Memory Consolidation in Adults With and Without Developmental Language Disorder and Dyslexia

Alexandra McSorley and F. Sayako Earle
Department of Communication Sciences and Disorders, University of Delaware

Abstract

Developmental language disorder (DLD) and dyslexia are common language-based learning disabilities that often co-occur, prompting debate regarding the nature of overlap in their learning and memory profiles. The current study examined how young adults with and without DLD or dyslexia learn and consolidate declarative, procedural, and speech-sound information over a 12-hour period. Participants completed learning tasks in the morning or evening and were retested on their performance after 12 hours. Declarative memory performance improved after 12 hours among evening-trained participants without DLD but not in morning-trained participants, nor in participants with DLD. Procedural memory performance improved after 12 hours among all participants without DLD, but not in participants with DLD. Sensitivity to the learned speech sounds improved after 12 hours across all participants. Together, these findings suggest that the time course of learning and consolidation differs across different types of learning and across different learning disability subtypes.

Keywords: Language disorder, reading disorder, memory consolidation, speech perception

Developmental language disorder (DLD) and dyslexia are common neurodevelopmental disorders that affect language abilities. Specifically, DLD is characterized by difficulties in language, including grammar, syntax, and language comprehension (Bishop et al., 2017), while dyslexia primarily impacts reading and spelling (Shaywitz & Shaywitz, 2005). Although DLD and dyslexia have distinct diagnostic criteria, they often co-occur and share certain characteristics.

A core debate in the field centers on whether these disorders arise from a shared underlying impairment or reflect different root causes (Bishop & Snowling, 2004; Ramus et al., 2013). The crux of this debate centers on the nature of the phonological deficits observed in both DLD and dyslexia (Ramus et al., 2013). In DLD, it has been proposed that impoverished speech representations affect the ability to acquire grammatical morphemes of low perceptual saliency (Phonological Deficit Hypothesis; Joanisse, 2007; Joanisse & Seidenberg, 2003). Phonological instability has been posited to hinder the establishment of stable phoneme-grapheme mappings for efficient decoding (Snowling, 1981). Thus, poor speech representations can account for much of the overlap in symptomology between the two conditions. It is quite possible, however, to arrive at poor speech representations through different mechanisms (Ramus et al., 2013). A better understanding of these mechanisms may help us to better predict which subset of children with DLD is more likely to struggle with the acquisition of literacy, facilitating intervention on pre-literacy skills prior to the onset of reading instruction.

While the literary landscapes of DLD and dyslexia differ in nuance, both include long-standing debates between a class of theories that posits atypical sensory processing vs. a class of theories that posits deficits in learning and memory. The processing perspective for DLD includes proposals on deficits in processing speed (Leonard et al., 2007; Zapparrata et al., 2023), phonological processing (Claessen et al., 2013; Joanisse, 2007), and predictive processing (Jones & Westermann, 2021). For dyslexia, proposals include deficits in auditory processing (Hämäläinen et al., 2013), atypical temporal sampling of auditory input (Goswami, 2011), and impaired processing of

transient visual and auditory input (Stein & Talcott, 1999). These differences in processing are thought to similarly underlie the phonological deficits observed in both DLD and dyslexia. Of course, processing and memory are not mutually exclusive, in that sensory processing affects encoding of representations and acoustic-phonetic representations affects linguistic processing speed.

The proposals on deficits in learning and memory have implicated selective weaknesses in procedural learning (Lum et al., 2014, 2018) and statistical learning (Lammertink et al., 2017; Schmalz et al., 2017) across both DLD and dyslexia. However, these proposals have been criticized for the task-specific nature of the observed weaknesses (Bogaerts et al., 2021; West et al., 2018).

A potential means of disambiguating the narrative might be to examine the neuroanatomical substrates that underlie performance across tasks in common. For example, the Procedural Circuit Deficit Hypothesis (PDH; Ullman et al., 2020) posits that various neurodevelopmental disorders of language, such as DLD and dyslexia, arise from structural differences in the procedural memory circuitry. As such, a tenet of the PDH is that declarative memory is relatively unaffected and that, moreover, implicit learning tasks, often considered "procedural," may be unimpaired if declarative memory can be recruited to compensate. Thus, a performance-based test of the PDH necessitates the use of procedural and declarative memory tasks that can reasonably be trusted to rely on the basal ganglia vs. the hippocampus, respectively.

Furthermore, a description of learning and memory function must consider not just the initial encoding of experience or practice, but the consolidation and retention of information over time. In the past two decades, a considerable body of work on memory consolidation in language learning has highlighted a critical role for sleep (see Gómez, 2011, and Schreiner & Rasch, 2017, for reviews). This literature has prompted an interest in a potential link between disorders of sleep and disorders of language (Botting & Baraka, 2018; McGregor & Alper, 2015).

Atypical sleep patterns have been reported in children with DLD (Knowland et al., 2021) and in children with dyslexia (O'Bruni et al., 2009), as well as atypical consolidation behaviors. In DLD, deficits in overnight consolidation has been reported for both procedural (Hedenius et al., 2011) and declarative memory (Earle & Ullman, 2021), as well as in speech-sound learning (Earle et al., 2018), suggesting a general weakness in converting new information to long-term knowledge (cf. Gordon et al., 2021).

Consolidation deficits have also been reported for dyslexia in procedural learning (Ballan et al., 2023; Hedenius et al., 2021; see Solbi & Earle, 2025, for review); however, it remains unclear if the patterns of learning and consolidation are the same across procedural and declarative learning in these populations. Important, the time course of consolidation is not uniform across procedural and declarative memory. That is, whereas a post-learning period of sleep is thought to support systems consolidation of declarative (i.e. hippocampal) learning (Diekelmann & Born, 2010), localized synaptic changes that support the enhancement of procedural learning is thought to occur as a function of time, regardless of state (Nemeth et al., 2010).

Establishing new speech-sound representation is not a monolithic skill, and likely relies on both declarative and procedural memory systems (Chandrasekaran et al., 2014; Earle & Myers, 2014). Potential weaknesses in the learning and retention of new acoustic-phonetic information may be attributable to weaknesses in procedural or declarative memory, or both, as well as subsequent consolidation. Furthermore, given the nature of the learning disabilities, it is unclear if patterns of learning and retention are the same for linguistic (e.g., speech-sound) and for nonlinguistic learning.

Rationale for the Current Study

The current study aimed to investigate the initial learning and consolidation of three types of memory: declarative memory, procedural memory, and speech-perceptual memory. We focused on young adulthood, as this stage of life is marked by increasing academic, professional, and social demands that require effective language use across various situations. Moreover, a growing literature points to lifelong difficulties experienced by those affected (Botting, 2020; Del Tufo & Earle, 2020; Earle & Del Tufo, 2021; McGregor et al., 2020). That is, if core memory deficits persist into adulthood, such challenges are likely to contribute to long-term educational and employment outcomes (Dubois et al., 2020).

To assess declarative memory, we used a recognition memory task due to its reliance on the hippocampus (Manns et al., 2003). To assess procedural memory, we used a serial reaction time task for its recruitment of the basal ganglia (Janacsek et al., 2020). To track the learning and consolidation of "new" acoustic-phonetic features, we used a nonnative contrast training task (Earle & Myers, 2015a, 2015b). Based on the PDH, we hypothesized that procedural memory would be compromised at initial learning (i.e., prior to consoli-

dation), but that initial learning in declarative memory would be unimpaired, for both DLD and dyslexia. For speech-sound learning, we predicted initial learning to be intact in DLD (Earle et al., 2018); however, we reasoned that documented deficits in auditory processing (e.g., Goswami, 2011) may compromise the ability of those with dyslexia to learn acoustic-phonetic features. Following an overnight interval, we predicted adults with DLD would show a deficit in all three memory tasks subsequent to poor initial learning for procedural memory and to weak consolidation for declarative and speech sound learning. We predicted adults with dyslexia would show a deficit in procedural and speech-sound learning tasks subsequent to poor initial learning, without an *a priori* hypothesis regarding consolidation of declarative memory. This pattern of results would provide insights into the different mechanisms underlying poor speech-perception performance in the two populations.

Method

Participants

Participants were recruited from the community surrounding the University of Delaware, which includes urban, rural, and suburban environments within a 15-mile radius. Flyers, social media, and e-mail advertisements were used. Targeted ads with language to recruit adults with a history of unspecified learning disabilities were also posted at the buildings surrounding disability support services, as well as on social media.

To participate, individuals had to be monolingual speakers of American English between the ages of 18 and 25 with a history of typical gestation, hearing, vision, nonverbal cognition, and sensory-motor development. Exclusion criteria included a history of autism spectrum disorder (ASD), neurological injury and/or condition, and attention deficit/hyperactivity disorder (ADHD).

