Spring 2019

Competitive Learning Processes: The Role of Verbal Mediation in Sequential Learning

Jeff Shymanski

COMPETITIVE LEARNING PROCESSES: THE ROLE OF VERBAL MEDIATION IN SEQUENTIAL LEARNING

by

Jeff Shymanski

A thesis submitted in partial fulfillment of the requirements
for graduation with Honors in the Speech Pathology and Audiology

Elizabeth A. Walker
Thesis Mentor

Spring 2019

All requirements for graduation with Honors in the
Speech Pathology and Audiology have been completed.

Yu-Hsiang Wu
Speech Pathology and Audiology Honors Advisor

College of Liberal Art and Sciences
The University of Iowa
Iowa City, Iowa

COMPETITIVE LEARNING PROCESSES: THE ROLE OF VERBAL MEDIATION IN SEQUENTIAL LEARNING

By

Jeffrey James Shymanski

A thesis submitted in partial fulfillment of the requirements for graduation with Honors in the Department of Communication Sciences and Disorders

Elizabeth Walker

Thesis Mentor

Spring 2019

ABSTRACT

Sequential learning is a statistical learning mechanism that supports extraction of rule-based linguistic patterns. Children born deaf lack early access to spoken language. Some research suggests this period of deafness restricts sequential learning development. However, sequential learning paradigms may measure different constructs depending on task stimuli—easily verbalized stimuli may be encoded and maintained by higher-order, language-dependent mechanisms (e.g., verbal mediation) rather than domain-general statistical learning mechanisms. The current feasibility study addresses the following questions: (1) do children demonstrate sequential learning with verbally mediated stimuli, (2) does verbal mediation affect explicit learning of stimuli sequences, and (3) do cognitive/linguistic skills predict sequential learning? Researchers tested 25 children with normal hearing using a battery of cognitive/linguistic measures and two reaction time-based sequential learning tasks, which included either verbally or nonverbally mediated stimuli sequences. Results indicated that children demonstrate sequential learning with nonverbally, but not verbally, mediated sequences. Explicit sequence recall did not differ significantly by task. Lastly, expressive vocabulary was negatively associated with performance on the verbally mediated sequential learning task; children with larger vocabularies demonstrated reduced sequential learning. These findings suggest a competition between general and higher-order learning systems, motivating future study of these constructs in children with hearing loss.

INTRODUCTION

Learning is a fundamental and life-long process. It begins prenatally; an unborn baby has access to language of the outside world in utero, shaping language preferences at birth. During infancy, a child develops a deeper awareness of the language or languages spoken in their environment—creating early representations of phonemes, rules for how these phonemes are put together, and strategies for parsing continuous speech into individual words (Saffran, Werker, & Werner, 2006). Infants have no blueprint for a fully developed language. They build linguistic concepts using statistical learning mechanisms which operate *implicitly.* As a child grows older, their understanding of language begins to shape further learning. School-age children begin using linguistic strategies (i.e., assigning labels to new information, verbally reciting these labels in their heads) to organize and encode new experiences. These linguistic processes differ from statistical learning in that linguistic learning strategies are conscious and acquired—they operate *explicitly*.

Consideration of explicit and implicit learning mechanisms has become increasingly relevant to cognitive hearing science, an interdisciplinary field examining the interplay between audition and cognitive processes underlying learning. All individuals, whether hearing or deaf, possess basic statistical learning mechanisms. However, only hearing infants can use these to access auditorily presented speech to develop language competencies noted above. Children who are deaf or hard-of-hearing often demonstrate language deficits, and these may impact development of explicit verbal (i.e., verbally rehearsed or verbally mediated) learning strategies. Thus, children with hearing loss may differ from children with normal hearing in use and efficacy of explicit learning strategies.

In this introduction, we will address sequential learning as a mechanism of implicit learning and overview its measurement in sequential learning paradigms. We will discuss how these paradigms have been implemented with individuals with normal hearing and those with cochlear implants and consider how resulting findings helped forge the Auditory Scaffolding Hypothesis. Dissenting studies are addressed, which suggest that “implicit” sequential learning paradigms may assess a broader system of constructs than those involved solely in implicit learning. We postulate that explicit, language-dependent learning mechanisms (e.g., verbal mediation) may mediate outcomes of sequential learning tasks and examine task demands that engage these explicit processes. This literature review lays groundwork for the current investigation, in which we explore manipulations of verbal encoding on a sequential learning task and gauge how these changes affect implicit and explicit representations of sequential learning.

Sequential Learning

Sequential learning occurs when statistical learning mechanisms encode patterned input over time. This type of learning operates along basic neural mechanisms, but the strategies these mechanisms construct are very powerful. These implicit mechanisms govern diverse domains of learning, as they underlie components of language development as well as habit- and skill-based learning (e.g., learning to ride a bike; Ullman, 2004). In a linguistic domain, sequential learning can parse complex, nuanced regularities found in speech (Saffran, 2002). Saffran demonstrated how quickly these mechanisms identify rules by presenting school-age children and adults with rule-based sequences of nonsense syllables or nonlinguistic acoustic input. In either case, both children and adults acquired representations of the input grammar after just 400 repetitions. These mechanisms are critical in developing linguistic representations as well, as the acquisition of syntax is directly associated with sequential learning (Kidd, 2012). Kidd assessed implicit learning and syntactic priming of active and passive sentences in young school-age children and found robust implicit learning skills to be closely related to a child's use of primed active and passive argument structures.

Implicit and explicit learning may operate in tandem for any particular learning task. Kidd's (2012) priming research indicates that implicit learning systems may dominate syntax learning, but acquisition of morphology may draw from both implicit and explicit learning systems. We often consider the implicit system to manage morphological development (which is primarily rule-based), but more conscious, explicit learning will be necessary to master irregular morphological markers (e.g., ran, mice, has). In this regard, these two learning systems act competitively.

