Mean(SD)	P value t(33)
NREM1	1.9% (1.2%)	4.4%(2.7%)	<.001
NREM2	37.4% (10.8%)	42.2% (10%)	.201
NREM3	34.1% (11.8%)	23.8% (9.7%)	.012
REM	23.5% (7.7%)	26.5% (6.3%)	.229
Wake	3.1% (1.8%)	3% (1.8%)	.912

We also compared the physiological features of sleep associated with memory consolidation between children and adults (see Figure 9). Adults had greater spindle density (*t*(33)=2.88, *p* = .007) and slow oscillation-spindle coupling than children (*t*(34)=5.07, *p*<.001). In contrast, children had greater slow oscillation density (*t*(34)=3.88, *p*<.001) and stage 3 delta power than adults (*t*(34) = 4.27, *p* <.001).

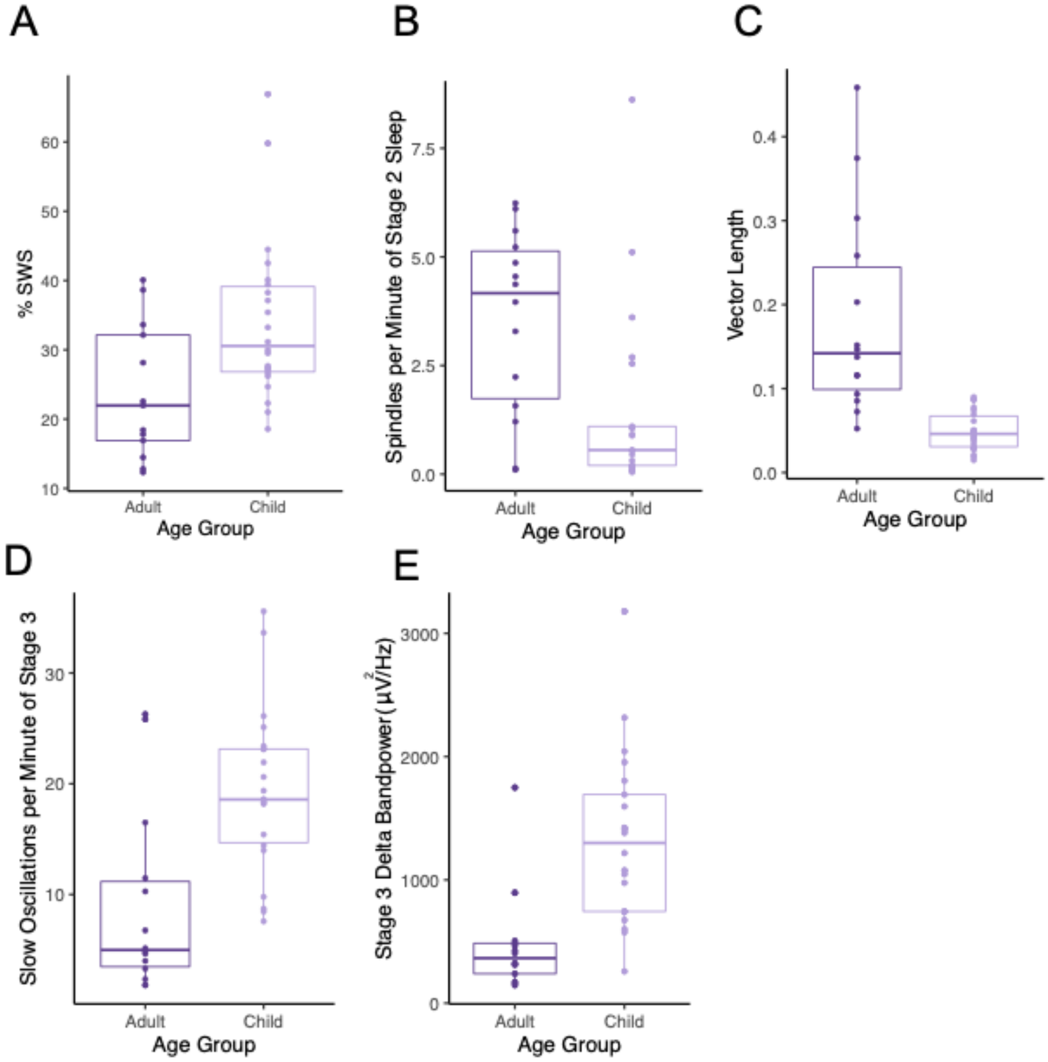


Figure 9. Boxplots where dots represent individual participant values for various sleep measures. (a) The percentage of time in SWS. (b) The number of spindles per minute of stage 2 sleep. (c) The average vector length of slow-oscillation spindle coupling. (d) The number of slow oscillations per minute of stage 3 sleep. (e) The average bandpower in the delta (0.5-4Hz) range during stage 3 sleep.

Finally, we ran exploratory correlations between sleep measures (percentage of time in SWS, spindle density, slow wave density, delta bandpower, strength of slow oscillation-spindle coupling) and session 1 to session 2 change in generalization performance, as well as change in the RLI from the last half of session 1 to the first half of session 2, separately for children and adults. None of the correlations revealed a significant relationship (all *p*'s > .05). We also ran exploratory correlations for all participants between self report sleep measures of total sleep duration and subjective sleep quality with change in generalization performance and RLI, but none of these correlations revealed a significant relationship (all *p*'s > .05). See Supplementary Table 3 for correlation values.

Chapter 4

4 Discussion

The aim of the current study was to examine developmental differences in the role of sleep in linguistic rule learning. Child and adult participants completed a language learning task, in which they learned four novel articles that followed an explicit grammatical rule, as well as a second, hidden, implicit grammatical rule. Participants performed the task before and after a night of sleep, during which their EEG was recorded using a portable EEG device.

Overall, our results indicate that both children and adults gained sensitivity to the implicit linguistic rule, as demonstrated by slower RTs and decreased accuracy to violation trials compared to canonical trials. Consistent with our hypothesis of a linguistic rule learning advantage in children, we found that sensitivity to the hidden rule emerged earlier in children than in adults. Children also outperformed adults on generalization of the implicit rule, which required applying the novel rule to nonsense words without any meaning, and achieved above-chance generalization performance by the end of the second session.

Additionally, we observed a developmental double dissociation in the effect of consolidation on explicit versus implicit rule learning, which was also broadly consistent with our hypotheses. In terms of accuracy, children performed better on the explicit rule after a 12-hour period containing sleep, while showing a transient *reduction* in implicit rule sensitivity. In contrast, adults showed no change in explicit rule performance after a period containing sleep, but showed an increase in implicit rule sensitivity, suggesting consolidation of the hidden rule. Physiological sleep analyses indicated that children had greater SWS durations, delta power, and slow oscillation density, whereas adults had greater spindle density and stronger spindle-slow oscillation coupling. However, contrary to our hypothesis, we did not find a relationship between physiological measures of sleep and linguistic rule consolidation, though our sleep analyses were likely underpowered to find such effects. Taken together, these results suggest that children can learn linguistic rules faster, and generalize rules better than adults. These findings are also consistent with the previously proposed idea that children's richer SWS may preferentially support consolidation of explicit memory, whereas adults' sleep may facilitate consolidation of implicit memory.

4.1 Children Demonstrate Linguistic Rule Learning Advantages Over Adults

While children are disadvantaged compared to adults on most high-level cognitive tasks, there are several domains—including language learning—where children typically outperform adults (Gualtieri & Finn, 2022; Johnson & Newport, 1989). Here, we find that on both the rate of implicit linguistic rule learning and generalization of this rule, children have an advantage over adults.