Interested individuals e-mailed our laboratory for details about the study. Upon e-mail confirmation that prospective participants, to their knowledge, met the inclusionary criteria, they were scheduled for two sessions in our laboratory 12 hours apart. Participants were compensated $50 in gift cards for study participation.

DLD Status

We indicated participants who reported a history of receiving services and were identified as being language-impaired by the procedures developed by Fidler et al. (2011, 2013) as positive for DLD status. This method applies the raw scores of an individual's Modified Token Test and the 15-word spelling test into a logit regression equation derived from a discriminant analysis. This method is widely used in adult DLD research due to the lack of standardized diagnostic instruments (e.g., Earle & Del Tufo, 2021; McGregor et al., 2020; Nippold et al., 2017).

Dyslexia Status

Participants who reported a history of reading disorder and obtained scores below 1 standard deviation below the mean on two or more measures of word-level reading were indicated as positive for dyslexia.

A total of 135 participants met these criteria and participated in the study. Of these, 24 participants were positively identified with DLD status, and 32 were positively identified with dyslexia. There was an overlap of 12 participants who met criteria for both DLD and dyslexia. Please see Table 1 for demographic breakdown of participants. Table 2 presents average performance on the cognition, language, and reading scores by status.

Materials

Questionnaires

In addition to an in-house questionnaire that asked for demographic information and developmental history, participants were asked to provide information about their habitual sleep quality (Pittsburgh Sleep Quality Index [PSQI]; Buysse et al., 1989), daytime sleepiness (Epworth Sleepiness Scale [ESS]; Johns, 1991), and circadian preference (Horne-Ostberg Morningness-Eveningness Questionnaire; Horne & Ostberg, 1976). They also completed the Behavior Rating Inventory of Executive Function–Adult Version (BRIEF-A; Roth et al., 2005) as a self-reported measure of executive function and self-regulation. Questionnaire administration and data storage were handled through Research Electronic Data Capture (REDCAP; Harris et al., 2019).

Assessment Materials

Standardized and nonstandardized instruments were administered to determine participants' DLD and/or dyslexia status. The Wechsler Abbreviated Scale of Intelligence, 2nd Ed. (WASI II; Wechsler, 2011) was administered to assess nonverbal cognition.

Table 1

Demographic Breakdown of Participants by Status

N		TD	DLD Only	Dyslexia Only	DLD + Dyslexia
		91	12	20	12
		77F:14M	9F:3M	17F:3M	8F:4M
Age					
	mean(stdev)	21.23(2.08)	20.70(1.97)	20.48(1.52)	21.41(1.73)
Non-Hispanic					
	White	80	9	15	8
	Black	1	2	3	2
	Asian	4			1
Hispanic					
	White	5	1	2	1
	Black	1			

Table 2

Participant Characteristics and Performance by Group

Measure	TD (*n* = 91)	DLD Only (*n* = 12)	Dyslexia Only (*n* = 20)	DLD + Dyslexia (*n* = 12)
Nonverbal Cognition				
Block Design	48.43 (9.10)	44.67 (8.08)	49.95 (8.09)	46.92 (10.84)
Matrix Reasoning	22.30 (2.68)	22.00 (2.89)	22.10 (2.71)	26.58 (13.89)
Word-Level Reading				
Untimed Word Reading	42.42 (2.44)	38.67 (3.55)	40.55 (2.05)	39.08 (2.15)
Untimed Nonword Reading	23.60 (1.60)	22.25 (1.14)	18.75 (2.05)	18.75 (3.02)
Timed Word Reading	95.45 (9.21)	89.33 (8.88)	88.35 (11.51)	86.25 (7.23)
Timed Nonword Reading	59.09 (5.49)	52.17 (8.32)	51.10 (6.82)	44.75 (12.48)
Spelling	11.93 (2.07)	8.67 (2.74)	9.65 (3.15)	6.00 (3.13)
Language				
Modified Token Test	39.78 (2.86)	34.33 (4.68)	40.50 (1.93)	30.92 (6.69)
Passage Comprehension	32.70 (1.60)	22.25 (1.14)	18.75 (2.05)	18.75 (3.02)
Executive Function				
Behavioral Regulation Index	41.37 (6.47)	45.42 (9.02)	42.30 (7.83)	41.83 (7.79)
Metacognition Index	56.41 (9.99)	59.50 (10.48)	54.20 (9.26)	60.50 (17.91)
Global Executive Composite	98.12 (14.54)	104.92 (18.49)	96.50 (15.00)	102.33 (24.40)

Note. Values are reported as *M (SD)*. TD = typically developing; DLD = developmental language disorder. Nonverbal cognition was measured using the Wechsler Abbreviated Scale of Intelligence, Second Edition (WASI-II; Wechsler, 2011); reading was measured using the Woodcock Reading Mastery Tests, Third Edition (WRMT-III; untimed; Woodcock, 2011) and Test of Word Reading Efficiency, Second Edition (TOWRE-2; timed; Torgesen et al., 2012); executive function was measured using the Behavioral Rating Inventory of Executive Function – Adult version (BRIEF-A; Roth et al., 2005). Higher scores indicate better performance across measures except for the BRIEF-A, in which higher scores correspond to elevated difficulty.

The Test of Word Reading Efficiency-II (TOWRE-II; Torgesen et al., 2012) and the Word Identification, Word Attack, and the Passage Comprehension subtests of the Woodcock Reading Mastery Test – III (WRMT-III; Woodcock, 2011) were administered to measure timed and untimed reading ability, respectively. We also administered nonstandardized assessments as described by Fidler et al. (2011, 2013), including a 15-word spelling test and the Modified Token Test, designed to assess spoken language processing.

Learning Tasks

Three types of learning tasks, declarative, procedural, and speech learning, were built using E-Prime 3.0 software (Psychology Software Tools; https://pst-net.com/).

Declarative Learning Task. The stimuli consisted of 128 black-and-white drawings of 64 real and 64 made-up objects, which were used for nameability and manipulability. The real objects in each set (encoding, recognition, and retention) were matched for word frequency, number of syllables, and number of phonemes. The same task has been used with those with DLD (Earle & Ullman, 2021) and dyslexia (Hedenius et al., 2013).

Procedural Learning Task. An image of a yellow smiley face was generated using the "Shapes" tool within Microsoft Powerpoint.

Speech-Learning Task. The visual stimuli were sourced from an online repository containing a range of novel visual objects ("Fribbles" stimulus images courtesy of Michael J. Tarr, Center for the Neural Basis of Cognition and Department of Psychology, Carnegie Mellon University, http://www.tarrlab.org/). The auditory stimuli comprised five examples each of the retroflex /ɖ/ and dental /d̪/ consonants, spoken in a /CVC/ frame context (/ɖug/-/d̪ug/, by a male native speaker of Hindi digitally recorded in a sound-proof audiology booth, cut to capture the burst onset, and rescaled to have 70dB mean amplitude using the root-mean-square method on PRAAT software (Boersma, 2011).

Procedures

All human subjects procedures were reviewed and approved by the University of Delaware institutional review board.

Study Overview

The study took place in two sessions, spaced approximately 12 hours apart. The majority (*n* = 115) of the participants completed the first session in the eve-ning and the second session in the morning, such that they had an opportunity to sleep between Sessions 1 and 2. A subset of 20 participants completed the first session in the morning and the second session in the evening. This allowed us to determine if the time of day of training (AM vs. PM) affected initial encoding on the three tasks and to examine if the changes following a 12-hr delay patterned differently according to whether sleep took place between sessions.

Upon arrival to the laboratory for their first session, participants first provided informed consent for study participation. Then they completed the study questionnaires, followed by the three learning tasks. All measures were administered by a trained graduate students. All participants completed the declarative learning task first, followed by procedural learning and then nonnative speech learning. Participants returned to the lab 12 hours later for their second session. Here they were first tested on the three tasks learned during the prior session. Upon completion of the memory tasks, the battery of cognitive, reading, and language tests were administered. Raw score sheets were converted to standard scores and percentiles by two independent scorers for accuracy, with discrepancies flagged and resolved by the last author.

Declarative Learning Task: Object Recognition

This task consisted of three phases: encoding, recognition, and retention. During the encoding phase, participants were seated in front of a computer and instructed to place one finger from each hand on the "S" and "L" keys on the keyboard, respectively. There were told that they would be presented with images of real and imaginary objects on the screen, and that they were to indicate via key press if the objects were real or made up. The words "real" and "made up" were displayed on either side of the screen to remind participants which key corresponded to which response. The correspondence of keys to the response was counterbalanced across participants. The trial began with a 1-second fixation cross at the center of the screen, followed by the presentation of the stimulus image. To control for the duration of exposure to the items, the images remained on the screen for exactly 500ms for every trial. The trial ended when the participant indicated a response.