Competition of implicit and explicit systems extends beyond morphological development and has been implicated in motor learning and categorization literature (Rousseau, 2015; Quam, Wang, Maddox, Golisch, & Lotto, 2018). Rousseau investigated claims that explicit information rehearsal strategies may interfere with the automaticity of learned complex motor behaviors like swinging a golf club. Researchers found that conscious rehearsal strategies impaired execution of a golf swing. Individuals who were more likely to verbalize steps of a motor behavior detracted from learning to swing a golf club, whereas individuals who were more likely to visualize steps of a behavior demonstrated more motor learning. This work suggests that motor learning (i.e., learning commonly attributed to implicit sequential learning) may be helped or hindered depending on how conscious, explicit learning processes are engaged. Quam and colleagues demonstrated on a category learning task that implicit sequential and explicit learning mechanisms may both be engaged in acquiring categorical knowledge but that these mechanisms suppress each other throughout training. With very limited training, explicit learning mechanisms guide initial learning. Given more training, category acquisition shifts to relying on more implicit mechanisms.

The Auditory Scaffolding Hypothesis

Cognitive researchers have traditionally viewed implicit mechanisms like sequential learning as immutable. However, some cognitive psychologists have suggested a critical period for these mechanisms. Researchers supporting this viewpoint postulate that early auditory access shapes the statistical mechanisms involved in language acquisition. Spoken language input contains richly temporal information and extracting meaning from this information may be needed to establish general sequential learning skills (Conway & Christiansen, 2009). Therefore, children who experience periods of early auditory deprivation may possess domain-general deficits in processing any type of sequenced information; this theory is known as the Auditory Scaffolding Hypothesis (Conway, Karpicke, & Pisoni, 2009). Early research corroborating this idea focused on comparing children with normal hearing (CNH) to children with cochlear implants (CIs) on implicit pattern learning tasks. Conway et al. (2011) adopted a pattern learning task from an earlier sequential learning adaptation of Milton Bradley's Simon game: a memory span task using a series of colors (Karpicke & Pisoni, 2004). Conway et al. incorporated sequential learning into the task by implicitly presenting color spans following a pattern (i.e., a grammatical sequence). Typically developing CNH were better able to recall these sequences than spans of randomized color order (i.e., an ungrammatical sequence), suggesting that these children had internalized the patterned sequence. In contrast, pattern sequence recall of children with CIs was no better than recall of ungrammatical sequences indicating that the children with CIs showed no implicit pattern learning.

Conway et al. (2011) proposed/posited that the sequential learning deficits were the underlying mechanism driving language delays in children with CIs. Children with CIs commonly show deficits in aspects of language governed by rule-based learning (e.g., morphology, syntax). Boons et al. (2013) found that, compared to CNH, children with CIs produced more morphological and syntactic errors on standardized assessments. Common morphological errors including incorrect lexemes (e.g., correct base word, incorrect affixes) and overgeneralizations as well as common syntactic error patterns in noun, verb, prepositional, and adverbial phrases point to ill-defined linguistic grammars.

However, more recent sequential learning findings have contested Conway et al.'s (2011) Simon Task findings. Researchers have failed to replicate group differences between children with normal hearing and children with CIs on the Simon task, and further artificial grammar learning research has revealed that both children with normal hearing and children with CIs implicitly track transitional probabilities in sequential learning (Hall, Eigsti, Bortfeld, & Lillo-Martin, 2015; Torkildsen, Arciuli, Haukedal, & Wie, 2018). Sequential learning research utilizing serial reaction time (SRT) tasks also challenge assumptions of the Auditory Scaffolding Hypothesis (Klein, Walker, & Tomblin, 2018). In gauging reaction times to presented stimuli, SRT tasks require participants to respond quickly by pressing a button corresponding to the stimulus. Thus, SRT tasks limit use of explicit learning strategies which involve greater cognitive load, resulting in delayed reaction time. Optimal performance on an SRT task involves *reacting* to the stimuli. This allows implicit mechanisms to process the information. Moreover, SRT tasks measure implicit learning because patterned sequences are built implicitly into the paradigm. Learning is then illustrated by reduced reaction times to items within patterned sequences.

Klein et al. (2018) showed that both CNH and children with CIs demonstrated significantly faster reaction times to stimuli within the 10-item pattern than to random stimuli with continual repetition of the patterned sequence. There were no significant differences between these groups with respect to learning. Participants completed 400 total trials apportioned into four blocks of 100 trials. The first and fourth blocks contained pseudo-randomly presented stimuli while the second and third blocks consisted of 20 repetitions of a 10-item patterned sequence. Given the consecutive repetitions of the patterned sequence, there should be a reduction in reaction time over the course of the middle blocks with a sharp increase at the onset of the final block, demonstrating a “interference effect” as participants’ expectancies of the pattern are violated. Klein et al. found no significant group differences in the rate of reaction time decrement through the patterned blocks and in the magnitude of the interference effect. These results corroborating findings of Hall et al. (2017) and Torkildsen et al. (2018), which that suggest children with CIs demonstrate intact implicit learning.

To understand these conflicting findings on implicit sequential learning in children with CIs, we must consider task differences of these learning paradigms. The Simon task (Karpicke & Pisoni, 2004) assesses recall accuracy of patterned and randomized spans which taxes both implicit learning mechanisms *and* working memory capacity (an explicit learning mechanism). Participants must consciously attend to and maintain information in temporary storage, and these explicit memory demands may override implicit learning systems. Much like the Simon task used in Conway et al. (2011) and Hall et al. (2017), Torkildsen et al.’s (2018) paradigm also required some degree of conscious recall in discriminating transitional probabilities of test sequences.

The SRT tasks used by Klein et al. (2018) are even farther removed from the Simon task, as SRT task learning requires no explicit awareness to demonstrate learning. Participants are not asked to make judgments on or recall patterned sequences. In the SRT paradigm it is rarely disclosed to participants that patterns are being presented. The stimuli selected for these tasks also discourage verbal mediation by using an identical stimulus varying only by location. Without cues that can easily be verbally coded, the brain is less likely to use conscious verbal processes and more likely to rely on implicit learning. In contrast, Simon task items vary by color, a cue easily assigned verbal codes as well as by position. This additional salient cue may further reinforce use of explicit verbal strategies on the Simon task, weakening Conway et al.'s claims of impaired implicit learning in individuals with CIs.

Taken together, current implicit sequential learning literature is difficult to compare due to the variability in learning paradigms. This ambiguity is further confounded by the types of targets used in each implicit learning task with stimuli varying in the degree to which they can be verbally coded. Verbal mediation poses a problem to a purely implicit learning paradigm, as it enacts explicit learning processes which may interfere with implicit learning mechanisms. No current research addresses the coordination or competition of these explicit and implicit systems within the context of sequential learning. As such, we cannot rule out the possibility that cognitive and linguistic constructs tapped by verbal mediation are subverting what we think to be implicit learning.