Both adults and children showed overall slower RTs to violation trials compared to canonical trials, indicating that both groups became implicitly sensitive to the hidden rule. However, in children this violation effect was present from very early on in learning, whereas adults did not show this effect initially but became increasingly more sensitive to the rule as the task progressed. An overall condition effect was also observed for accuracy, with both groups showing overall better accuracy for canonical trials than violation trials, providing additional evidence of general rule sensitivity. However, in contrast to the RT results, the violation effect for accuracy showed a similar time course between groups. To reconcile the finding that there were age group differences in the time course of learning using RT, but not accuracy, we turned to an integrated measure of speed and accuracy that combines the two factors at equal weights, called the Balanced Integration Score (BIS; Liesefeld & Janczyk, 2019). The BIS measure supported the RT findings, indicating that children first became sensitive to the hidden rule early in the first session, whereas adults did not show sensitivity until later in the second session, after a period of sleep.

These results closely parallel findings from a recent study that compared children and adults' learning of phonotactic constraints—that is, the sequences of speech sounds that are allowed in a given language (Smalle et al., 2017). In that study, 9-10 year old children reliably showed evidence of learning second order phonotactic constraints after just a quarter of the way through the first day of training. In contrast, adults only showed evidence of learning by the second session, after a period of sleep, closely converging with our findings. Additional findings from the phonotactic learning literature suggest that sleep may promote, or even be necessary, for phonotactic learning to occur in adults. Gaskell et al. (2014) found that adults who slept, but not adults who stayed awake, showed evidence of learning phonotactic constraints. Another study in adults tested whether a period of consolidation benefits phonotactic constraint learning over and above more exposure to the regularities (Warker, 2013). The authors found that a consolidation period resulted in a greater learning benefit than a longer initial training session. Our results extend these findings from the phonotactic constraint literature to a novel linguistic paradigm, supporting the idea that children can learn linguistic rules after only a few exposures, whereas adults may require a period of consolidation to stabilize this implicit knowledge. However, we also note that our design does not allow us to disentangle the effects of additional exposure to the rule from effects of consolidation. In our study, both additional rule exposure and the opportunity for consolidation may have contributed to the eventual emergence of implicit rule sensitivity in adults during the second session.

The mechanisms underlying children's advantage for language acquisition are still under debate. Classic theories argue that there is an innate biological process that governs when language is acquired, and a critical period for optimal language acquisition that ends around puberty (Chomsky, 1976; Johnson & Newport, 1989; Lenneberg, 1967). A proposed mechanism for children's language learning advantage is offered by Newport's "Less-is-More" hypothesis (Newport, 1988). This hypothesis suggests that children's limited perceptual and memory capabilities may allow them to excel at language learning, since they are able to focus on smaller morphological units of information that actually carry meaning, rather than whole form-meaning relationships. As children age, their perceptual and memory capabilities increase, making the task of language learning paradoxically more difficult. Children's abilities are thus particularly well suited to learning sequential properties of language such as grammar and phonology, processes that involve the analysis of the components of language, whereas adults are biased towards whole word strategies, allowing them to excel in memory and vocabulary (Newport et al., 2001). Our finding that children can implicitly detect the hidden grammatical rule more rapidly than adults provides support for this hypothesis, adding to the growing body of literature on children's advantage for learning linguistic regularities.

Another theory, which contrasts with strict critical period explanations, proposes that language learning mechanisms may be continuously present, but change in their efficiency over development (Thiessen et al., 2016). This approach suggests that learning statistical regularities in language through the extraction and integration of environmental input is one mechanism of language learning that is continuously used throughout the lifespan, but that learning outcomes fundamentally change as a result of entrenched linguistic experiences and decreased neuroplasticity into adulthood. Supporting this theory, adults have a greater ability to control their attention and try to learn languages explicitly, which may inhibit their ability to implicitly detect regularities from linguistic input (Fletcher et al., 2005).

Interestingly, children also showed better rule generalization performance than adults, more accurately indicating the animacy when a novel article was presented with a meaningless nonword (e.g., *ro badupi*). While generalization performance in both groups was generally poor, children did eventually achieve above chance generalization performance in the final block. Both continued exposure to the linguistic rule as well as consolidation effects may have contributed to children's eventual successful rule generalization, particularly since we did not see a clear jump in generalization performance in the block directly after consolidation. While we cannot disentangle these contributions in the current study, the possibility that memory consolidation during sleep may have been beneficial is supported by previous evidence that sleep promotes generalization and integration of linguistic rules in infants and children (Gomez et al., 2006; Henderson et al., 2012). Gomez and colleagues (2006) found that infants who had a nap showed a greater ability to abstract sequential dependencies to new sentences than infants who stayed awake. Similarly, Henderson and colleagues (2012) tested 7-12 year old children for lexical integration of novel words, where newly learned words act as a competitor to existing lexical items, and is measured using a pause detection task where slower RTs to existing competitors indicate integration. They found that children only improved after a period of sleep, but not a similar period of wake. Another highly relevant study directly compared children and adults' ability to integrate novel words using eye movements (e.g., fixating on a novel item *biscal* after hearing the existing word *biscuit*), after a period of consolidation (Weighall et al., 2017). The authors found that 7-8 year old children, but not adults, showed boosted integration for items trained the previous day as compared to new items. Thus, sleep appears to play a role in facilitating the integration of new linguistic knowledge into existing neural networks, allowing for the production of new associations and leading to the abstraction of the novel words into new contexts. These studies suggest that children in particular may benefit from a period of consolidation on tasks of abstraction and generalization.

Finally, we found that a numerically higher proportion of children reported becoming aware of the hidden rule than adults, but this difference was not significant. Surprisingly, not many participants became aware of the hidden rule, with only 38% of children and 23% of adults reporting awareness. This is fewer than in the previous Batterink et al. (2014) study, in which about half of the adult participants became aware of the hidden rule. The difference in rates of awareness may be due to task differences, as participants in our study made concurrent (rather than sequential) animacy and distance judgements, possibly giving them less opportunity to consider animacy as a potentially relevant, isolated factor.

Although we did not find strong evidence that consolidation contributes to rule awareness in the current study, some prior research has shown that sleep may contribute to the explicit gain of insight into implicit or hidden patterns. Wagner et al. (2004) found that more than twice as many participants gained insight into a hidden numerical rule if they slept than if they stayed awake. Wilhelm et al. (2013) demonstrated that children were able to extract explicit knowledge from an implicitly learned sequence better after sleep than wake, and better than adults. However, another study found that sleep-enhanced consolidation of grammatical rule generalization performance only occurred if participants were aware of the rules before sleep (Kim & Fenn, 2020). Taken together, this suggests that rule awareness may be more likely to occur after a period of sleep compared to wake. In addition, if awareness does emerge prior to sleep, sleep-dependent consolidation may impact generalization performance.

4.2 The Effect of Consolidation on Linguistic Rule Learning

Another hypothesis addressed by the current study is that, relative to adults, children's richer slow wave sleep would lead to a larger increase in explicit knowledge of the hidden rule. As expected and consistent with prior literature (Ohayon et al., 2004; Wilhelm et al., 2013), children in our study showed richer SWS. Specifically, children showed significantly longer NREM3 duration, greater slow oscillation density during NREM3, and higher power in the delta range during NREM3. We also sought to investigate the temporal coordination of SO-spindle coupling, which is thought to be a key mechanism of sleep-dependent memory formation (Helfrich et al., 2018; Rasch & Born, 2013). Consistent with prior literature, we found stronger coupling in our adult sample than in children (Hahn et al., 2020). Hahn and colleagues (2020) used a longitudinal approach to characterize SO-spindle coupling from childhood to adolescence, finding that as participants aged, their spindles become more tightly coupled to SOs, and this in turn predicted memory on a word pair task. We also found that adults had a greater spindle density than children. This aligns with the reported developmental trajectory of spindle density, which has been found to peak in young adulthood (approximately ages 15-25) and decline thereafter (Clawson et al., 2016). A notable success of the current study is that we were able to replicate previously reported developmental effects on sleep physiology, acquired using gold-standard lab polysomnography (Clawson et al., 2016; Hahn et al., 2020; Ohayon et al., 2004), using a portable EEG headband with only two channels.