Participants first completed three practice trials, and then proceeded to 64 trials, consisting of 32 real and 32 imaginary objects. Images were presented in a pseudo-random order to limit the number of consecutive trials in a single trial type to no more than three.

The recognition phase took place roughly 10 mins after the encoding phase. Participants were presented with images of real and made-up objects and asked to indicate if they had seen these objects before (i.e., during encoding) or not. The trials began with a 1-second presentation of a fixation cross, followed by presentation of the stimulus image. The words "Seen before?" appeared on the screen above the stimulus image, with prompts "yes" and "no" written on either side of the screen to indicate which key corresponded to which response. After 5 practice trials with feedback, participants completed 128 trials without feedback, comprising 64 objects that had been presented during the encoding phase and 64 objects that had not been presented before.

The retention phase took place approximately 12 hours later, during Session 2. It had the same trial structure as the recognition phase, using a new set of unfamiliar objects. As in the encoding phase, stimulus images were presented in a pseudo-random order, with a different presentation order coded across the recognition and retention phases.

Procedural Learning: Serial Reaction Time (SRT) Encoding/Assessments

Procedural learning was evaluated using a modified version of Nissen and Bullemer's (1987) Serial Reaction Time (SRT) task. Participants viewed a dark display showing the outlines of four boxes arranged horizontally, and were asked to place one finger on each of four adjacent, marked keys on a keyboard. On each trial, a smiley face appeared in one of the four positions, and participants were instructed to press the key corresponding to that position as quickly and accurately as possible. The trials were self-paced, such that the stimulus image appeared in the next location immediately after the participant indicated a response.

On Day 1, the session began with a 40-trial practice block in which the smiley face appeared in a pseudo-random order. This was followed by four blocks of 80 trials each, in which the stimulus followed a repeating sequence of 10 locations (sequence trials: 4,3,2,1,3,2,4,3,2,1, as used by Nissen & Bullemer, 1982). The session ended with an additional 80-trial block presented in pseudo-random order, such that the frequency of occurrence in each position equaled that of the sequence trials. On Day 2, participants again completed a 40-trial pseudo-random warm-up block, followed by an 80-trial sequence block and a final 80-trial pseudo-random block. At the end of the task on Day 2, participants

were asked if they were aware of any structure to the trial order.

Speech-Sound Learning: Nonnative Contrast Training

Participants were assessed on their speech-sound learning by completing perceptual training on a non-native speech-sound contrast training and assessments. Participants wore circum-aural headphones during the task, and auditory stimuli were presented at 70dB. During the first session, participants first completed a baseline discrimination probe, followed by a familiarization sequence, identification training, the first post-training identification test, and the first post-training discrimination test. During the second session, participants completed an identification test, followed by a discrimination test.

During the discrimination tests, the participants were told that they would hear a sequence of two sounds, and were instructed to indicate whether the word onsets were the same or different using the computer mouse. The screen prompted participants to "click left for 'same,' right for 'different.'" Two tokens were played in sequence (800ms inter-stimulus interval [ISI]). Only responses indicated by participants after the second sound were recorded. The trial ended when the participants indicated a response; the next trial began after a 500ms delay. Each discrimination test contained a total of 64 trials (32 same/32 different). In the "different" trials, dental and retroflex tokens were used (ɖug/ɖug2), whereas the "same" trials used acoustically different tokens of the same category (i.e., ɖug1/ɖug2). Stimulus presentation was set to random order on E-Prime.

During the familiarization sequence, participants were told that they would now be presented with each picture along with the corresponding "word." A "fribble" appeared on the screen while each auditory token in the stimulus set for the dental tokens (5 per target) was played in sequence, with a 1-second ISI. The second fribble then appeared, whereupon each auditory token for the retroflex set was presented at 1-second ISI. For identification training, participants were told that they would learn a set of "new" speech sounds. Following a short familiarization sequence, they were asked to choose the novel visual object (out of two options) corresponding to the "word" that they heard. Two novel objects were presented on the screen to indicate which button on the mouse corresponded to which image. The trial began with the presentation of the target auditory token. Immediately after the participant indicated a response, written

feedback (Correct!/incorrect) was presented for 1 second. The next trial began after a 500ms delay. Participants completed 200 trials with a 2-minute break halfway through. For the identification tests, participants completed 50 trials of the same 2 alternative forced-choice tasks without feedback.

Analyses and Results

Data Overlap With Prior Publications

The current dataset overlaps with a portion of the data presented in a prior publication on the overnight consolidation of declarative and procedural memory tasks in adults with and without DLD (Earle & Ullman, 2021). Specifically, the subset of the Earle and Ullman (2021) dataset collected at the University of Delaware is included within the current data. In addition, a subset of the speech learning data was presented in a prior publication on the relationship between overnight consolidation of speech and reading (Williams & Earle, 2022), and a subset of the reading and language assessment data has appeared in papers describing the skill profiles of adults with DLD and/or dyslexia (Del Tufo & Earle, 2020; Earle & Del Tufo, 2021). Data on the morning-trained control group, the speech-sound learning data for adults with DLD, and all data on adults with dyslexia, have not been presented elsewhere and are original contributions of the current manuscript.

Data Processing

For declarative learning, we first examined the data to ensure that participants met a threshold of at least 90% accuracy during the encoding phase to ensure task compliance and engagement. To account for response bias in measuring sensitivity to familiar/unfamiliar objects and the dental/retroflex sounds, percent accuracy on the declarative and speech tasks was converted to D-Prime scores (MacMillan & Creelman, 2004). D-Prime scores were calculated for real and made-up objects separately, and then averaged, to arrive at a single score per participant per session. For the speech learning task, D-Prime scores were calculated for discrimination and identification tasks separately for each participant at each time point.

For the procedural learning task, we examined the data to ensure that participants met a threshold of at least 90% accuracy as an assurance of task engagement. We then retained only trials in which participants keyed the correct location of the image on the screen. We then removed reaction times deemed

outliers (more than two standard deviations beyond the mean), and averaged reaction times over the last sequence and last random blocks for each person at each time point. While we examined accuracy performance, the differences between the average reaction time between the random block and the sequence block were used as the primary outcome measure of procedural learning for the analyses below.

The dataset contained missing values due to participant attrition, failure of experiment platform, experimenter error, and/or data corruption. Specifically, the total number of missing data points were 11/135 for Day 1 declarative learning, 11/135 for Day 2 declarative learning, 14/135 for Day 1 procedural learning, 11/135 for Day 2 procedural learning, 9/129 for baseline discrimination, 9/135 for Day 1 discrimination, 8/135 for Day 2 discrimination, 9/135 for Day 1 identification, and 8/135 for Day 2 identification. The missing values approximated 7.5% of the total dataset.

In order to reduce bias and to improve model performance, missing values were imputed via linear mixed-effects-based multivariate imputation by chained equation to allow for missing values to be derived from the model's predictive distribution. Imputations were carried out using the MICE package in R (Van Buuren & Groothuis-Oudshoorn, 2011). The full dataset of outcome variables (including imputed values) and the code used for imputation and analyses are publicly available through the Open Science Framework (https://osf.io/rtcdu/?view_only=12f9ac445d734617828d4a97a2906d98).

Learning and Consolidation Patterns Across Groups

Outcome measures were modeled using a linear mixed-effects approach, which is the recommended approach for examining within-subjects measures across uneven sample sizes. The models were implemented using the lme4 package in R (Bates et al., 2015). Marginal and conditional $R2$ values on the mixed-effects models were calculated using the MuMIn package (Bartoń, 2015), and effect sizes for parameter estimates were calculated using the r2glmm package (Jaeger, 2017). Significant interaction(s) in the omnibus model determined the pairwise comparisons to be conducted. *T*-tests were conducted on the estimated marginal means via the emmeans package (Lenth, 2024), with the Tukey correction applied for multiple comparisons. Conditional and marginal coefficients of determination for the generalized mixed-effect models were calculated using the MuMIn package. Categorical variables

were effects-coded for the purpose of examining interactions between categorical variables.

Declarative Memory

The declarative learning scores were modeled with a four-way interaction term between Time (Session 1 vs. Session 2), Time of Day (TOD) of training (Morning vs. Evening), DLD status, and dyslexia status, with by-participant intercepts entered as the random effect. The resultant model (Akaike Information Criterion [AIC] = 530.7, Bayesian Information Criterion [BIC] = 595.5, R^2_m = .11, R^2_c = .65) contained a significant interaction between Time, TOD, and DLD (Estimate [EST] = -1.54, Standard Error [SE] = .65, t = -2.37, p = .019, R^2 = .012), and a main effect of Time (EST = -.18, SE =. 07, t = -.99, p <.001, R^2 = .02). Pairwise comparisons examining the nature of the three-way interaction revealed that Session 2 scores were greater than Session 1 scores (EST = .35, SE = .08, t ratio = 4.25, p = .001) for adults without DLD who were trained in the Evening, but not for those trained in the Morning (p >.999), nor for adults with DLD (p = .583). All other pairwise comparisons that met significance involved morning-trained adults with DLD (n = 2), but the lack of a sufficient sample prevents meaningful interpretation.