Verbal Mediation

Foundational study on verbal mediation focused on the phonemic rehearsal routines that accompanied verbal working memory (Baddeley & Hitch, 1975). Baddeley and Hitch's span experiments demonstrated that modality-specific (e.g., visual, verbal) short-term memory traces are supported by more central mechanisms to maintain these traces in working memory. Baddeley and Hitch posited that phonemic rehearsal (i.e., verbal mediation) may supplement the phonological loop's storage system by processing input greater than at a basic phonological level. These higher-order processes likely depend on activating word-level representation in the lexicon (Morey, Morey, Reijden, & Holweg, 2013).

Verbal mediation emerges during early school-age years and becomes a mature, automatic process shortly before adolescence (Guttentag, 1984). From a cognitive perspective, verbal mediation is highly dependent on amount of attentional resources available (e.g., attentional capacity) and direction of these resources (e.g., attentional allocation) to first push meaningful input from the brain's sensory buffers to short-term storage. If information is not first stored in a short-term trace, there is no way verbal mediation can act upon information in working memory. By young adulthood, verbal mediation strategies become incredibly efficient, require fewer attentional resources than during childhood, and are closely tied to verbal working memory (Morey et al., 2013; Morra, 2015). As such, we view verbal mediation as a mechanism responsible for the encoding and maintenance of information into working memory.

Verbal mediation must also be considered in relation to linguistic factors. While verbal mediation is usually considered a covert rehearsal process, researchers frequently approximate the speed of verbal mediation using articulatory rate and find speed of articulation closely associated with executive functions (e.g., working memory, verbal fluency, inhibition; Morra, 2015; AuBuchon, Pisoni, & Kronenberger, 2015). This measurement assumes that covert rehearsal rate matches rate of productive articulation. Morra's adult verbal working memory findings suggest verbal mediation to be negatively associated with number of errors in a verbal span task, and this strongly suggests that verbal mediation may be implicated in performance on Simon task. No research currently supports how verbal mediation may operate on a more implicit sequential learning measure like SRT tasks, which does not base performance off a span score.

Implicit & Explicit Task Biases

We have established that sequential learning may be supported by opposing implicit and explicit systems learning systems. We must also consider how these systems contribute to awareness of learned information. Many sequential learning paradigms (e.g., artificial grammar learning tasks) require participants to formulate some explicit understanding of the task. School-age children tasked with memorizing series of patterned stimuli can effectively differentiate novel sequences governed by the learned grammar from sequences governed by some other unlearned rule set (Torkildsen et al., 2018; Pavlidou, Kelly, & Williams, 2010). This form of artificial grammar learning engages both explicit learning to memorize sequences (i.e., primary learning task) and implicit learning to generalize rules from the memorized input (i.e., secondary learning task). However, Conway et al.'s (2011) artificial grammar learning task differs from these paradigms in that the Simon task is arguably a more basic measure of explicit learning. Researchers prefaced the Simon task by informing participants that they would view a pattern—thus drawing participant's awareness to pattern learning as their primary learning task. Disclosing the presence of a pattern may contribute to participants' ability to effectively recreate patterned sequences in Conway et al.'s task but not in comparable artificial grammar learning studies.

Some sequential learning measures may not necessitate *any* conscious learning. In the SRT tasks utilized by Hall et al. (2017) and Klein et al. (2018), researchers did *not* inform participants of a patterned sequence. Moreover, SRT pattern learning is primarily supported by implicit learning (Jimenez, 2002). A reaction-time based task should limit a participant's use of conscious, analytical strategies that might otherwise promote explicit learning. A visual, nonverbal SRT requires no decision-making from the participant unlike the grammaticality judgments of artificial grammar learning paradigms, further minimizing explicit learning strategies. Spatial layout of stimuli inhibits the use of easily verbalized rehearsal strategies that might otherwise promote maintenance of stimuli sequences in verbal working memory. As such, SRT learning reflects a modern information processing perspective of implicit learning that may best capture the function of sequential learning mechanisms (Radvansky & Ashcraft, 2014). This model

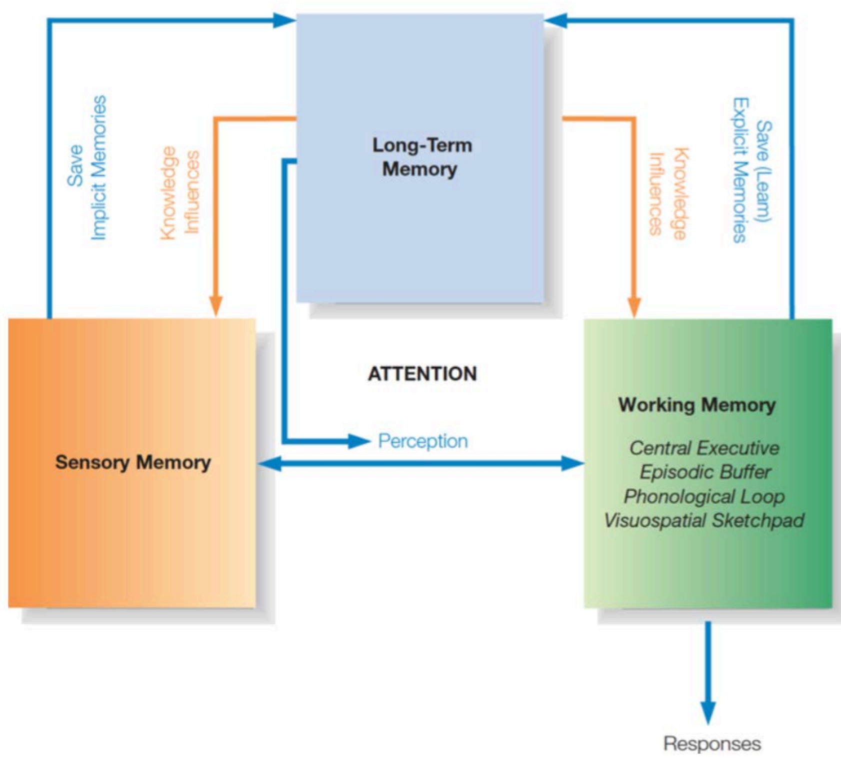

Figure 1. Information may be processed via implicit and/or explicit learning systems. This contemporary information processing account assumes short-term and working memory subserve explicit systems. Reprinted from *Educational Psychology* (14th ed.), by A. Woolfolk, 2019, New York, NY: Pearson Education. Copyright 2019 by Pearson.

posits that implicit learning fully bypasses declarative memory systems (e.g., working memory, systems supported by verbal mediation). Moreover, it describes working memory as a component of the explicit memory pathway, as permanent outputs of working memories are always explicit memories (Persuh, LaRock, & Berger, 2018). See Figure 1 for a more comprehensive account of this model.