Although we did find the expected developmental patterns of sleep physiology, we did not find any correlations between these measures of sleep and behavioural changes in explicit or implicit knowledge of the hidden animacy rule. Due to the nature of our task where learning and testing occurred throughout each session, we do not have a "pure" measure of pre-sleep and post-sleep knowledge. Data from the second session reflects a mixture of learning due to continued exposure to the article system, and potential consolidation effects. In addition, we were limited by our small sample size for sleep analyses, which was caused by technical difficulties with the portable sleep recording device, and particularly affected the adult sample. Thus, we were underpowered to detect any correlational relationships between physiological measures of sleep and improvement on knowledge of the hidden grammatical rule.

At the group level, our more fine-grained analyses of the different types of errors made across learning (Figure 7) suggest that there are dissociable consolidation effects on implicit versus explicit rule learning as a function of development. From the block immediately before sleep to the block immediately after sleep, adults showed an increase in the proportion of animacy errors made to violation trials, reflecting a gain in implicit rule sensitivity. In contrast, children's sensitivity to the implicit rule transiently decreased after a period of sleep. The opposite pattern of results was observed for the explicit distance rule. Children showed a decrease in errors from the block before sleep to the block after sleep, potentially reflecting consolidation of the explicit distance rule. In contrast, adults did not show a difference in errors between those blocks.

These results are in line with our hypotheses that consolidation will preferentially benefit implicit memory in adults, and explicit memory in children. This aligns with the general idea that SWS preferentially strengthens hippocampal-dependent, explicit memory representations, whereas REM-rich sleep has beneficial effects for implicit memories (Diekelmann & Born, 2010; Rasch & Born, 2013). Fischer and colleagues (2007) found that implicit knowledge decreased in children after sleep, and increased in adults after sleep, which mimics our pattern of results. The authors speculated that this decrease in implicit knowledge in children may be due to the competing enhancement of explicit knowledge, although the study did not directly test pre-sleep or post-sleep levels of explicit knowledge. Another study looked at the consolidation of both declarative and procedural tasks in 6-8 year old children and adults (Wilhelm et al., 2008). The authors found that both children and adults improved more on declarative tasks after a period of sleep than an equivalent period of wake. On the procedural task, adults also improved more after sleep than wake, whereas children showed the reverse pattern, improving more after *wake* than sleep. Studies in adults on early night SWS-rich sleep compared to late night REM-rich sleep reveal that SWS-rich sleep benefits explicit memories, whereas REM-rich sleep benefits procedural or implicit memories (Born et al., 2006). Again, these results highlight that implicit knowledge in children is less likely to be consolidated or enhanced by sleep. This dissociation between implicit and explicit knowledge in children's overnight consolidation may be reflective of SWS strengthening hippocampal dependent knowledge, to the detriment of other types of knowledge. Taken together, our results support the notion that children’s richer SWS preferentially stabilizes and enhances explicit (rather than implicit) knowledge.

An alternative possibility is that these effects relate to the strength of the memory trace prior to the 12-hour consolidation period, rather than the implicit versus explicit nature of the memories. Adults may have been at a ceiling level of performance on the explicit distance rule, so the sleep-dependent consolidation effect emerged only for implicit knowledge of the hidden animacy rule that was at a weaker level of performance before sleep. This account follows from Stickgold’s (2009) theory that the extent of memory consolidation depends on its initial strength, and follows an inverted U-shaped curve, where intermediate levels of performance show the greatest benefit from sleep-dependent consolidation. Indeed, Wilhelm et al. (2012) found that children and adults with an intermediate level of performance on a motor skill benefitted the most from sleep-dependent consolidation.

The current study was designed to address whether sleep may account for children’s language learning advantage. Our results only partially support this notion, with a period of consolidation benefiting explicit knowledge in children, but not adults. However, children’s implicit learning was present very early on, and consolidation did not benefit implicit knowledge of the linguistic rule in children. We also found that children had an advantage for generalization over adults, but found no strong evidence that consolidation supported generalization performance. This points to mechanisms other than sleep and consolidation, such as developmental differences in perception, attention, and memory, as the driver of children’s relatively rapid acquisition of implicit linguistic regularities.

4.3 Limitations and Future Directions

One limitation of this study was the lack of a wake condition, and thus we are unable to draw any direct comparisons about memory consolidation benefits of sleep versus wake. In addition, as mentioned earlier, we also lacked an isolated measure of pre-sleep and post-sleep performance, since each trial simultaneously contributed to learning and acted as a measure of knowledge. This means that any post-sleep improvement in performance may be driven by consolidation or continued rule exposure.

We also were limited by the at-home sleep recording technology. While in-lab polysomnography remains the gold standard for sleep research, a portable EEG headband provides many practical benefits. These include easier access to child and adult participants (which may have been particularly problematic for the current study due to the Covid-19 pandemic) and the capability of assessing sleep in the home environment rather than in a foreign and potentially stressful lab environment (Kelly et al., 2012). Nonetheless, data from the portable EEG system is much more limited and definitively poorer in quality than laboratory EEG data. In addition, data from many subjects (15% of children; 53% of adults) were lost due to technical difficulties, limiting our sample size and decreasing power to detect any relationship between sleep features and the strength of linguistic rule knowledge. We would recommend that future sleep studies using portable EEG technology incorporate an adaptation night, so that any potential issues with the recording quality may be addressed before the experimental night.

We also saw a trend of increasing RTs and decreasing accuracy in children by the very end of the second session, possibly indicating general fatigue or boredom with the task. Future studies could consider shorter tasks and a wider variety of tasks to prevent attentional confounds, since children have greater difficulty than adults when paying attention to the task at hand (Plebanek & Sloutsky, 2017).

In addition, our study was not optimized to capture the time course of rule awareness when it did occur. Participants' self-reports of when they became aware of the rule provide only limited and perhaps not always accurate information, and depend on both memory and introspection abilities. These are likely to be especially poor in children. We had originally planned for the generalization trials to represent a potential index of awareness, since a large, sudden jump in accuracy on these trials would likely indicate that the participant had become aware of the rule. However, the generalization data were ultimately too variable at an individual level to serve as a reliable index of awareness.

Another limitation of our paradigm was that we did not have participants complete source attribution judgements for the generalization trials (i.e., in which participants indicate whether each judgment reflects a guess, intuition, recollection, or application of a specific rule; Dienes &

Scott, 2005). Thus, given previous research demonstrating that above-chance performance on this type of forced-choice task may in principle be supported by implicit memory (Voss et al., 2008; Voss & Paller, 2009; Williams, 2005), we cannot be sure whether generalization performance was supported by implicit or explicit knowledge. The source attribution judgment paradigm was previously used in a prior study of sleep-dependent consolidation and grammar learning by Kim & Fenn (2020), who classified knowledge as implicit if it was based on guess or intuition, and explicit if it was based on recollection or rule. Interestingly, the authors found that generalization only improved after sleep if participants had explicit knowledge of the grammatical rule before sleep. In the current study, collecting source attribution judgements would be a way to disentangle whether participants were using implicit or explicit knowledge, although it may also have had the undesired consequence of alerting them to the presence of the hidden grammatical rule.