To summarize, the Time main effect suggested that performance, on average, improved between Sessions 1 and 2. This observation was qualified by TOD of training for adults without DLD, however. For adults without DLD, performance was stable across 12 hours for those who trained in the morning. For those without DLD who trained in the evening, performance improved after 12 hours. For adults with DLD, performance did not improve after 12 hours. Dyslexia status did not significantly influence the pattern of change (or lack thereof) in behavior over time. See Figure 1 for graphical depiction of the pattern of behavior.

Procedural Memory

The procedural learning scores (the difference between average reaction time between random and sequence blocks) were modeled with a four-way interaction term between Time, TOD of training, DLD status, and dyslexia status, with by-participant intercepts entered as the random effect. The resultant model (AIC = 2572.3, BIC = 2637.1, R^2_m = .26, R^2_c = .26) contained a significant two-way interaction between Time and DLD status (EST = 36.09, SE = 15.73, t = 2.23, p = .023, R^2 <.01). All other main effects and interactions were not statistically significant. Pairwise comparisons examining the nature of these interactions revealed that
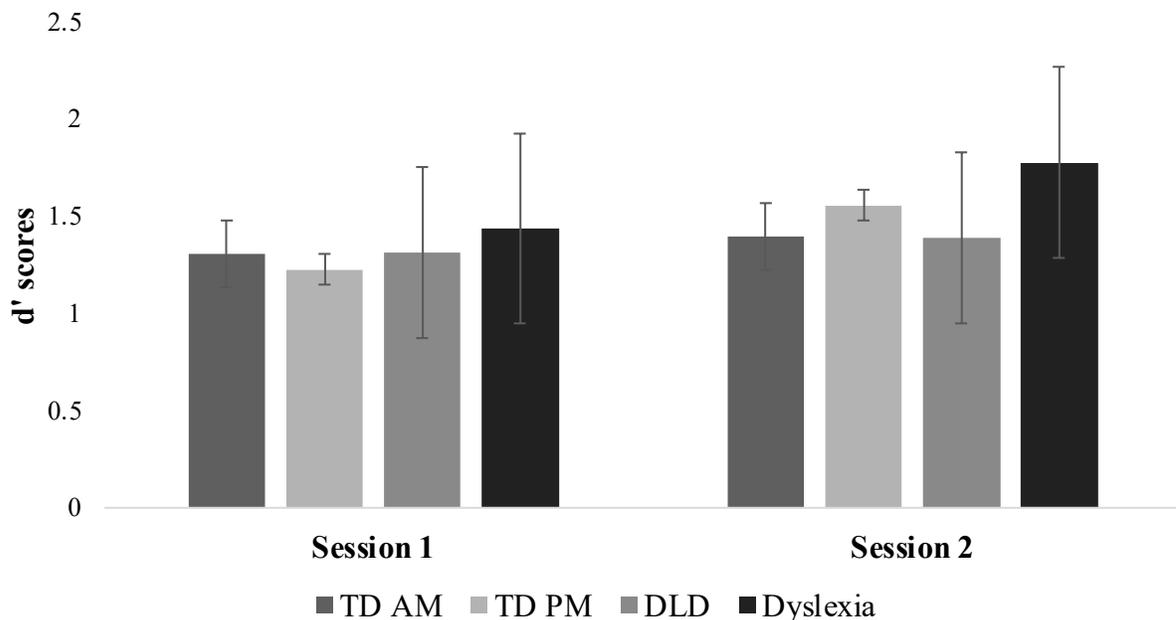

Figure 1

Declarative Memory Performance Across 12 Hours

Note. AM = morning training; PM = evening training; TD = typically developing; DLD = developmental language disorder. Figure 1 provides a graphical presentation of declarative learning performance at Session 1 and performance 12 hours later at Session 2. TD plots depict performance by participants without DLD or dyslexia. The plots depict estimated marginal means of *d* scores by session; error bars depict standard errors of the mean.

individuals without DLD significantly improved their procedural performance after 12 hours (EST = 26.50, SE = 7.68, *t* ratio = 3.45, *p* = .004). Also, those without DLD outperformed those with DLD on the procedural task at Session 2 (EST = 31.34, SE = 11.47, *t* ratio = 2.73, *p* = .036). The results of all other pairwise comparisons were not significant.

To determine if accuracy differed over time and across groups, we modeled response accuracy as the outcome measure, with a four-way interaction term between Time, TOD, DLD status, and dyslexia status, with block type (Random vs. Sequence) as covariate, and with by-participant intercepts entered as the random effect. The resultant model (AIC = -2191.7, BIC = -2110.1, R^2_m = .09, R^2_c = .24) contained a significant four-way interaction (EST = -.11, SE = .05, *t* = 2.30, *p* = .022, R^2 <.01), as well as two-way interactions between Time and TOD (EST = .03, SE = .01, *t* = -2.44, *p* = .015, R^2 <.01) and between Time and DLD status (EST = .02, SE = .01, *t* = 2.08, *p* = .038, R^2 <.01). The model also contained a main effect of block type (sequence>random; EST = .01, SE <.01, *t* = 5.50, *p* <.001, R^2 = .02). Follow-up pairwise comparisons revealed no statistically significant differences in accuracy across groups or over time. See Table 3 for means and standard deviations of accuracy performance by group.

In summary, the Time main effect suggests that performance, on average, improved between Sessions 1 and 2. This was qualified by the observation that whereas those without DLD improved their performance over 12 hours, those with DLD did not. That is, those without DLD outperformed those with DLD at Session 2, even though a group-level difference was not observed at Session 1. Dyslexia status did not significantly influence the pattern of change in behavior over time. See Figure 2 for a graphical depiction.

Speech-Sound Learning

The post-training speech-discrimination scores were modeled with a four-way interaction term between Time, TOD, DLD status, and dyslexia status, with baseline discrimination scores as covariate, and with by-participant intercepts entered as the random effect. The resultant model (AIC = 641.9, BIC = 710.3, R^2_m = .23, R^2_c = .72) contained a significant four-way interaction (EST = 2.74, SE = 1.20, *t* = 2.27, *p* = .025, R^2 <.01) and three-way interactions between Time, TOD, and DLD status (EST = -1.68, SE = .60, *t* = -2.79, *p* = .006, R^2 <.01), and between Time, DLD status, and dyslexia status (EST = -1.33, SE = .60, *t* = -2.21, *p* =. 029, $R2$ <.01). In addition, two-way interactions were found between Time and DLD status (EST = -.68, SE = .30, *t* = -2.25, *p* = .026, R^2 <.01), between TOD and DLD status (EST = 1.36, SE = .64, *t* = 2.12, *p* = .036, R^2 <.01), and between Time and dyslexia status (EST = .75, SE = .30, *t* = 2.51, *p* = .013, R^2 <.01), and between Time and TOD (EST = -.85, SE = .30, *t* = -2.82, *p* = .005, R^2 <.01). Additionally, the model contained main effects of Time (EST = -.43, SE = .15, *t* = -2.85, *p* = .005, R^2 <.01) and baseline discrimination ability (EST = .55, SE = .10, *t* = 5.55, *p* <.001, R^2 = .09). Following these interactions, the only pairwise comparisons that met statistical significance included morning-trained adults with DLD (*n* = 2), but a lack of a sufficient sample prevents meaningful interpretation.

The speech-identification scores were modeled with a four-way interaction term between Time, TOD, DLD status, and dyslexia status, with baseline discrimination scores as covariate, and with by-participant intercepts entered as the random effect. The resultant model (AIC = 810.3, BIC = 878.6, R^2_m = .30, R^2_c = .54) contained significant main effects of Time (EST = -.93, SE = .25, *t* =3.72, *p* <.001, $R2$ <.01) and baseline discrimination ability (EST = .74, SE =.11, *t* = 6.68, *p* <.001, $R2$ = .11). All other main effects and interactions were not significant.