If we consider sequential learning to be better supported by implicit mechanisms, serial reaction time paradigms may be a more valid measure than the Simon Task in assessing sequential learning. As previously stated, we believe Conway et al.'s (2011) Simon Task may actively promote explicit learning mechanisms and verbal mediation through its working memory span structure, verbalizable stimuli, and upfront notification to participants of the task's pattern. However, the primary purpose of this thesis is not to judge the construct validity of sequential learning measures. We instead seek to characterize explicit strategies (e.g., verbal mediation) use in the context of an implicit sequential learning task. Using a traditional SRT, a modified SRT, and an SRT recall task by Lee (2012), we will compare implicit and explicit learning on two tasks varying by degree of explicit, verbal strategy use. Through this, we can investigate how explicit learning may be recruited on an otherwise implicit learning task to examine the interface of implicit and explicit learning.

Current Study

In this study, the effect of strategy use on learning of novel information is assessed with a pair of serial reaction time tasks—a task conventionally used to gauge implicit learning. This feasibility study seeks to investigate how linguistic and cognitive skills differentially interact with verbally and nonverbally mediated SRT tasks. The following questions are addressed:

1. Is implicit sequential learning impacted by verbal mediation on an SRT task? *Using interference effect as a measure of learning, we predict that children will show a significant interference effect on the nonverbally mediated SRT task. On the verbally mediated SRT, we predict that verbal mediation will inhibit sequential learning and thus result in a weaker interference effect. We do not expect differences in overall reaction time (e.g., reaction time to randomly presented stimuli) or response accuracy between verbally and nonverbally mediated tasks.*
2. Does a serial reaction time task encouraging verbal mediation promote explicit learning of patterned sequences? *We predict that by verbally encoding and maintaining information, children will recreate longer correct strings of the verbally mediated patterned sequence from memory than strings of the nonverbally mediated pattern. We expect that correct strings recalled from the verbally mediated task will exceed chance performance (i.e., correct string length of random, computer-generated responses).*
3. Do cognitive and linguistic skills predict sequential learning? *As receptive grammar is a product of rule-based learning, we predict that receptive grammar will be positively correlated with the nonverbal, but not the verbal, task. We predict vocabulary and executive function will be negatively correlated with implicit sequential learning, as vocabulary and executive function are less rule-based and may support mechanisms of verbal mediation.*

METHODS

Participants

Participants included 25 CNH between the ages of seven and fourteen years. All participants spoke English as a native language and were not colorblind or diagnosed with ADHD. To confirm hearing status, an audiologist or supervised research assistant conducted a pure tone audiometric screening. All 25 participants passed the screening, having air conduction thresholds equal to or below 20 dB HL at 500, 1000, 2000, and 4000 Hz. Participants completed all testing at the Pediatric Audiology Lab or in the lab's mobile testing unit.

Procedures

Sequential learning measures. Participants began and ended the current study with an SRT task. The order of these assessments was counterbalanced. These measures require participants to press one of four buttons on a button box in response to stimuli appearing on a computer monitor, with each button corresponding to one of four locations shown on-screen. Each SRT task begins with four practice trials to accustom the child to each stimulus before progressing to test trials. In both training and testing, a stimulus appears for a maximum of 1000 msec. The stimulus disappears as soon as a correct or incorrect button press is made (or if the participant fails to answer within the allotted time), and the next trial begins following a 500-msec intertrial interval. The testing phase of each SRT task consists of 400 successive trials, with participants' reaction time and accuracy recorded on each trial. In the first 100 trials of testing, the stimuli are presented pseudorandomly (random sequence 1). The following 200 trials are organized in a patterned sequence in which a 10-item sequence is repeated twenty times (pattern sequence). The final 100 trials return to a pseudorandom presentation (random sequence 2). This random-pattern-random progression is not disclosed to the participant before or during the task.

As an implicit learning task, SRT paradigms traditionally rely on basic statistical learning mechanisms rather than explicit learning strategies (e.g., verbal rehearsal). One SRT presents identical stimuli (a green monster) in each of the four on-screen locations. Thus, the four stimuli in this task (hereafter described as a *nonverbal* SRT) only differ visuospatially—for which assigning verbal labels may be an inefficient strategy. Another SRT task employed in this study is nearly identical to the former; however, instead of four indistinguishable stimuli, this SRT task (hereafter referred to as a *verbally mediated* SRT) uses a distinct verbal label for each location by assigning a color to each location. Because stimuli in this paradigm differ both by location and color, verbally encoding the stimuli becomes a more viable strategy.

Free Serial Recall. Following completion of the second SRT task, participants completed a recall task modeled after the task in Lee (2012). Experimenters told each participant that a section of the task contained a series of stimuli following a pattern. Each participant was shown the first three items in the 10-item sequence and was subsequently presented with a series of empty boxes. To finish the task, participants were instructed to press the button corresponding to the next item in the sequence whenever the empty boxes appeared. This serial recall addendum was not a forced-response task; if after 2000 msec a button press had not registered, the program advanced to the next set of empty boxes. In total, participants were given thirteen trials to complete the pattern. Thirteen trials were chosen instead of ten to provide participants more opportunity in responding.