Quite surprisingly, adults in the first three blocks and children in the first block showed significantly *below*-chance performance on generalization trials. Subsequent analyses suggested that this below-chance performance was due to an inherent bias to select the inanimate option for the “gi” and “ul” articles, which actually predicted animate items in our task. Although Williams (2005) did not find that the specific assignment of animacy to articles affected learning, counterbalancing article assignment as animate or inanimate would have helped prevent any inherent biases resulting from the phonological or linguistic properties of the articles themselves. Anecdotally, many participants also reported sorting generalization trials based on whether the nonword (e.g., *badupi*) sounded like an English word they already knew, rather than utilizing the novel article to assist in their sorting decisions. Future studies could consider using white noise bursts or other non-linguistic sounds to avoid any unintended associations with existing words.

Taken together, the results of this study reveal interesting developmental differences in language learning and associated consolidation effects. Future studies could build on this work by studying children older than 10 years to pinpoint whether there is a specific age at which it becomes more difficult to quickly learn linguistic regularities. This data would provide important insight into the debate between the critical period hypothesis (Hartshorne et al., 2018; Johnson & Newport, 1989), or whether there is a more gradual change in the speed of language learning (Birdsong, 2006; Thiessen et al., 2016). Future studies could also use larger sample sizes, use lab polysomnography, and employ a sleep/wake comparison to isolate effects of sleep-dependent consolidation from general effects associated with the mere passage of time.

4.4 Conclusion

This study was conducted to provide a greater understanding of developmental differences in the implicit learning and sleep-associated consolidation of linguistic regularities. We found that children rapidly gained sensitivity to the hidden rule and were able to generalize the rule, whereas adults showed sensitivity to the rule only after extended exposure to the artificial article system and a period of consolidation. These findings support the view that, relative to adults, children have an advantage in their ability to rapidly and implicitly acquire linguistic rules. Furthermore, we found evidence for dissociable consolidation effects of implicit and explicit knowledge across development. This has implications for theories of sleep-dependent consolidation, providing evidence for the view that children’s sleep preferentially strengthens explicit knowledge over implicit knowledge, potentially as a result of their richer SWS. While more research is needed to establish if children’s explicit knowledge of language is directly supported by their richer SWS, our findings provide indirect, preliminary support for this theory. These findings are important for understanding the unique neurocognitive abilities of children that shape learning during a time of rapid growth in childhood. These results may also have practical applications, suggesting that adult language learners can utilize sleep and consolidation to strengthen implicit knowledge of linguistic regularities learned prior to sleep.

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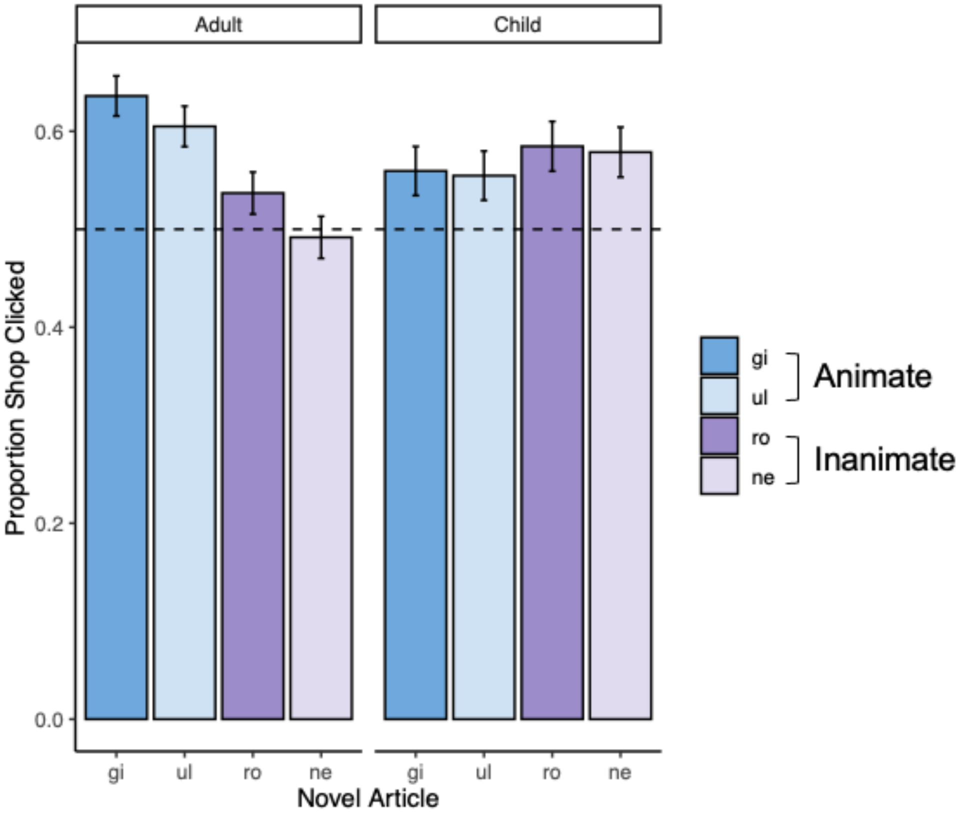
Appendix A: Supplementary Tables and Figures



Supplemental Figure 1. The proportion of generalization trials in which the correct distance was selected where the shop was clicked (i.e., the article and nonword were judged to be inanimate).

Supplemental Table 1

Summary of implicit animacy error rate model results

Model	Animacy error model Percentage animacy errors ~ Condition* Block* Age Group + (1| participant)			
Parameter	estimate	SE	*t*	*p*
intercept	.052	.012	4.49	<.001
Condition	.004	.015	.260	.795
Block	-.003	.004	-.684	.494
Age Group	.008	.017	.524	.601
Condition*Block	.004	.005	.829	.408
Condition* Age Group	.015	.022	.602	.548
Condition* Block* Age Group	.001	.008	.122	.903

Note: The reference level for condition is canonical. The reference level for age group is adult.

Supplemental Table 2

Summary of generalization model results with all trials included

Model	Generalization model Correct ~ Trial * Session * Age Group + (1| participant)			
Parameter	estimate	SE	*z*	*p*
intercept	-.517	.127	-4.06	<.001
Trial	.0009	.0007	1.22	.221
Session	-.015	.334	-.046	.963
Age Group	-.169	.196	-.858	.391
Trial*Session	-.0001	.001	-.183	.855
Trial*Age Group	.001	.001	.978	.328
Session*Age Group	.785	.503	1.55	.120
Trial*Session*Age Group	-.002	.002	-1.44	.150

Note: The reference level for age group is adult.