In summary, post-training speech perception improved on average between Sessions 1 and 2 across tasks after controlling for baseline discrimination ability. The improvement in discrimination was qualified by

Table 3

Accuracy Performance on the Serial Reaction Time Task

	Session 1		Session 2	
	Random	Sequence	Random	Sequence
TD AM	.96(.04)	.97(.03)	.97(.03)	.98(.02)
TD PM	.96(.03)	.97(.02)	.96(.05)	.98(.03)
DLD	.98(.02)	.98(.03)	.97(.03)	.98(.02)
Dyslexia	.96(.03)	.98(.01)	.94(.04)	.97(.04)

Note. AM = morning training; PM = evening training; TD = typically developing; DLD = developmental language disorder. Values expressed are mean accuracy (% correct) and standard deviations.
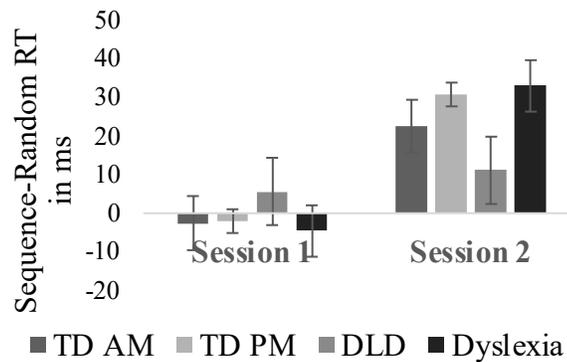
Figure 2

Procedural Memory Performance Across 12 Hours

Note. AM = morning training; PM = evening training; TD = typically developing; DLD = developmental language disorder. Figure 2 provides a graphical presentation of procedural learning performance at Session 1 and performance 12 hours later at Session 2. Procedural learning is expressed as a difference between the reaction time (RT) during the last sequence block and the last random block in milliseconds. The plots depict estimated marginal means; error bars depict standard errors of the mean.

interactions with TOD, DLD status, and dyslexia status; however the follow-up pairwise comparisons revealed no contrasts that survived correction. See Figure 3 for a graphical depiction of speech behaviors over time.

Relationships Between Memory Measures and Language Skills

To determine if the learning measures were associated with functional measures of language and reading, we conducted a series of Pearson product-moment correlation analyses between the outcome measures of declarative, procedural, and speech-sound learning, and word-level reading, reading comprehension, and sentence-level processing. The Holms-Bonferroni method of correction was applied to control for the family-wise error rate to below .05. Out of the 63 correlations, 3 relationships were found to be significant after correction.

Untimed word and timed nonword reading abilities, as well as spoken language processing, were positively correlated with Day 1 identification scores. The full matrix of R and p-values is provided in the Supplementary Materials.
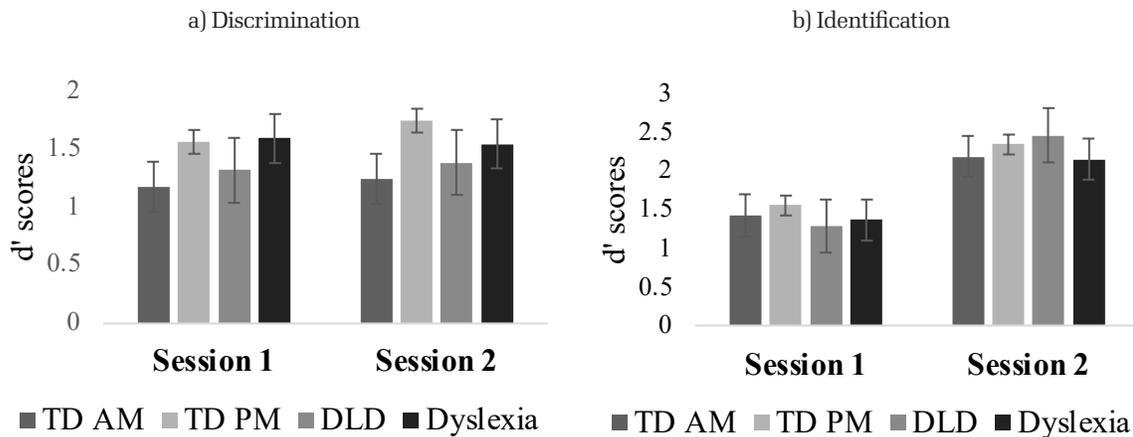

Figure 3

Procedural Memory Performance Across 12 Hours

Note. AM = morning training; PM = evening training; TD = typically developing; DLD = developmental language disorder. Figure 2 provides a graphical presentation of procedural learning performance at Session 1 and performance 12 hours later at Session 2. Procedural learning is expressed as a difference between the reaction time (RT) during the last sequence block and the last random block in milliseconds. The plots depict estimated marginal means; error bars depict standard errors of the mean

Discussion

This study examined how adults with DLD and/or dyslexia learn and consolidate learned information over a 12-hour period compared to adults with typical language and reading abilities. Below, we interpret each of these findings in the context of the literature and consider their implications for memory consolidation in individuals with and without learning disabilities.

Declarative Memory

We predicted that recognition memory performance would be comparable across groups initially, but that performance gains in the evening-trained TD group following the 12-hour interval would result in group-level differences in retention. The pattern of behavior in typical adults, that is, improvement for the evening-trained group, but not for the morning-trained group, is consistent with the broad literature on the benefit of sleep for the consolidation of declarative memory (see Diekelmann & Born, 2010, for review). Furthermore, the lack of overnight performance gains in the individuals with DLD is consistent with a previous report on the absence of overnight consolidation of declarative memory in those with DLD (Earle & Ullman, 2021). It is unclear if the lack of overnight gains observed in DLD stems from atypical sleep or from initial learning that subtly differs from those without DLD. In any case, these findings suggest that adults with DLD may struggle with retention of declarative memory. In contrast, participants with dyslexia were observed to demonstrate a similar learning and consolidation pattern to that of adults without DLD or dyslexia.

Interesting, Figure 1 suggests a numerically, if not statistically, greater performance by those with dyslexia. This observation echoes findings by Hedenius et al. (2013), who reported enhanced declarative memory performance in children with dyslexia. Enhanced declarative memory has been hypothesized as a compensation mechanism for certain neurodevelopmental disorders, including dyslexia (Hedenius et al., 2013; Ullman & Pullman, 2015). While our findings do not directly support this compensation hypothesis, we note that ~50% of participants in our dyslexia sample also met the criteria for DLD, consistent with the known high rate of co-occurrence of these conditions (Adlof & Hogan, 2018). Thus, the elevated performance in the dyslexia sample hints at a possibility that declarative memory performance is enhanced in adults with dyslexia without concurrent DLD. In any case, declarative learning and retention appears unimpaired in those with dyslexia.

Procedural Memory

We predicted poor initial performance, and in subsequent retention, on the SRT task in adults with DLD and dyslexia relative to TD. Instead, we found task performance to be low when tested immediately after learning across all groups (see Figure 2); that is, performance during Session 1 alone did not provide strong evidence of learning. It is not entirely clear why performance was so low at Session 1, although we find performance to generally improve in Session 2.

SRT performance of participants without DLD improved over 12 hours regardless of whether they engaged in learning in the morning or in the evening, suggesting that the delayed improvement in the procedural memory task was not specific to a sleep-containing interval. These outcomes align with the suggestion that the consolidation of procedural memory reflects localized changes to synaptic strengths that occur over time spent in the absence of interfering input (Diekelmann & Born, 2010) and do not necessitate sleep (Janacsek & Nemeth, 2012; Nemeth et al., 2010; Pan & Rickard, 2015).

The performance of adults with DLD did not improve over time, resulting in a delayed deficit in procedural memory performance at Session 2. A similar observation was reported in Hedenius et al. (2011), in which children with DLD demonstrated typical-like performance on the SRT task tested immediately after learning, but lacked the improvement observed in typical children on the next day. As all groups performed poorly at Session 1, it is unclear if the performance deficit observed in DLD is attributable to poor encoding or consolidation.

Those with dyslexia were found to have a similar performance profile to that of typical adults. This finding is counter to reports of a procedural learning deficit in children with dyslexia (see Lum et al., 2013, for meta-analysis). One possibility for this difference is that adults with dyslexia are more practiced in compensating for procedural deficits with alternate strategies. In any case, the current findings better support the Procedural Circuit Deficit Hypothesis in those with DLD than in those with dyslexia.

Speech-Sound Learning

We predicted that adults with DLD would demonstrate a delayed deficit in the recall of nonnative acoustic-phonetic cues at Session 2, whereas we expected adults with dyslexia to be compromised at initial learning. Despite significant interactions observed in the omnibus model for discrimination per-

formance, follow-up pairwise comparisons did not reveal any significant group-level differences in the pattern of changes to performance.