As in Lee (2012), researchers coded participant responses as numeric strings, in which each digit signified the position of the selected stimulus (e.g., 1, 2, 3, 4). Because this recall section was not programmed to be a forced-response task, missed recall trials were coded as zeroes. Researchers compared participant strings to the 10-digit task key (e.g., 3-4-2-1-4-3-1-2-

4-1 for the nonverbal task pattern, 2-4-4-2-3-4-2-4-1-3 for the verbal task pattern) using a Java script. This script assessed the longest consecutive segment in each participant's response that matched the task key. The script also simulated 13-digit test strings to establish chance performance. Sixteen thousand computer-generated strings were recorded for both the verbal and nonverbal tasks, with the script analyzing the longest consecutive segment matching the keys of each task. Researchers averaged these correct matched segments for both tasks to establish chance recall performance on the verbal and nonverbal tasks. Participant strings were then compared to chance performance.

Cognitive measures. Participants completed the Odd-One-Out subtest of the Automated Working Memory Assessment (AWMA; Alloway, 2007) as a measure of visuospatial working memory and the Matrix Reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) as a measure of nonverbal intelligence. A parent of each subject completed the Behavior Rating Inventory of Executive Function (BRIEF; Gioia, Isquith, Guy, & Kenworthy, 2000) at the time of testing, rating their child's inhibitory control, attentional control, and emotional regulation.

Language assessment. Participants were also administered the Expressive Vocabulary Test (EVT-2; Williams, 2007) to assess productive vocabulary and the Test for Reception of Grammar (TROG-2; Bishop, 2003) to gauge receptive morphosyntax.

RESULTS

Research Aim 1: Implicit Sequential Learning in Verbally and Nonverbally Mediated Tasks

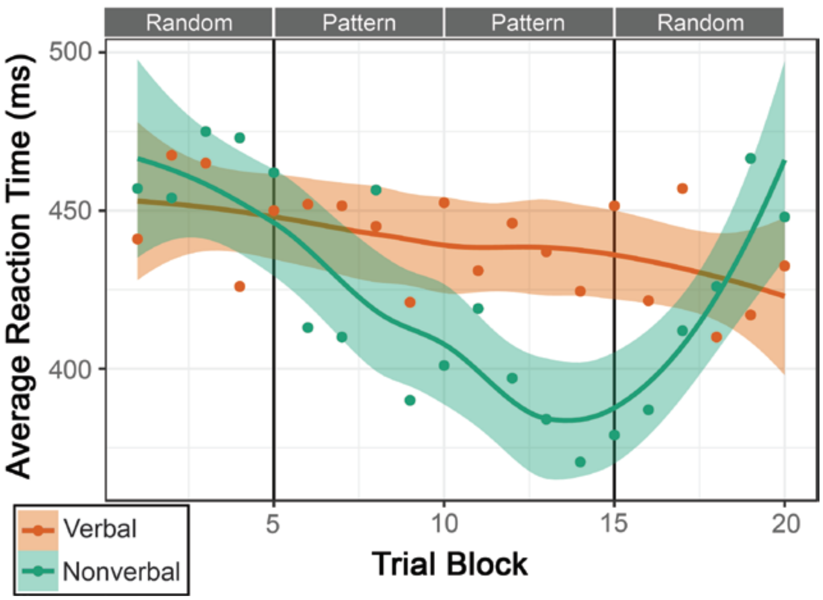

Figure 2. Verbally and nonverbally mediated SRT task reaction times organized into blocks by 20-trial medians, represented as points. Each phase comprises five blocks, and the solid vertical lines indicate breaks between the pattern and random phases. The bolded line indicates approximate change in RT based on 20-trial median data, and the shaded area depicts a 95% confidence interval. Significant between-task differences in reaction time can be found where shaded areas do not overlap.

There were no significant differences in response accuracy on the verbal and nonverbal SRT tasks during random (p = 0.46) or patterned (p = 0.08) phases. Participants demonstrated similar overall reaction times (e.g., reaction time during the random phases) between tasks (p = 0.56). In the verbally mediated SRT, participants responded more quickly to the second pattern phase than the second random phase, resulting in a significant interference effect (p = 0.03). However, children displayed similar reaction times to the second pattern and random phases in the nonverbal SRT; this interference effect did not differ from zero (p = 0.92). Verbal and nonverbal interference effects were significantly different (p < 0.01). Figure 2 plots change in average reaction time throughout each SRT task, while Figure 3 depicts resulting interference effects.

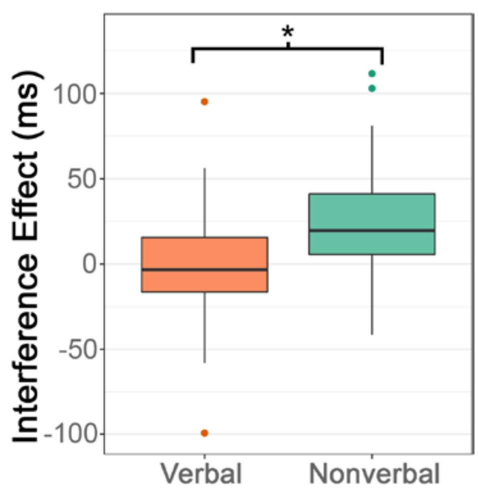

Figure 3. Interference effect calculated in milliseconds by subtracting the averaging reaction time from the second pattern phase from the second random phase. Boxplot fences represent values 1.5*(IQR) above or below the 75th and 25th percentiles, respectively.

Research Aim 2: Explicit Sequential Learning in Verbally and Nonverbally Mediated Tasks

Including missed responses (e.g., trials in which participants waited too long to respond), average correct string length during serial recall of the verbal and nonverbal sequential learning tasks did not differ significantly (p = 0.99); participants recalled an average of 3.08 (SD = 1.08) consecutive items of the verbal SRT pattern and 3.15 (SD = 1.32) consecutive nonverbal pattern items. Performance on both tasks fell below chance, as the 16,000 computer-generated strings yielded an average correct string length of 3.31 (SD = 0.89) on the verbal SRT and 3.65 (SD = 0.89) on the nonverbal SRT. However, these simulations did not account for missed responses. Figure 4 displays the longest consecutive correct string for each participant.