Supplemental Table 3

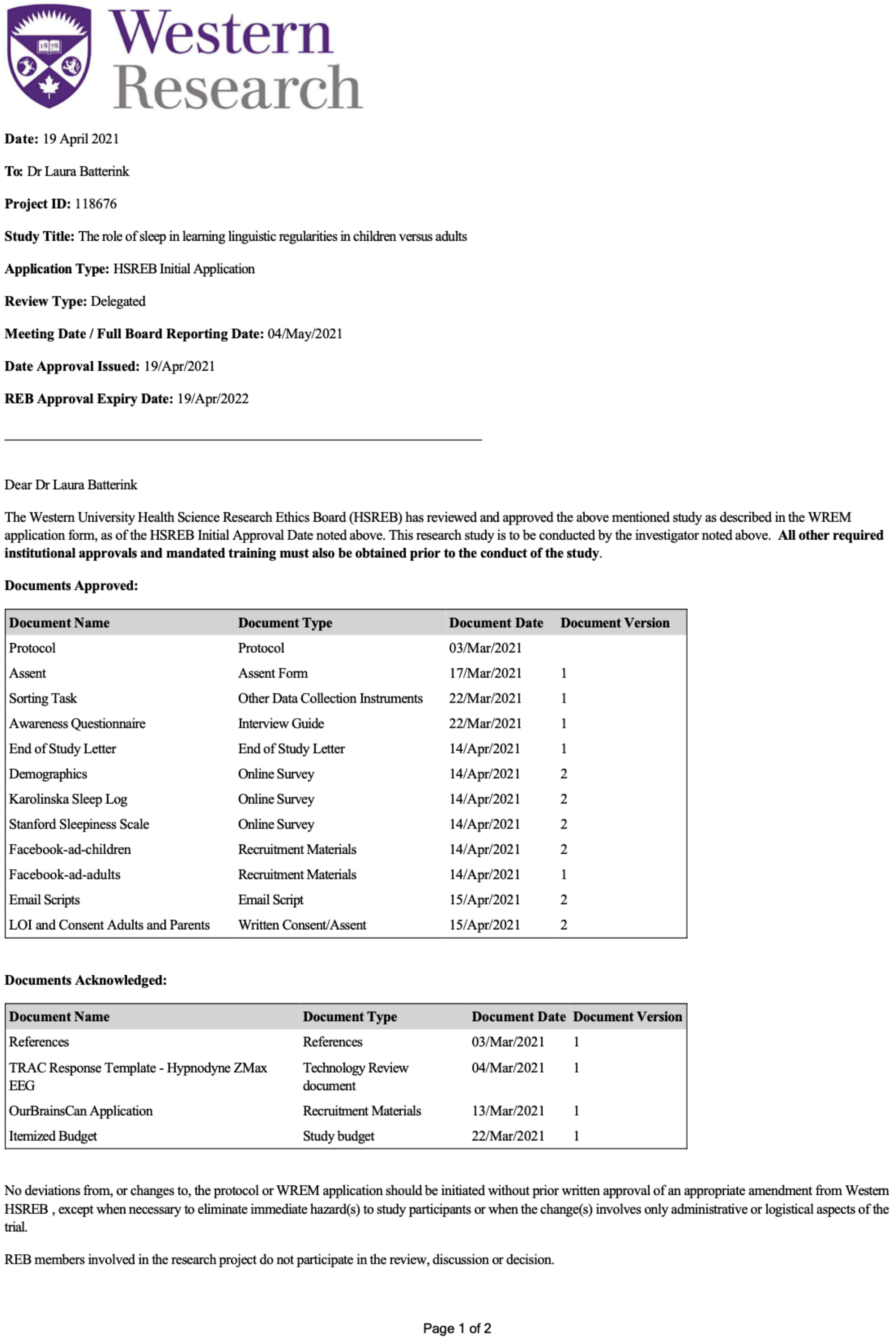
Correlations between sleep and behavioural measures

	Children		Adults	
Variable	RLI Change	Generalization Change	RLI Change	Generalization Change
SWS Percentage	-.035	-.250	-.247	-.018
Spindle Density	.087	.133	-.029	.099
Slow Oscillation Density	.020	-.047	.027	.093
Delta Bandpower	.168	.205	-.478	.002
Vector Length	.161	-.051	.267	.192
Total Sleep Hours †	-.113	.205	.036	.110
Average Sleep Quality †	-.121	.068	.266	.019

Note: Pearson R correlation values reported. No correlations were significant at p > .05.

† Includes the full participant sample

Appendix B: Ethics Approval



Western Research

Date: 19 April 2021

To: Dr Laura Batterink

Project ID: 118676

Study Title: The role of sleep in learning linguistic regularities in children versus adults

Application Type: HSREB Initial Application

Review Type: Delegated

Meeting Date / Full Board Reporting Date: 04/May/2021

Date Approval Issued: 19/Apr/2021

REB Approval Expiry Date: 19/Apr/2022

Dear Dr Laura Batterink

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above mentioned study as described in the WREM application form, as of the HSREB Initial Approval Date noted above. This research study is to be conducted by the investigator noted above. **All other required institutional approvals and mandated training must also be obtained prior to the conduct of the study**.

Documents Approved:

Document Name	Document Type	Document Date	Document Version
Protocol	Protocol	03/Mar/2021	
Assent	Assent Form	17/Mar/2021	1
Sorting Task	Other Data Collection Instruments	22/Mar/2021	1
Awareness Questionnaire	Interview Guide	22/Mar/2021	1
End of Study Letter	End of Study Letter	14/Apr/2021	1
Demographics	Online Survey	14/Apr/2021	2
Karolinska Sleep Log	Online Survey	14/Apr/2021	2
Stanford Sleepiness Scale	Online Survey	14/Apr/2021	2
Facebook-ad-children	Recruitment Materials	14/Apr/2021	2
Facebook-ad-adults	Recruitment Materials	14/Apr/2021	1
Email Scripts	Email Script	15/Apr/2021	2
LOI and Consent Adults and Parents	Written Consent/Assent	15/Apr/2021	2

Documents Acknowledged:

Document Name	Document Type	Document Date	Document Version
References	References	03/Mar/2021	1
TRAC Response Template - Hypnodyne ZMax EEG	Technology Review document	04/Mar/2021	1
OurBrainsCan Application	Recruitment Materials	13/Mar/2021	1
Itemized Budget	Study budget	22/Mar/2021	1

No deviations from, or changes to, the protocol or WREM application should be initiated without prior written approval of an appropriate amendment from Western HSREB , except when necessary to eliminate immediate hazard(s) to study participants or when the change(s) involves only administrative or logistical aspects of the trial.

REB members involved in the research project do not participate in the review, discussion or decision.

Page 1 of 2

The Western University HSREB operates in compliance with, and is constituted in accordance with, the requirements of the TriCouncil Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2); the International Conference on Harmonisation Good Clinical Practice Consolidated Guideline (ICH GCP); Part C, Division 5 of the Food and Drug Regulations; Part 4 of the Natural Health Products Regulations; Part 3 of the Medical Devices Regulations and the provisions of the Ontario Personal Health Information Protection Act (PHIPA 2004) and its applicable regulations. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Please do not hesitate to contact us if you have any questions.

Appendix C: Consent and Assent Forms

Is it a child or adult participating?

○ Child (1)

○ Adult (2)

Project Title: Studies of Sleep and Development

Principal Investigator:
Dr. Laura Batterink
Department of Psychology, The University of Western Ontario, London, ON
Telephone: [redacted]; Email: [redacted]
Funding: This study is funded by The Natural Sciences and Engineering Research Council of Canada (NSERC)

1. Invitation to Participate
You (or your child) are being invited to participate in a research study about the role of sleep in memory consolidation and language learning.

The purpose of this letter is to provide you with information required for you to make an informed decision regarding participation in this research. It is important for you to understand why the study is being conducted and what it will involve. Please take the time to read this carefully, and feel free to ask questions if anything is unclear or if there are words or phrases you do not understand.

2. Why is this study being done?

The purpose of the study is to investigate how sleep contributes to the learning, consolidation and retention of different aspects of language, and how this changes over the course of development. The results from this research will help us understand how sleep contributes to language learning, including clarifying whether sleep plays a more central role in learning some aspects of language compared to others. Our results will also help to pinpoint the underlying physiological mechanisms during sleep that may contribute to language learning and consolidation, and how these may change from childhood to adulthood.
This study will also investigate how the consolidation of memories occurs during sleep. The results of this investigation will provide a better understanding on the underlying neurophysiological mechanisms contributing to memory consolidation during sleep. This research may eventually lead to further insight into possible techniques and methods that individuals can adopt, to facilitate and enhance memory consolidation during sleep.