In general, discrimination and identification performance on the nonnative contrast improved across 12 hours, regardless of time of day of training. In other words, performance on the speech training task patterned more similarly to SRT performance than the recognition memory task. It has been observed previously that performance on speech identification is enhanced following a delay, but that a period of sleep stabilizes discrimination performance against conflicting input (Earle & Myers, 2015a) and facilitates generalization of perceptual skill (Earle & Myers, 2015b; Fenn et al., 2003; Qin et al., 2025). Thus, the current findings are consistent with prior observations on the time course of speech-perceptual learning on trained items in typical adults.

With respect to the speech-sound learning behavior in adults with DLD, we did not observe a consolidation deficit as previously reported in Earle et al. (2018). We note that the analysis approach here differed slightly from that of Earle et al. (2018), in that we entered baseline discrimination performance as a covariate in the post-training perceptual scores. However, this does not explain why the current sample of adults with DLD was observed with offline enhancement in speech-perceptual performance after demonstrating an impairment at Session 2 in both the declarative and procedural tasks. Furthermore, that adults with dyslexia were found with speech-perceptual behavior comparable to that of adults without dyslexia was unexpected, given that speech perception is a known difficulty in this population (Lieberman et al., 1985; Manis et al., 1997; Serniclaes et al., 2004; Ziegler et al., 2009). One possible explanation of this unexpected finding is that speech perception is a more pronounced deficit for those with dyslexia during childhood (Hazan et al., 2009; Law et al., 2014). This is an area in which further exploration is necessary, to better understand the relationship between speech-sound learning and language and reading disabilities.

Correlations Between Learning Ability and Language/Reading Skills

Correlational analyses revealed significant relationships between speech learning and reading ability, as well as spoken language processing (see Supplemental Table). In general, it appears that speech-sound learning is strongly associated with functional language and reading abilities, although the directionality

of these relationships is unclear. Beyond these specific associations, it is worth noting that the strengths of the associations between reading/language ability and different memory measures appear to differ over time.

To illustrate, the R values suggest that declarative and speech-sound memory measures have positive associations with reading and language measures across sessions in general. In contrast, SRT performance appears to have negative relationships with reading and language measures at Session 1 but positive relationships at Session 2. This may relate to poor task performance across individuals without DLD (see Figure 2), wherein those with DLD demonstrated slightly (though not significantly) higher performance at Session 1. While the mechanisms underlying these relationships are unclear, learning and memory abilities continue to be associated with reading and language abilities in adulthood.

Study Limitations

There are important limitations in the current study that challenge our interpretations. First, our samples included a large overlap between subjects with DLD and dyslexia, with insufficient numbers of those with DLD or dyslexia only to compare behavioral profiles across those with vs. without co-occurring conditions. This limits our ability to interpret patterns of behavior attributable to "pure" diagnostic categories. Second, we did not ask participants about their explicit awareness of the repeated sequences in the SRT task, so, given that task-based performance measures of memory place a heavy burden of interpretation on the tasks that are used, and no task-based measures of memory are infallible, it is possible that some individuals relied on declarative knowledge about the sequence trials to perform this task. A battery of different tasks to measure declarative and procedural memory would afford a more robust interpretation of learning and consolidation patterns in these populations. Third, our study design conflated time of day of learning with the likelihood that the post-learning interval contains sleep. Thus, we were unable to disentangle effects of sleep vs. circadian influences on consolidation, and our interpretation of results reflect this limitation. Finally, our speech-sound learning measure did not include a measure of generalization, which would have allowed us to better track systems consolidation on perceptual performance.

Conclusion

Despite these limitations, however, the current work offers some important insights into learning and

retention across individuals with different learning disabilities. Notably, consolidation patterns were observed to be quite different between individuals with DLD and those with dyslexia. Specifically, DLD status was associated with a lack of offline improvement across our task-based measures of declarative and procedural memory that led to a performance deficit 12 hours after learning. In contrast, participants with dyslexia patterned similarly to typical adults on memory tasks. This may suggest that, despite the frequent co-occurrence between these disorders and etiological frameworks that highlight similar weaknesses between them, the learning and memory profiles of these disorders may be distinct, thereby underscoring the importance of tailored support for those with these neurodevelopmental conditions into adulthood.

References

Adlof, S. M., & Hogan, T. P. (2018). Understanding dyslexia in the context of developmental language disorders. *Language, Speech, and Hearing Services in Schools*, *49*(4), 762-773. https://doi.org/10.1044/2018_LSHSS-DYSLC-18-0049

Ballan, R., Durrant, S. J., Manoach, D. S., & Gabay, Y. (2023). Failure to consolidate statistical learning in developmental dyslexia. *Psychonomic Bulletin & Review*, *30*(1), 160-173. https://doi.org/10.3758/s13423-022-02169-y

Bartoń, K. (2025). *MuMIn: Multi-model inference* [R package]. https://CRAN.R-project.org/package=MuMIn

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R., Singmann, H., & Bolker, M. B. (2015). *lme4: Linear mixed-effects models using Eigen and S4* [R package]. https://CRAN.R-project.org/package=lme4

Bishop, D. V., & Snowling, M. J. (2004). Developmental dyslexia and specific language impairment: Same or different? *Psychological Bulletin*, *130*(6), 858. https://doi.org/10.1037/0033-2909.130.6.858

Bishop, D. V., Snowling, M. J., Thompson, P. A., Greenhalgh, T., & Klee, T. M. (2017). CATALISE: A multinational and multidisciplinary Delphi consensus study of problems with language development. Phase 2. *Journal of Child Psychology and Psychiatry*, *58*(10), 1068-1080. https://doi.org/10.1111/jcpp.12721

Boersma, P. (2011). *Praat: doing phonetics by computer* [Computer program]. http://www.praat.org/

Bogaerts, L., Siegelman, N., & Frost, R. (2021). Statistical learning and language impairments: Toward more precise theoretical accounts. *Perspectives on Psychological Science*, *16*(2), 319-337. https://doi.org/10.1177/1745691620953082

Botting, N. (2020). Language, literacy and cognitive skills of young adults with developmental language disorder (DLD). *International Journal of Language & Communication Disorders*, *55*(2), 255-265. https://doi.org/10.1111/1460-6984.12518

Botting, N., & Baraka, N. (2018). Sleep behaviour relates to language skills in children with and without communication disorders. *International Journal of Developmental Disabilities*, *64*(4-5), 238-243. https://doi.org/10.1080/20473869.2017.1283766

Buysse, D. J., Reynolds III, C. F., Monk, T. H., Berman, S. R., & Kupfer, D. J. (1989). The Pittsburgh Sleep Quality Index: A new instrument for psychiatric practice and research. *Psychiatry Research*, *28*(2), 193-213. https://doi.org/10.1016/0165-1781(89)90047-4

Chandrasekaran, B., Yi, H. G., & Maddox, W. T. (2014). Dual-learning systems during speech category learning. *Psychonomic Bulletin & Review*, *21*(2), 488-495.

Claessen, M., Leitão, S., Kane, R., & Williams, C. (2013). Phonological processing skills in specific language impairment. *International Journal of Speech-Language Pathology*, *15*(5), 471-483. https://doi.org/10.3109/17549507.2012.753110

Del Tufo, S. N., & Earle, F. S. (2020). Skill profiles of college students with a history of developmental language disorder and developmental dyslexia. *Journal of Learning Disabilities*, *53*(3), 228-240. https://doi.org/10.1177/0022219420904348

Diekelmann, S., & Born, J. (2010). The memory function of sleep. *Nature Reviews Neuroscience*, *11*(2), 114-126. https://doi.org/10.1038/nrn2762

Dubois, P., St-Pierre, M. C., Desmarais, C., & Guay, F. (2020). Young adults with developmental language disorder: A systematic review of education, employment, and independent living outcomes. *Journal of Speech, Language, and Hearing Research*, *63*(11), 3786-3800. https://doi.org/10.1044/2020_jslhr-20-00127

Earle, F. S., & Del Tufo, S. N. (2021). Literacy-supporting skills in college students with specific reading comprehension deficit and developmental language disorder. *Annals of Dyslexia*, *71*(2), 282-298. https://doi.org/10.1007/s11881-020-00211-z

Earle, F. S., Landi, N., & Myers, E. B. (2018). Adults with specific language impairment fail to consolidate speech sounds during sleep. *Neuroscience Letters*, *666*, 58-63. https://doi.org/10.1016/j.neulet.2017.12.030

Earle, F. S., & Myers, E. B. (2014). Building phonetic categories: An argument for the role of sleep. *Frontiers in Psychology*, *5*, 1192.