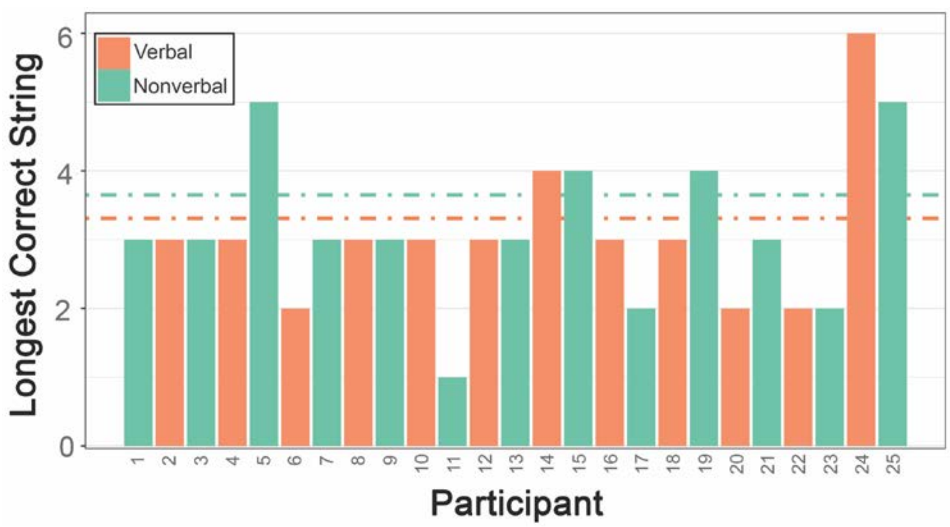

Figure 4. Consecutive correct string lengths for each participant. Bar color depicts the SRT for which participants completed a serial recall task (i.e., each participant's second task). The dashed lines indicate chance performance on each task.

Research Aim 3: Cognitive and Linguistic Correlates of Sequential Learning

Receptive grammar did not correlate with either the verbal (*r* = 0.12; *p* = 0.57) or nonverbal (*r* = 0.04; *p* = 0.83) implicit learning task. Metacognitive executive functions (e.g., organization, self-monitoring, working memory) also demonstrated no associations with the verbal (*r* = -0.14; *p* = 0.64) and nonverbal (*r* = -0.09; *p* = 0.50) tasks. Expressive vocabulary was not correlated with the nonverbal SRT (*r* = -0.23; *p* = 0.26); however, it showed a significant negative correlation with implicit learning on the verbal task (*r* = -0.41; *p* = 0.04). Children with larger expressive vocabularies demonstrated poorer implicit sequential learning than children with smaller vocabularies when stimuli were verbally mediated. Participant age exhibited an even stronger negative correlation with the verbally mediated task (*r* = 0.48; *p* = 0.02). However, controlling for age as a covariate in a partial correlation, expressive vocabulary remained highly correlated with verbal SRT performance (*r* = -0.42, *p* = 0.04). Table 1 provides correlational coefficients between the verbal/nonverbal task and our cognitive/linguistic outcome measures.

Correlations Between Sequential Learning Outcomes and Performance on Cognitive/Linguistic Measures

	Interference Effect: Verbal SRT	Interference Effect: Nonverbal SRT
Working Memory, Self-Monitoring: *Behavioral Rating Inventory of Executive Function (BRIEF), Metacognitive Index*	-0.1426	-0.0984
Receptive Grammar: *Test for Reception of Grammar (TROG-2)*	0.1203	0.0441
Expressive Vocabulary: *Expressive Vocabulary Test (EVT-2)*	**-0.4148***	-0.2340

Table 1. Correlational coefficients between SRT task performance and cognitive/linguistic outcome measures. A significant correlation ($p < 0.05$) is bolded and starred.

DISCUSSION

The aim of the current investigation was to consider the role of verbal mediation, an explicit language-dependent learning strategy, in a sequential learning task. In pursuit of this goal, we attempted to illustrate verbal mediation effects in an SRT task. By using two SRT tasks differing only by stimuli (i.e., to encourage or to discourage verbal mediation), we can study how recruiting more conscious, verbal knowledge impacts implicit and explicit learning on this task. Results from this investigation indicate (1) that school-age children with normal hearing show poorer sequential learning when task stimuli may be verbally mediated, (2) that school-age children show minimal recall of both verbally mediated and nonverbally mediated SRT tasks sequences, and (3) that expressive vocabulary skills are negatively correlated with performance on the verbally mediated implicit sequential learning task.

Research Aim 1: Implicit Sequential Learning in Verbally and Nonverbally Mediated Tasks

Nonverbally mediated sequential learning findings replicate the results of Klein et al. (2018). With only visuospatial cues differentiating task stimuli, children clearly demonstrate implicit sequential learning. However, by changing the stimuli to differ both spatially and by color, implicit sequential learning is heavily impacted. Examiners provided the same instructions to children in both tasks, so this result suggests that the mere presence of easily verbalized stimuli cues changes the neural pathways involved in learning. Verbal mediation strategies provide an efficient learning approach, so neural processes underlying verbal strategy use may automatically engage with recognition of easily verbalized input. However, in this learning task, verbally mediating input is an unproductive strategy. As such, children with more robust language skills are more likely to automatically engage language-dependent learning strategies which may override implicit learning systems. This corroborates a competitive framework of explicit and implicit learning systems.

The notion of verbal encoding and maintenance as an ineffective learning strategy is not a new idea; problems with verbal mediation have also been addressed in motor learning literature.

Much like performance on the SRT, complex motor skill learning relies heavily on implicit sequential learning processes that may be undercut by conscious processing. While motor skill learning is not impacted by *all* conscious, explicit learning processes, individuals trained to complete complex behaviors demonstrate poorer learning when verbalizing steps of a behavior (Rousseau, 2015). In fact, conscious processing proved far more successful if individuals instead rehearsed information by visualizing steps of a behavior. This suggests that learning typically attributed to implicit sequential mechanisms may be helped or hindered depending on how conscious, explicit learning processes are engaged. Moreover, it further complicates measurement of true implicit sequential learning, as both demands of a task as addressed in the current experiment and individual differences in explicit learning strategy use may be confounded with implicit learning.