3. How long will you be in this study?

It is expected that this study will take place over one night and morning. The testing protocol will require approximately 0.5 hours per testing session, with one session in the evening and one the next morning. An overnight sleep session will take place that night. While you or your child sleeps in your normal home environment over this study period, brain activity will be recorded.

4. What are the study procedures?

The experiments conducted as part of this study will test how humans process and learn about different types of stimuli, such as syllables, words, phrases and locations of images. If you agree to participate, you will first complete a demographic information sheet, a neurological history and sleep habit/quality questionnaire. For child participants, parents can complete these forms. Then you will be asked to listen to language-related or non-language related auditory stimuli, read words and sentences on a screen and/or memorize the locations of images on a screen. At the end of the study we will do a Zoom interview where you will be asked to answer questions about your strategies during the computer game. Tasks will be performed in your own home on an online platform. The researcher will be available by phone or email when the tasks are performed on the online platform.

Your brain activity will be recorded using a technique called electroencephalography (EEG), where electrodes placed on the forehead measure electrical signals that brain cells use to communicate. The electrode patches will be placed on your forehead and will be secured using a headband strap. The electrode patches are re-usable, however new electrode patches will be provided to each participant. The headband connects wirelessly to a computer and data can be recorded to an SD card or to a hard drive on the computer.

You will be given the opportunity to sleep in your own home while your brain activity is recorded using EEG. The EEG headbands will either be dropped off at your home or can be collected from the Brain and Mind Institute in the Western Interdisciplinary Research Building (WIRB) on the University of Western Ontario campus. If the headbands are collected from the Brain and Mind Institute, you will receive instructions on how to use the system at the Brain and Mind Institute. If the headbands are dropped off at your home, one of the research team members will organize a Zoom session to provide instructions on the system. You will be asked to sleep overnight with the headband on. The experimenter will be available throughout the night if needed and can be contacted by phone.

5. What are the risks and harms of participating in this study?

There may be a risk of a very minor skin irritation due to the adhesive. You may also experience a minor inconvenience as some gel may remain on your forehead at the end of the study. The gel can easily be removed by washing your forehead. Safety protocols pertaining to the COVID-19 outbreak will be followed, as all equipment will be sanitized prior to and after the investigation and social distancing protocols will be enforced, when required.

6. What are the benefits?

You do not directly stand to benefit from this study. Although you may not directly benefit from your participation, the information gathered may provide benefits to society as a whole, which include enhancing our scientific understanding of sleep, memory consolidation, language, learning, development, and the brain, and leading to advancements in second language training and treatment of language-related disorders (for example, specific language impairment and autism).

7. Can participants choose to leave the study?

You or your child may refuse to participate, refuse to answer any questions or withdraw from the study at any time during the participation in the study. If you or your child decide to withdraw from the study, you have the right to request withdrawal of information collected about you. If you wish to have the information removed please let the researcher know. Withdrawing or refusing to answer questions will not result in loss of promised compensation. After the research has been disseminated to the public, it may not be possible for us to fully withdraw or recall your or your child's data.

8. How will participants' information be kept confidential?

Any personal or identifying information obtained from this study will be kept confidential and will be accessible only to the investigators of this study. Identifiable information that will be collected during the study includes your full name, age, telephone number, and email address. Since we are collecting direct identifiers for this study, there is the potential for a privacy breach. If lab facilities are deemed inaccessible due to the COVID-19 pandemic, we will collect your home address and postal code, in order, for researchers to drop off the equipment to your home. In the event of publication, any data resulting from your participation will be identified only by case number, without any reference to name or personal information. Only the research team will have access to identifying information to carry out this research study. Data will be stored securely on servers administered by online experimental platforms, such as Qualtrics and Pavlovia, which adhere to the General Data Protection Regulation (GDPR), only for the period that is required for data analysis. Otherwise data will be store in a secure place that is only accessible by the primary researchers conducting the study. The ZMax Hypnodyne system will only be collecting EEG data and will collect to your computer via Bluetooth. All EEG data will be stored and encrypted on an SD card inserted into the ZMax system. Upon completion of the investigation, the SD card will be collected with the EEG system by the researcher, and all data will be stored encrypted in a secure place only accessible by the primary researchers conducting the study.

If files are shared with other researchers or the results are made public, any personal identifying information will be removed. Only anonymized data will be shared outside the research team (e.g., in an open access repository for publication purposes, or for other researchers to verify the findings or re-analyze).

Any documents identifying you or your child by name will be kept separately from the data and will be destroyed after 7 years. De-identified and anonymous study records will be maintained for a minimum of 7 years. A list linking your study number with your name will be kept by the researcher in a secure place, separate from your study file. If the results of the study are published, your name will not be used

Representatives of the Western University Health Sciences Research Ethics Board may require access to your study-related records to monitor the conduct of the research.

9. Are participants compensated to be in this study?

You or your child will receive monetary compensation ($50 per overnight session + $14/h for online behavioural testing) for your participation in this study. The online behavioural testing sessions are expected to last 0.5-0.75 hours each, so you or your child will be paid $10 per behavioural testing session (no matter how long it takes to complete). If you or your child do not complete the entire study, you will still be compensated for the sessions you completed or started. However, you or your child will not be compensated for subsequent tasks. For example, if you or your child withdraws during the first behavioural session, you will be compensated $10 for your participation, but will not receive compensation for the sleep session or the second behavioural session. Compensation will be provided in the form of an Amazon Gift Card.

10. What are the rights of participants?

Your participation in this study is voluntary. You may decide not to be in this study. Even if you consent to participate you have the right to not answer individual questions or to withdraw from the study at any time. If you are a student at Western and you choose not to participate or to leave the study at any time, it will have no effect on your academic standing.

We will give you new information that is learned during the study that might affect your decision to stay in the study.

You do not waive any legal right by signing this consent form.

11. Whom do participants contact for questions?

If you have questions about this research study please contact Laura Batterink, Principal Investigator, Telephone: [redacted]; Email: [redacted]

If you have any questions about your rights as a research participant or the conduct of this study, you may contact The Office of Human Research Ethics [redacted]; or the long distance toll-free number: [redacted]

Display This Question:

If Is it a child or adult participating? = Child

Assent Letter

Project Title: Studies of sleep and development
Document Title: Assent form - Children
Principal Investigator + Contact:
Dr. Laura Batterink
Department of Psychology, The University of Western Ontario, London, ON
Telephone: [redacted]; Email: [redacted]

Why are you here? You are here today because we want to tell you about a study that we are doing that you can participate in. You can help us with our research project by playing a computer game and sleeping while wearing a special headband.

Why are they doing this study? We want to learn about how sleeping helps people learn languages, and how this changes as we grow up.

What will happen to you? If you want to be in this study, you will do a few different things with us:

First you will play a computer game where you will learn some new words, and then use those words to help you sort animals and objects into different places. Then, you will sleep in your own bed while wearing a special headband that records activity from your brain while you sleep. The next morning you will play that computer sorting game again. Finally, we will ask you a few questions about what you thought while playing the computer game.

Will there be any tests? This is not a test, and it will not have an effect on any of your marks in school.

Will the study help you?

This study will not help you directly, but it might help us know more about how sleep helps us learn languages.

Do you have to be in the study? You do not have to be in the study. No one will be mad at you if you do not want to do this. If you do not want to be in the study, tell the researcher or your parents. Even if you say yes, you can change your mind later. It is up to you.