Earle, F. S., & Myers, E. B. (2015a). Sleep and native language interference affect nonnative speech sound learning. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(6), 1680. https://doi.org/10.1037/xhp0000113

Earle, F. S., & Myers, E. B. (2015b). Overnight consolidation promotes generalization across talkers in the identification of nonnative speech sounds. *The Journal of the Acoustical Society of America*, *137*(1), EL91-EL97. https://doi.org/10.1121/1.4903918

Earle, F. S., & Ullman, M. T. (2021). Deficits of learning in procedural memory and consolidation in declarative memory in adults with developmental language disorder. *Journal of Speech, Language, and Hearing Re-*

search, *64*(2), 531-541. https://doi.org/10.1044/2020_JSLHR-20-00292

Fenn, K. M., Nusbaum, H. C., & Margoliash, D. (2003). Consolidation during sleep of perceptual learning of spoken language. *Nature*, *425*(6958), 614-616. https://doi.org/10.1038/nature01951

Fidler, L. J., Plante, E., & Vance, R. (2011). Identification of adults with developmental language impairments. *American Journal of Speech-Language Pathology*, *20*(1), 2-13. https://doi.org/10.1044/1058-0360(2010/09-0096)

Fidler, L. J., Plante, E., & Vance, R. (2013). Erratum: Identification of adults with developmental language impairments. *American Journal of Speech-Language Pathology, 22*(3), 577. https://doi.org/10.1044/1058-0360(2013/13-0018)

Gómez, R. L. (2011). Memory, sleep and generalization in language acquisition. In I. Arnon & E. V. Clark (Eds.), *Experience, variation and generalization: Learning a first language* (pp. 261-276). Benjamins Publishing Company. https://doi.org/10.1075/tilar.7.15gom

Gordon, K. R., Storkel, H. L., Lowry, S. L., & Ohlmann, N. B. (2021). Word learning by preschool-age children with developmental language disorder: Impaired encoding and robust consolidation during slow mapping. *Journal of Speech, Language, and Hearing Research*, *64*(11), 4250-4270. https://doi.org/10.1044/2021_JSLHR-21-00046

Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, *15*(1), 3-10. https://doi.org/10.1016/j.tics.2010.10.001

Hämäläinen, J. A., Salminen, H. K., & Leppänen, P.H.T. (2013). Basic auditory processing deficits in dyslexia: Systematic review of the behavioral and event-related potential/field evidence. *Journal of Learning Disabilities*, *46*(5), 413-427. https://doi.org/10.1177/0022219411436213

Harris, P. A., Taylor, R., Thielke, R., Payne, J., Gonzalez, N., & Conde, J. G. (2009). Research electronic data capture (REDCap) – A metadata-driven methodology and workflow process for providing translational research informatics support. *Journal of Biomedical Informatics*, *42*(2), 377-381. https://doi.org/10.1016/j.jbi.2008.08.010

Hazan, V., Messaoud-Galusi, S., Rosen, S., Nouwens, S., & Shakespeare, B. (2009). Speech perception abilities of adults with dyslexia: Is there any evidence for a true deficit? *Journal of Speech, Language, and Hearing Research*, *52*(6), 1510-1529. https://doi.org/10.1044/1092-4388(2009/08-0220)

Hedenius, M., Persson, J., Tremblay, A., Adi-Japha, E., Veríssimo, J., Dye, C. D., Alm, P., Jennische, M., Tomblin, B., & Ullman, M. T. (2011). Grammar predicts procedural learning and consolidation deficits in children with specific language impairment. *Research in Developmental Disabilities*, *32*(6), 2362-2375. https://doi.org/10.1016/j.ridd.2011.07.026

Hedenius, M., Ullman, M. T., Alm, P., Jennische, M., & Persson, J. (2013). Enhanced recognition memory after incidental encoding in children with developmental dyslexia. *PloS One*, *8*(5), e63998. https://doi.org/10.1371/journal.pone.0063998

Horne, J. A., & Ostberg, O. (1976). A self-assessment questionnaire to determine morningness-eveningness in human circadian rhythms. *International Journal of Chronobiology*, *4*(2), 97-110.

Jaeger, B. (2017). *r2glmm: Computes R² for mixed (multilevel) models* [R package]. https://CRAN.R-project.org/package=r2glmm

Janacsek, K., & Nemeth, D. (2012). Predicting the future: From implicit learning to consolidation. *International Journal of Psychophysiology*, *83*(2), 213-221. https://doi.org/10.1016/j.ijpsycho.2011.11.012

Janacsek, K., Shattuck, K. F., Tagarelli, K. M., Lum, J. A., Turkeltaub, P. E., & Ullman, M. T. (2020). Sequence learning in the human brain: A functional neuroanatomical meta-analysis of serial reaction time studies. *NeuroImage*, *207*, 116387. https://doi.org/10.1016/j.neuroimage.2019.116387

Joanisse, M. F. (2007). Phonological deficits and developmental language impairments: Evidence from connectionist models. In S. Sirois, G. Westermann, & D. Mareschal (Eds.), *Neuroconstructivism: Perspectives and prospects* (pp. 205-229). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198529934.003.0009

Joanisse, M. F., & Seidenberg, M. S. (2003). Phonology and syntax in specific language impairment: Evidence from a connectionist model. *Brain and Language*, *86*(1), 40-56.

Johns, M. W. (1991). A new method for measuring daytime sleepiness: The Epworth Sleepiness Scale. *Sleep*, *14*(6), 540-545. https://doi.org/10.1093/sleep/14.6.540

Jones, S. D., & Westermann, G. (2021). Predictive processing and developmental language disorder. *Journal of Speech, Language, and Hearing Research*, *64*(1), 181-185. https://doi.org/10.31234/osf.io/gzk9n

Knowland, V., Gaskell, G., Walker, A. S., Van Rijn, E., Norbury, C., & Henderson, L. M. (2021). Sleep behaviour in children with language disorder. *Language Development Research*, *1*(1), 283-318. https://doi.org/10.34842/fs09-ga12

Lammertink, I., Boersma, P., Wijnen, F., & Rispens, J. (2017). Statistical learning in specific language impairment: A meta-analysis. *Journal of Speech, Language, and Hearing Research*, *60*(12), 3474-3486. https://doi.org/10.1044/2017_JSLHR-L-16-0439

Law, J. M., Vandermosten, M., Ghesquiere, P., & Wouters, J. (2014). The relationship of phonological ability, speech perception, and auditory perception in adults with dyslexia. *Frontiers in Human Neuroscience*, *8*, 482. https://doi.org/10.3389/fnhum.2014.00482

Lenth, R. (2025). *emmeans: Estimated marginal means, aka least-squares means* [R package]. https://CRAN.R-project.org/package=emmeans

Leonard, L. B., Weismer, S. E., Miller, C. A., Francis, D. J., Tomblin, J. B., & Kail, R. V. (2007). Speed of processing, working memory, and language impairment in children. *Journal of Speech, Language, and Hearing Research*, *50*(2), 408-428. https://doi.org/10.1044/1092-4388(2007/029

Lieberman, P., Meskill, R. H., Chatillon, M., & Schupack, H. (1985). Phonetic speech perception deficits in dyslexia. *Journal of Speech, Language, and Hearing Research*, *28*(4), 480-486. https://doi.org/10.1044/jshr.2804.480

Lum, J. A., Conti-Ramsden, G., Morgan, A. T., & Ullman, M. T. (2014). Procedural learning deficits in specific language impairment (SLI): A meta-analysis of serial reaction time task performance. *Cortex*, *51*, 1-10. https://doi.org/10.1016/j.cortex.2013.10.011

Lum, J. A., Ullman, M. T., & Conti-Ramsden, G. (2013). Procedural learning is impaired in dyslexia: Evidence from a meta-analysis of serial reaction time studies. *Research in Developmental Disabilities*, *34*(10), 3460-3476. https://doi.org/10.1016/j.ridd.2013.07.017

Macmillan, N. A., & Creelman, C. D. (2004). *Detection theory: A user's guide.* Psychology Press. https://doi.org/10.4324/9781410611147

Manis, F. R., McBride-Chang, C., Seidenberg, M. S., Keating, P., Doi, L. M., Munson, B., & Petersen, A. (1997). Are speech perception deficits associated with developmental dyslexia? *Journal of Experimental Child Psychology*, *66*(2), 211-235. https://doi.org/10.1006/jecp.1997.2383

Manns, J. R., Hopkins, R. O., Reed, J. M., Kitchener, E. G., & Squire, L. R. (2003). Recognition memory and the human hippocampus. *Neuron*, *37*(1), 171-180. https://doi.org/10.1016/S0896-6273(02)01147-9

McGregor, K. K., & Alper, R. M. (2015). Sleep disorders as a risk to language learning and use. *EBP Briefs*, *10*(1), 1.