Research Aim 2: Explicit Sequential Learning in Verbally and Nonverbally Mediated Tasks

Our findings suggest that neither verbally nor nonverbally mediated implicit sequential learning enabled participants to recreate patterned sections from memory. However, we cannot overlook demographic and task limitations that may underlie these results. This study's recall task was modelled after a paradigm used in Lee (2012), which showed that young adults could capably recall patterned sequences from SRT paradigm similar to the current study's nonverbally mediated task. We expected similar findings in the current investigation and reasoned that the verbally mediated task may show a stronger explicit recall effect if verbal mediation formed a more explicit representation of the pattern. Our null findings may result from a younger subject pool. Lee (2012) tested young adults, whose more mature attentional capacities may have supported serial recall. The current recall task could potentially be improved with a longer SRT paradigm, but a longer task may have impacted task performance in school-age children. Moreover, the current study also contains fewer patterned trials and more random trials than in Lee (2012), which have hindered formation of robust explicit memories of patterned sequences.

Studies using more complex artificial grammars have yielded similar findings: while children and young adults may be able to discriminate elements of learned vs. unlearned grammars, they cannot freely recreate complex, rule-based sequences (Pavlidou et al., 2010). Similarly, in the current investigation, children frequently told researchers that they were aware of the pattern they were shown, but this awareness did not translate to recall. This disconnect supports a perspective of discrimination and recreation/recall as two distinct degrees of awareness (Ivanchei & Moroshkina, 2018). Further research should investigate what factors contribute to this graded awareness of learning.

Research Aim 3: Cognitive and Linguistic Correlates of Sequential Learning

The cognitive and linguistic outcome measures were chosen according to constructs we hypothesized may be engaged in the SRT paradigm. We hypothesized the Metacognitive Index of the BRIEF may correlate with implicit task learning on the verbally mediated SRT task if participants demonstrated self-monitoring during the SRT trials. This composite index also considers a child’s working memory; however, the BRIEF is a parent-report measure capturing a broad range of executive functions, so it may not be the most accurate depiction of working memory by itself. Correlations between BRIEF and verbal/nonverbal SRT interference effect failed to reach significance, suggesting that verbally and nonverbally mediated SRT performance does not heavily implicate complex working memory and executive functioning. Similarly, we hypothesized that SRT performance may correspond to receptive grammar performance, as both tasks are believed to draw from implicit, rule-based learning systems. We found no significant associations between performance on either SRT task and receptive grammar, indicating either that accumulated rule-based knowledge of English grammar may not be an appropriate analogue for implicit, rule-based SRT learning or that our receptive grammar measure was unable to capture differences in participants' underlying grammatical competencies. The latter explanation may be more likely, as the vast majority of participants answered most items correctly on the receptive grammar measure, depicting a ceiling effect.

Unlike general executive functioning and linguistic grammar knowledge, we found a significant relationship between expressive vocabulary and SRT performance—expressive vocabulary was negatively correlated with verbally mediated implicit sequential learning. Vocabulary acquisition is thought to be less rule-based than development of morphosyntax, and it becomes increasingly explicit (i.e., via fast mapping) through the school-age years. As such, an inverse relationship between an explicitly learned aspect of language and verbally mediated implicit learning is not unusual. Robust, explicit language knowledge may be related to the verbal mediation strategies masking implicit learning mechanisms on the verbal SRT task. This further reinforces a competitive perspective of implicit and explicit learning processes.

These correlational findings are not fully unexpected, but it is surprising that expressive vocabulary data shows the strongest associations with implicit learning. Perhaps vocabulary knowledge served as a proxy for linguistic experience necessary to recruit language-dependent learning mechanisms, indirectly measuring the verbal mediation in a way working memory or receptive grammar could not. While possible, the strength of these correlations may also be rooted in characteristics of the outcome measures. The expressive vocabulary assessment (EVT-2) was the only open-set assessment used as a predictor in the correlational analysis. The closedset receptive grammar assessment (TROG-2) and parent behavior questionnaire (BRIEF) offer far more limited data sets.

Implications and Future Directions

The current study's demonstration of inhibited sequential learning through verbal mediation lays groundwork for the study of these constructs in children with CIs. This thesis has explored the competition of implicit sequential mechanisms and more conscious, explicit learning mechanisms in children with normal hearing, but the dynamics of these opposing systems may be entirely different in children with CIs. We know that language outcomes and verbal working memory are poorer in children with CIs, and that verbal mediation skills are less affiliated with executive functions in these children (Boons et al., 2013; Nittrouer et al., 2017; AuBuchon et al., 2015). We can form working hypotheses for verbally and nonverbally mediated SRT performance for this population given this information. If explicit cognitive and linguistic learning processes drive explicit learning, and these processes are more fragile in children with CIs, two possible hypotheses may be generated.

Children with CIs may just as likely as age mates with normal hearing to engage explicit learning processes on a verbally mediated SRT task. If so, these children should show even poorer implicit learning performance (and potentially slower overall reaction times) when using doubly ineffective explicit strategies (i.e., inefficient for implicit SRT learning, inefficient by means of poorer cognitive/linguistic skills). On the other hand, children with CIs may less likely to engage explicit learning processes like verbal mediation because they possess less robust cognitive and linguistic skills underpinning these processes. Under this assumption, verbal mediation should be less automatic in children with CIs, and these children should be more likely to rely on implicit sequential mechanisms in SRT sequence learning. "Verbally mediated" SRT performance in children with CIs may then instead look like the current study's nonverbally mediated SRT performance. We endorse the latter of these hypotheses, speculating that poorer and less automatic verbal mediation skills would fail to disengage implicit sequential learning.

We expect implicit sequential learning may be weighted more heavily in an implicit vs explicit competitive framework of learning in children with CIs. As a follow-up investigation, we will recruit seven- to thirteen-year-old children with CIs to complete verbally and nonverbally mediated SRT tasks and a revised cognitive/linguistic battery. This subsequent study should assess verbal mediation skills directly and address how these skills contribute to the inhibition of implicit learning. We intend to add the CELF-5 Rapid Automatized Naming (RAN) subtest and a timed reading measure to assess components of verbal mediation (e.g., perceptual encoding speed, articulatory rate). These measures will allow us to determine if perceptual encoding and articulatory rate mediate the relationship between vocabulary and implicit sequential learning or if vocabulary knowledge remains associated with verbally mediated sequential learning independent of these skills.

CONCLUSIONS

Verbally and nonverbally mediated SRT performance in the current feasibility study suggests that general statistical learning mechanisms and higher-order, language-dependent mechanisms operate competitively in children with normal hearing. This proposed framework likely depends upon task demands, as only verbally encoded stimuli disrupted sequential learning. Verbal mediation not only interfered with implicit learning but did not appear to facilitate explicit recall of patterned sequences. Finally, children with larger expressive vocabularies demonstrated weaker learning on the verbally mediated sequential learning task compared to children with smaller vocabularies; this effect remained significant after controlling for age. These results may indicate that more advanced language skills predispose the use of language-dependent learning strategies—even when general statistical mechanisms may be more effective for learning.