What if you have any questions? If you have questions, you can ask questions at any time, now or later. You can talk to the researcher or your parents.

Display This Question:

If Is it a child or adult participating? = Child

For the child: Indicate here that you want to participate in this study by typing your name

____

I agree to be contacted for future research studies.

○ Yes (1)

○ No (3)

I have read the Letter of Information, have had the nature of the study explained to me and I agree for my child to participate. All questions have been answered to my satisfaction.

Parent/Guardian Name

____

Parent/Guardian Signature:

____

Display This Question:

If Is it a child or adult participating? = Adult

I have read the Letter of Information, have had the nature of the study explained to me and I agree to participate. All questions have been answered to my satisfaction.

Participant full name

____

Participant Signature

____

Q15 (For the experimenter only) My signature means that I have explained the study to the participant named above. I have answered all questions.

____

Q16 Experimenter Name

Q17 Experimenter signature

Appendix D: Word List

Animals

alligator
anaconda
angelfish
ant
anteater
antelope
ape
armadillo
baboon
badger
barracuda
bear
beaver
bee
beetle
bird
bison
blackbird
bluebird
bluejay
bobcat
brownbear
buffalo
bull
bulldog
bullfrog
bumblebee
bunny
butterfly
camel
canary
cardinal
caribou
cat
caterpillar
catfish
centipede
chameleon
cheetah
chicken
chihuahua
chimpanzee
chinchilla
chipmunk
clam
clownfish
cobra
cockatoo
cockroach
cougar
cow
coyote
crab
cricket
crocodile
crow
dalmatian
deer
dinosaur
dodo
dog
dolphin
donkey
dove
dragon
dragonfly
duck
duckling
eagle
earthworm
earwig
eel
elephant
elk
emu
falcon
ferret
firefly
fish
flamingo
flea
fly
fox
foxhound
frog
fruitfly
gazelle
gecko
gerbil
giraffe
glowworm
goat
goldfish
goose
gopher
gorilla
grasshopper
greyhound
grizzlybear
groundhog
guppy
hamster
hawk
hedgehog
hen
heron
hippopotamus
honeybee
hornet
horse
hummingbird
husky
hyena
iguana
insect
jackal
jaguar
jay
jellyfish
kangaroo
kitten
koala
labradoodle
ladybug
lamb
lemur
leopard
lion
lionfish
lizard
llama
lobster
lynx
manatee
mantaray
meerkat
millipede
minnow
mole
monkey
moose

mosquito
moth
mule
narwhal
newt
nightingale
octopus
opossum
orangutan
orca
ostrich
otter
owl
ox
oyster
panda
panther
parakeet
parrot
partridge
peacock
pelican
penguin
pig
pigeon
piranha
platypus
pony
poodle
porcupine
porpoise
pufferfish
puma
pup
puppy
python
quail
rabbit
raccoon
ram
rat
rattlesnake
raven
reindeer
reptile
rhino
roach
robin
rooster
salamander
salmon
sardine
scorpion
seagull
seahorse
seal
shark
sheep
sheepdog
shrimp
silkworm
skunk
sloth
slug
snail
snake
sparrow
spider
squid
squirrel
starfish
stingray
stork
swan
swordfish
tadpole
tarantula
termite
tiger
toad
tortoise
toucan
trout
tuna
turkey
turtle
viper
vulture
walrus
warthog
wasp
weasel
whale
wolf
woodchuck
woodpecker
worm
yak
zebra

<u>Objects</u>

airplane
ambulance
anchor
apron
arrow
backpack
ball
balloon
bandage
bandaid
barrel
basket
basketball
bathrobe
bathtub
battery
bed
belt
bench
bicycle
binder
blanket
blender
boat
book
boot
bottle
bowl
bowtie
bracelet
brick
briefcase
broom
bucket
buckle
button
cage
camera
candle

canoe
car
cards
carpet
carriage
cart
chain
chair
chalk
chalkboard
clock
closet
comb
cord
couch
cradle
crate
crib
cup
curtain
deck
dice
disc
dollhouse
domino
doorknob
doormat
drawer
dress
drill
drum
dumpster
engine
envelope
eraser
eyeglasses
fence
file
firetruck
fireworks
flag
flashlight
flute
football
fork
garbage
gift
glass
glove
glue
goggles
guitar
hairbrush
hammer
harp
hat
headband
helicopter
helmet
highchair
hook
hose
iceskate
jacket
jar
jug
kayak
kettle
key
keyboard
knife
ladder
lamp
laptop
lawnmower
limo
lipstick
lock
locket
lollipop
lunchbox
magazine
mailbox
map
marble
marker
mat
mattress
microphone
microscope
microwave
mirror
mitten
mixer
money
mop
motorcycle
mug
necklace
net
newspaper
nightstand
notebook
oven
pacifier
paddle
paint
painting
pants
pen
pencil
penny
perfume
phone
piano
pillow
plate
pocket
pole
pool
postcard
pot
printer
puppet
purse
puzzle
pyjamas
radio
refrigerator
remote
ring
roof
rope
ruler
sandbox
scarf
scissors
screen
shed
shoe
shoelace
shorts
shovel
shower
sink
skirt
sled
snorkel
soap
sock
spaceship
spatula
sponge

spoon
stairs
stapler
stepstool
sticker
stocking
stool
stove
string
sunglasses
sunscreen
sweater
swing
sword
table
tambourine
tape
telescope
thermometer
tie
tire
toaster
toilet
toothbrush
toothpaste
towel
toybox
train
trashcan
tray
tricycle
trunk
tv
umbrella
unicycle
van
vase
vest
violin
wallet
washcloth
wheel
wheelbarrow
wheelchair
window
wrench
yacht
zipper

<u>Nonwords</u>

blerlds
blolphs
boathe
brenk
brumbs
brurdle
clurme
crolt
dodes
doopth
drighm
dwimed
dwyggs
dwyped
eelte
egam
esprype
fenth
flawkned
frighnte
fryles
geambo
ghronth
gnulked
grourn
gwoints
inklyte
intwerp
joogway
klalv
kwokt
loogned
neech
onthreff
phloarphth
phooved
phrars
phrup
plarr
plawls
preuks
proant
queps
quosk
reuth
rhergs
sckoxts
scralv
scwoughse
sharced
shroons
shunched
skoal
skwatwe
slirl
sluint
smirse
spirp
spleeph
spolge
squieghed
squolths
stroobs
stuiz
swoust
tarb
thoabbs
trebe
troarphed
trorth
tweip
twynce
unstume
wheembs
wherphot
wortle
wumps
yoarph
zefths
zoam

Appendix E: Participant Information Form

Are you a child or adult? If this form is being filled out for a child, please have your parent/guardian help you with filling out these answers.

○ Child (1)

○ Adult (2)

What time of day are you completing this? (e.g. 9pm)

____

Select your birth year and month:

Month (1)	▼ January - December
Year (2)	▼ 1900-2020

Select your gender

○ Male (1)

○ Female (2)

○ Non-binary / third gender (3)

○ Prefer not to say (4)

Do you consider yourself:

○ Left-handed (1)

○ Right-handed (2)

○ Ambidextrous (3)

Is English the first language that you learned?

○ Yes (1)

○ No (2)

Skip To: Q10 If Is English the first language that you learned? = Yes

What language did you first learn?

____

At what age did you first begin learning English? And in what context?

____

In which language (English or your native language) are you more comfortable?

○ English (1)

○ Native Language (2)

Are you fluent in any language other than English?

○ Yes (1)

○ No (2)

Display This Question:
If Are you fluent in any language other than English? = Yes

List the language(s) you are fluent in

____

Are you regularly exposed to any language other than English?