McGregor, K. K., Arbisi-Kelm, T., Eden, N., & Oleson, J. (2020). The word learning profile of adults with developmental language disorder. *Autism & Developmental Language Impairments*, *5*, 2396941519899311. https://doi.org/10.1177/2396941519899311

Nemeth, D., Janacsek, K., Londe, Z., Ullman, M. T., Howard, D. V., & Howard Jr, J. H. (2010). Sleep has no critical role in implicit motor sequence learning in young and old adults. *Experimental Brain Research*, *201*(2), 351-358.

Nippold, M. A., Frantz-Kaspar, M. W., & Vigeland, L. M. (2017). Spoken language production in young adults: Examining syntactic complexity. *Journal of Speech, Language, and Hearing Research*, *60*(5), 1339-1347.

Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, *19*(1), 1-32. https://doi.org/10.1016/0010-0285(87)90002-8

O'Bruni, O., Ferri, R., Novelli, L., Finotti, E., Terribili, M., Troianiello, M., Valente, D., Sabatello, U., & Curatolo, P. (2009). Slow EEG amplitude oscillations during NREM sleep and reading disabilities in children with dyslexia. *Developmental Neuropsychology*, *34*(5), 539-551. doi:10.1080/87565640903133418

Pan, S. C., & Rickard, T. C. (2015). Sleep and motor learning: Is there room for consolidation? *Psychological Bulletin*, *141*(4), 812. https://doi.org/10.1037/bul0000009

Qin, Q. Z., Wu, R., & Zhang, C. (2025). Daytime naps consolidate Cantonese tone learning through promoting cross-talker perception: The role of prior knowledge. *Brain and Language*, *265*, 105568. https://doi.org/10.1016/j.bandl.2025.105568

R Core Team. (2021). *R: A language and environment for statistical computing* [Software]. https://www.r-project.org

Ramus, F., Marshall, C. R., Rosen, S., & van der Lely, H. K. (2013). Phonological deficits in specific language impairment and developmental dyslexia: Towards a multidimensional model. *Brain*, *136*(2), 630-645. https://doi.org/10.1093/brain/aws356

Roth, R. M., Isquith, P. K., & Gioia, G. A. (2005). *Behavior Rating Inventory of Executive Function – Adult version (BRIEF-A)*. Psychological Assessment Resources. https://doi.org/10.1037/t86244-000

Schmalz, X., Altoè, G., & Mulatti, C. (2017). Statistical learning and dyslexia: A systematic review. *Annals of Dyslexia*, *67*(2), 147-162. https://doi.org/10.1007/s11881-016-0136-0

Schreiner, T., & Rasch, B. (2017). The beneficial role of memory reactivation for language learning during sleep: A review. *Brain and Language*, *167*, 94-105. https://doi.org/10.1016/j.bandl.2016.02.005

Serniclaes, W., Van Heghe, S., Mousty, P., Carré, R., & Sprenger-Charolles, L. (2004). Allophonic mode of speech perception in dyslexia. *Journal of Experimental Child Psychology*, *87*(4), 336-361. https://doi.org/10.1016/j.jecp.2004.02.001

Shaywitz, S. E., & Shaywitz, B. A. (2005). Dyslexia (specific reading disability). *Biological Psychiatry*, *57*(11), 1301-1309. https://doi.org/10.1016/j.biopsych.2005.01.043

Snowling, M. J. (1981). Phonemic deficits in developmental dyslexia. *Psychological Research*, *43*(2), 219-234.

Solbi, A., & Earle, F. S. (2025). The role of sleep in memory consolidation and reading in dyslexia. *Journal of Cognitive Neuroscience*, *37*(3), 532-542. https://doi.org/10.1162/jocn_a_02282

Stein, J., & Talcott, J. (1999). Impaired neuronal timing in developmental dyslexia – The magnocellular hypothesis. *Dyslexia*, *5*(2), 59-77. https://doi.org/10.1002/(SICI)1099-0909(199906)5:2<59::AID-DYS134>3.0.CO;2-F

Torgesen, J. K., Wagner, R. K., & Rashotte, C. A. (2012). *Test of Word Reading Efficiency-Second Edition (TOWRE-2): Examiner's manual.* Pro-Ed.

Ullman, M. T., & Pullman, M. Y. (2015). A compensatory role for declarative memory in neurodevelopmental disorders. *Neuroscience & Biobehavioral Reviews*, *51*, 205-222. https://doi.org/10.1016/j.neubiorev.2015.01.008

Ullman, M. T., Earle, F. S., Walenski, M., & Janacsek, K. (2020). The neurocognition of developmental disorders of language. *Annual Review of Psychology*, *71*(1), 389-417. https://doi.org/10.1146/annurev-psych-122216-011555

Van Buuren, S., & Groothuis-Oudshoorn, K. (2011). mice: Multivariate imputation by chained equations in R. *Journal of Statistical Software, 45*, 1-67.

Walker, M. P., Brakefield, T., Allan Hobson, J., & Stickgold, R. (2003). Dissociable stages of human memory consolidation and reconsolidation. *Nature*, *425*(6958), 616-620. https://doi.org/10.1038/nature01930

Wechsler, D. (2011). *Wechsler Abbreviated Scale of Intelligence – Second edition (WASI-II).* American Psychological Association. https://doi.org/10.1037/t15171-000

West, G., Vadillo, M. A., Shanks, D. R., & Hulme, C. (2018). The procedural learning deficit hypothesis of language learning disorders: We see some problems. *Developmental Science*, *21*(2), e12552. https://doi.org/10.1111/desc.12552

Williams, L. C., & Earle, F. S. (2022). Overnight consolidation of speech sounds predicts decoding ability in skilled adult readers. *Scientific Studies of Reading*, *26*(1), 79-88. https://doi.org/10.1080/10888438.2021.1904936

Woodcock, R. W. (2011). *Woodcock Reading Mastery Tests* (3rd ed.). Pearson.

Zapparrata, N. M., Brooks, P. J., & Ober, T. (2023). Developmental language disorder is associated with slower processing across domains: A meta-analysis of time-based tasks. *Journal of Speech, Language, and Hearing Research*, *66*(1), 325-346. https://doi.org/10.1044/2022_JSLHR-22-00221

Ziegler, J. C., Pech-Georgel, C., George, F., & Lorenzi, C. (2009). Speech-perception-in-noise deficits in dyslexia. *Developmental Science*, *12*(5), 732-745. https://doi.org/10.1111/j.1467-7687.2009.00817.x

Acknowledgments

Supplemental Table

Correlation Matrix of Learning Measures With Reading and Language Ability

| | | | Declarative Memory | | Procedural Memory | | Speech-Sound Learning | | | |
| | | | | | | | Discrimination | | Identification | |
	Word-Level Reading		Day 1	Day 2	Day 1	Day 2	Day 1	Day 2	Day 1	Day 2
Untimed	Word	Pearson's R	0.16	0.18	-0.21	0.11	0.15	0.24	0.31	0.09
		P-value	0.059	0.038	0.017	0.187	0.088	0.004	<0.001*	0.323
	Nonword	Pearson's R	0.06	0.05	-0.16	0.05	0.01	0.11	0.21	0.05
		P-value	0.513	0.546	0.066	0.547	0.947	0.195	0.015	0.596
Timed	Word	Pearson's R	-0.02	0.02	-0.21	-0.03	-0.02	0.06	0.16	0.08
		P-value	0.857	0.819	0.016	0.747	0.859	0.499	0.065	0.357
	Nonword	Pearson's R	0.23	0.26	-0.17	-0.01	0.12	0.22	0.34	0.19
		P-value	0.007	0.003	0.046	0.913	0.163	0.009	<0.001*	0.026
	Spelling									
		Pearson's R	0.10	0.08	-0.26	0.07	0.17	0.28	0.27	0.14
		P-value	0.272	0.372	0.002	0.423	0.043	0.001	0.001	0.113
	Language Processing									
Spoken	Modified Token Task	Pearson's R	0.14	0.22	-0.19	0.25	0.27	0.20	0.32	0.15
		P-value	0.113	0.012	0.030	0.003	0.001	0.022	<0.001*	0.084
Written	Passage Comprehension	Pearson's R	0.17	0.08	-0.10	0.20	0.13	0.13	0.19	0.03
		P-value	0.045	0.385	0.266	0.020	0.127	0.124	0.031	0.694

S1 presents the matrix of Pearson's *R* and *p*-values across experimental measures and cognitive, reading, and language measures. Word-level reading was assessed with the Word Identification and Word Attack subtests of the WRMT-III (untimed; Woodcock, 2011) and the Sight Word Efficiency and Phonemic Decoding subtests of the TOWRE-2 (timed; Torgesen et al., 2012). The spelling and modified token task were taken from Fidler et al. (2011). Passage comprehension was measured using the passage comprehension subtest of the WRMT-III (Woodcock, 2011).

*Statistical significance at .05 level following Holms-Bonferroni adjustments for multiple correlations.