ACKNOWLEDGEMENTS

This project was funded by an American Speech-Language-Hearing Foundation Clinical Research Grant (PI: Elizabeth Walker), a fellowship from the Iowa Center for Research by Undergraduates (PI: Jeffrey Shymanski), and an award from the John & Elsie Mae Ferentz Undergraduate Research Fund (PI: Jeffrey Shymanski). The authors would like to thank Wendy Fick, Marlea O'Brien, and Joanna Chen Lee for help with project coordination, database management, and data processing; Margaret Dallapiazza, Caitlin Sapp, Jonathan Stirn, and Kristen Ponturiero for help with data collection; as well as the children and families who participated in this study.

References

Alloway, T. (2007). The automatic working memory assessment (AWMA) [computer software]. London, UK: Harcourt Assessment.

AuBuchon, A. M., Pisoni, D. B., & Kronenberger, W. G. (2015). Verbal processing speed and executive functioning in long-term cochlear implant users. *J Speech Lang Hear Res, 58*(1), 151-162. doi:10.1044/2014_JSLHR-H-13-0259

Baddeley, A. D., & Hitch, G. (1974). Working Memory. In G. H. Bower (Ed.), *Psychology of Learning and Motivation* (Vol. 8, pp. 47-89): Academic Press.

Boons, T., De Raeve, L., Langereis, M., Peeraer, L., Wouters, J., & van Wieringen, A. (2013). Expressive vocabulary, morphology, syntax and narrative skills in profoundly deaf children after early cochlear implantation. *Res Dev Disabil, 34*(6), 2008-2022. doi:10.1016/j.ridd.2013.03.003

Conway, C. M., Pisoni, D. B., Anaya, E. M., Karpicke, J., & Henning, S. C. (2011). Implicit sequence learning in deaf children with cochlear implants. *Dev Sci, 14*(1), 69-82. doi:10.1111/j.1467-7687.2010.00960.x

Guttentag, R. E. (1984). The mental effort requirement of cumulative rehearsal: A developmental study. *Journal of Experimental Child Psychology, 37*(1), 92-106. doi:10.1016/0022-0965(84)90060-2

Gioia, G. A., Isquith, P. K., Guy, S. C., & Kenworthy, L. (2000). Behavior rating inventory of executive function. Odessa, FL: Psychological Assessment Resources.

Hall, M. L., Eigsti, I. M., Bortfeld, H., & Lillo-Martin, D. (2018). Auditory access, language access, and implicit sequence learning in deaf children. *Dev Sci, 21*(3), e12575. doi:10.1111/desc.12575

Ivanchei, I. I., & Moroshkina, N. V. (2018). The effect of subjective awareness measures on performance in artificial grammar learning task. *Conscious Cogn, 57*, 116-133. doi:10.1016/j.concog.2017.11.010

Karpicke, J. D., Pisoni, D. B., (2004). Using immediate memory span. *Memory & Cognition, 32*(6), 956-964. doi:10.3758/BF03196873

Kidd, E. (2012). Implicit statistical learning is directly associated with the acquisition of syntax. *Dev Psychol, 48*(1), 171-184. doi:10.1037/a0025405

Klein, K. E., Walker, E. A., & Tomblin, J. B. (2019). Nonverbal Visual Sequential Learning in Children With Cochlear Implants: Preliminary Findings. *Ear Hear, 40*(1), 213-217. doi:10.1097/AUD.0000000000000564

Morey, C. C., Morey, R. D., van der Reijden, M., & Holweg, M. (2013). Asymmetric cross-domain interference between two working memory tasks: Implications for models of working memory. *Journal of Memory and Language, 69*(3), 324-348. doi:10.1016/j.jml.2013.04.004

Morra, S. (2015). How do subvocal rehearsal and general attentional resources contribute to verbal short-term memory span? *Front Psychol, 6*, 145. doi:10.3389/fpsyg.2015.00145

Nittrouer, S., Caldwell-Tarr, A., Low, K. E., & Lowenstein, J. H. (2017). Verbal Working Memory in Children With Cochlear Implants. *J Speech Lang Hear Res, 60*(11), 3342-3364. doi:10.1044/2017_JSLHR-H-16-0474

Pavlidou, E. V., Kelly, M. L., & Williams, J. M. (2010). Do children with developmental dyslexia have impairments in implicit learning? *Dyslexia, 16*(2), 143-161. doi:10.1002/dys.400

Perush, M., LaRock, E., & Berger, J. (2018). Working memory and consciousness: The current state of play. *Frontiers in Human Neuroscience, 12*(78). doi:10.3389/fnhum.2018.00078

Quam, C., Wang, A., Maddox, W. T., Golisch, K., & Lotto, A. (2018). Procedural-Memory, Working-Memory, and Declarative-Memory Skills Are Each Associated With Dimensional Integration in Sound-Category Learning. *Front Psychol, 9*, 1828. doi:10.3389/fpsyg.2018.01828

R. Saffran, J., Werker, J., & Werner, L. (2007). The Infant's Auditory World: Hearing, Speech, and the Beginnings of Language. In (Vol. Vol. 6).

Saffran, J. R. (2002). Constraints on Statistical Language Learning. *Journal of Memory and Language, 47*(1), 172-196. doi:10.1006/jmla.2001.2839

Torkildsen, J. V. K., Arciuli, J., Haukedal, C. L., & Wie, O. B. (2018). Does a lack of auditory experience affect sequential learning? *Cognition, 170*, 123-129. doi:10.1016/j.cognition.2017.09.017

Ullman, M. T. (2004). Contributions of memory circuits to language: the declarative/procedural model. *Cognition, 92*(1-2), 231-270. doi:10.1016/j.cognition.2003.10.008

Wechsler, D. (1999). Weschler abbreviated scale of intelligence. The Psychology Corporation: Harcourt Brace & Company. New York, NY.

Williams, K. T. (2007). EVT-2: Expressive vocabulary test. New York, NY: Pearson.