○ Yes (1)

○ No (2)

Display This Question:
If Are you regularly exposed to any language other than English? = Yes

Which language and in what context?

____

Are there are other languages not asked about above that you know?

○ Yes (1)

○ No (2)

Display This Question:

If Are there are other languages not asked about above that you know? = Yes

Which languages do you know and how did you learn them?

____

Display This Question:

If Are you a child or adult? If this form is being filled out for a child, please have your parent/g... = Adult

What is your field of study/major?

____

Display This Question:

If Are you a child or adult? If this form is being filled out for a child, please have your parent/g... = Child

What grade are you in?

____

Have you ever had brain surgery?

○ Yes (1)

○ No (2)

Have you ever had, or do you currently have, any neurological disorders (e.g., seizures, schizophrenia)?

○ Yes (1)

○ No (2)

Display This Question:

If Have you ever had, or do you currently have, any neurological disorders (e.g., seizures, schizoph... = Yes

Please explain

____

Are there any known neurological problems in your family?

○ Yes (1)

○ No (2)

Display This Question:
If Are there any known neurological problems in your family? = Yes

Please explain

____

Are you currently taking any medication(s) that may affect brain functioning (including but not limited to anti-depressants, anti-psychotics, anti-seizure)?

○ Yes (1)

○ No (2)

Display This Question:
If Are you currently taking any medication(s) that may affect brain functioning (including but not l... = Yes

Please explain

____

Have you ever had, or do you currently have, any speech, hearing, learning, or psychiatric disorders?

○ Yes (1)

○ No (2)

Display This Question:
If Have you ever had, or do you currently have, any speech, hearing, learning, or psychiatric disord... = Yes

Please explain

____

Do you have normal or corrected-to-normal vision (i.e. glasses or contacts)?

○ Yes, I have normal vision or corrected-to-normal vision (1)

○ No, I do not have normal vision or corrected-to-normal vision (2)

Do you have normal hearing?

○ Yes (1)

○ No (2)

How many hours of sleep did you get last night?
▼ 1-12 hours (select 1)

How many hours of sleep do you typically get per night?
▼ 1-12 hours (select 1)

Do you feel like you got enough sleep last night to function normally both physically and mentally?

○ Yes (1)

○ No (2)

Display This Question:
If Do you feel like you got enough sleep last night to function normally both physically and mentally? = No

Please explain

____

Is there any other circumstance (not asked about above) that makes you feel like you are not at your mental best right now?

○ Yes (1)

○ No (2)

Display This Question:
If Is there any other circumstance (not asked about above) that makes you feel like you are not at y... = Yes

Please comment

____

Please rate your level of current fatigue on a 1-10 scale, where 1 is “so tired I can barely function today” and 10 is “I feel super rested, I’ve never felt better.”

Very Tired Feel Great

0 1 2 3 4 5 6 7 8 9 10

Fatigue level ()	

Appendix F: Sleep Questionnaire

What time did you go to bed and turn the light off last night? (e.g. 11:15pm)

____

What time did you wake up this morning (e.g. 8 am)

____

How long did you sleep? Hours and minutes (e.g. 8 hours and 45 minutes)

____

How long did it take you to fall asleep? Hours and minutes. (e.g. 20 minutes)

____

How many times did you wake up last night?

____

How many minutes were you awake for in the middle of the night?

____

Did you have any caffeine this morning?

○ Yes (1)

○ No (2)

Display This Question:

If Did you have any caffeine this morning? = Yes

How much caffeine did you have?

____

How well did you sleep?

○ Very poorly, 1 (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ Very well, 5 (5)

Did you feel refreshed after you woke up this morning?

○ Not at all, 1 (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ Completely, 5 (5)

Did you sleep soundly?

○ Very restless (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ Very soundly (5)

Did you sleep throughout the night?

○ Woke up much too early (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ Slept through the night (5)

How easy was it for you to wake up?

- ○ Very easy (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ Very difficult (5)

How easy was it for you to fall asleep?

- ○ Very easy (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ Very difficult (5)

How much did you dream last night?

- ○ None (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ A lot (5)

How sleepy are you right now?

- ○ Feeling active, vital, alert, or wide awake (1)
- ○ Functioning at high levels, but not fully alert (2)
- ○ Awake, but relaxed; responsive but not fully alert (3)
- ○ Somewhat foggy, let down (4)

○ Foggy; losing interest in remaining awake; slowed down (5)

○ Sleepy, woozy, fighting sleep; prefer to lie down (6)

○ No longer fighting sleep, sleep onset soon; having dream-like thoughts (7)

Appendix G: Awareness Assessment

Subject ID

Session 2 start time:

Did you ever wonder why there were two different forms for each word (near and far)? Did you try to figure out why this might be? That is, did you intentionally analyze the sentences to try to figure out if there was a pattern or rule?

When you had to sort those weird words that you didn't know (i.e. a nonword), what criteria did you use to make your choice? (if they don't mention using the novel words - gi, ro, ul, ne - ask if they used those to help them decide)

How confident are you that this criteria is correct?

○ Extremely confident (1)

○ Somewhat confident (2)

○ Not very confident (3)

○ Not at all confident (4)

○ N/A - no criteria (5)

Classify participant as aware or unaware

○ Aware (1)

○ Unaware (2)

Display These Questions:
If Classify participant as aware or unaware = Aware

At what point in the experiment did you become aware of the animacy rule?

○ Beginning of Session 1 (1)

○ Middle of Session 1 (2)

○ In between Session 1 and 2 (3)

○ Beginning of Session 2 (4)

○ Middle of Session 2 (5)

○ End of Session 2 (6)

○ Other (7) ____

Can you describe the relationship between the new words (gi, ro, ul, ne) and noun animacy?

____

Prompt if necessary: which words typically went before animals, and which before objects?

____

Display These Questions:
If Classify participant as aware or unaware = Unaware

Did you think that the new words (gi,ro,ul,ne) had anything to do with whether what it was paired with was an animal or an object?

____

If they still haven't answered, explain to them that gi and ul usually went before animate objects and ro and ne usually went before inanimate objects. Any comments?

____

Anything else to add?

____

Curriculum Vitae

Name:	Sarah Berger
Post-secondary Education and Degrees:	Western University London, Ontario, Canada 2020-2022 M.Sc. Psychology
	Queen’s University Kingston, Ontario, Canada 2015-2019 B.Sc. Psychology major, Biology minor
Honours and Awards:	Natural Sciences and Engineering Research Council of Canada (NSERC) Canada Graduate Scholarship Masters (CGSM) 2021-2022
	Province of Ontario Graduate Scholarship (OGS) 2020-2021
Related Work Experience	Teaching Assistant The University of Western Ontario 2020-2022
	Psychology Lab Manager University of Toronto 2019-2020

Poster Presentations:

Berger, S. & Batterink, L. (2022, April). Developmental differences in the consolidation of linguistic regularities during sleep. Cognitive Neuroscience Society (CNS) Conference, San Francisco.

Cho, H., Berger, S., Gordienko, A. & Duncan, K. (2022, April). Minimizing stimulus variability in episodic memory: The object memorability image normed database software (O-MINDS). Cognitive Neuroscience Society (CNS) Conference, San Francisco.

Berger, S. & Batterink, L. (2021, March). The role of sleep in learning linguistic regularities in children versus adults. Cognitive Neuroscience Society (CNS) Conference, Virtual.

Berger, S., Moskowitz, J. & Flanagan R. (2019, April). The influence of motor costs on visual search when reaching for target objects. Undergraduate Thesis Poster Presentations, Kingston.