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Implicit Learning in Preschool Children with and without Developmental Language Disorder

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Implicit Learning in Preschool Children with and without Developmental Language Disorder

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Abstract

The study below was designed to compare implicit learning in fifty-two preschool-aged children with and without developmental language disorder (DLD) to test the Procedural Deficit Hypothesis (PDH). The PDH claims that procedural memory, the basis of implicit learning, is the main impairment in DLD. Using a computer-based program to conduct sound-meaning-mapping tasks, we asked children to select one of two images according to the corresponding sound they heard. After all the participants were tested, an additional cue was found in the experiment that impacted the data. Instead of the children attuning to the sounds to depict the correct answer, the children picked up on an unintended visual cue: the target image tended to alternate from one side to another. Both children with DLD and TLD showed implicit learning of the visual alternation, in contradiction to the PDH. We relate these findings to the debate over the PDH and alternative hypotheses regarding the etiology of DLD.

CHAPTER 1: Introduction

1.1 Developmental Language Disorder

The purpose of this study was to test implicit learning in preschool-age children with and without developmental language disorder (DLD). The experiment included fifty-two age-matched participants (4-5 years), half with typical language development (TLD) and half with DLD. The children were monolingual English speakers. The experimental design intended to test implicit learning through sound-meaning-mapping activities delivered through a computer program. However, after the experiment was completed, an additional visual cue was discovered that strongly impacted the data. Children still showed implicit learning, just through the visual cue v. the intended sound cue.

According to Bishop et al. (2017), developmental language disorder is defined by difficulty producing and/or understanding language that impacts a child's daily life, where a prognosis is poor, and the language disorder is not associated with an underlying bio-medical condition. DLD is specifically associated with impairments related to: syntax, morphology, semantics, word-finding, pragmatics, discourse, verbal learning, and memory (Bishop et al., 2017). DLD had been previously termed specific language impairment (SLI). According to Bishop et al. (2017), using the term SLI for this language disorder has been problematic due to how SLI is described to present itself in a patient and does not consider co-occurring symptoms that may hide or muffle characteristics of DLD. This inherently excludes patients from accessing certain services for speech therapy due to the limited description of SLI and how it may present itself differently in a patient, for example: Co-occurring disorders in children such as attention hyperactivity disorder (ADHD) or Autism may impact how DLD presents itself in the client. Due to this difference in presentation, the language disorder may not be obvious and could be misdiagnosed or mistreated (Bishop et al., 2017). The term SLI itself also excluded a lot of patients from receiving treatment and brought limitations to research around this language disorder (Bishop et al., 2017). Since DLD presented itself differently in clients, especially clients with co-occurring conditions, the limited set of descriptors for SLI excluded a lot of clients who did in fact have DLD and did not get diagnosed, treated, or included in research. It was recently decided by a panel of experts to redefine the disorder as developmental language disorder, DLD (Bishop et al., 2017).

1.2 Defining the Procedural Deficit Hypothesis

Some studies have tested implicit learning and children with DLD. These studies can speak to the procedural deficit hypothesis (PDH), which posits that abnormalities in brain structure associated with procedural memory, the basis of implicit learning, is the core impairment in SLI [DLD] (Ullman et al., 2005; Lum et al., 2011). Procedural memory is an unconscious "learning and retrieval of [long-term] information" (Lum et al., 2013). Lum et al (2011) also posited that declarative memory in individuals with SLI [DLD] remained intact. Evans et al. (2009) conducted a study testing the PDH where two groups of children with and without SLI [DLD] would listen to a recorded stream of speech derived from 12 syllables combined to make 6 different words for a period of 21 minutes. The speech stream played in the background while the children were tasked to draw while listening. The sequence of syllables contained higher transitional probability within words than between words, and the experimental question was whether the children would implicitly use transitional probabilities to find word forms (Evans et al, 2009). Transitional probabilities are: "probability statistic[s] that measure the predictiveness of adjacent element[s]" (Thompson & Newport, 2007)--in this case, syllables. So, they were looking to see how well the children were able to predict which syllable would come next. This process is referred to as adjacent sound anticipation. They were then asked to make a choice between two words that most reflected the sounds they heard during the 21-minute familiarization. Evans et al. (2009) find there is a difference between implicit learning of adjacent sound anticipation in children with SLI [DLD] and in children without SLI [DLD]. The group with SLI [DLD] showed poorer attention to the transitional probabilities to find word forms in speech. The mean score averaged across word and tone conditions for finding word forms through transitional probability in children with SLI [DLD] (measured via the word-choice task) was 52% (at chance) and the mean for TLD children was 58% (above chance; Evans et al., 2009). The group with SLI [DLD] showed above chance performance in the speech condition but was at chance in the tone-condition (Evans et al., 2009). The authors argued the inconsistent results from the group with SLI show a possible impairment in implicit learning when using transitional probabilities to find word boundaries (Evans et al. 2009).

Lum et al. (2012) conducted another study which showed evidence of declarative memory remaining intact in children with DLD, but of working memory being affected by the same brain structures as procedural memory, which exhibit neurodivergence in DLD: “frontal [lobe]/basal-ganglia circuits” (Ullman et al., 2005). A later meta-analysis authored by Lum et al. (2013) reviews how the PDH was first defined (Ullman et al., 2005) and how procedural memory and implicit learning has been tested throughout different studies. Lum et al. (2013) states that a “consensus is yet to be reached whether declarative and procedural memory systems are impaired in SLI”. Despite a lack of consensus, Lum et al. (2013) does have some hypotheses as to why declarative memory might be coming up as an impairment in DLD in certain studies. Participants in some studies described in Lum et al. (2013)’s meta-analysis showed an impairment in declarative memory in the speech condition. These studies tested declarative memory in participants with and without DLD by using assessments that tasked participants to recall words from a list that is repeated to them a certain amount of times (Lum et al. 2013). The participants with DLD showed lower performance in recall of words from the word lists than participants without language impairment, thus strongly suggesting a possible impairment of declarative memory in DLD: “[These studies testing declarative memory] suggest that children with SLI learn fewer pieces of verbal information than non-language impaired children of the same age. These findings might indicate impairments related to the learning mechanisms of the declarative memory system in SLI" (Lum et al. 2013). However, Lum et al. (2013) suggests that this is due to the effects of working memory which relies on the same brain structures as procedural memory and also supports access to and use of the declarative system. It is also suggested that the level of impairment in participants with DLD may contribute to the inconsistent results for declarative memory performance in conflicting studies described in Lum et al. (2013)'s meta-analysis. However, this is a hypothesis and may require more research.

Gómez & Edgin (2015) claim that procedural memory along with other memory systems have "distinct roles for substructures within these [memory] systems" (Gómez & Edgin, 2015). This could mean that certain substructures within these memory systems could be tapped by other forms of stimuli. According to Hitch et al. (2020), there are different parts of attentional processes in working memory. Since procedural memory does not have a designated assessment to reliably test for it in participants (West, 2017) and research is still being done to understand procedural memory more comprehensively, it is not always clear whether different assessments designed to tap procedural memory are actually tapping the same neural substrates. This may have an impact on results as there are now other potential memory systems possibly contributing to DLD in children described in some studies (Lum et al., 2013; , not just procedural memory (Lum et al., 2011, 2012). Lum et al. (2015)'s results support the argument from Lum et al. (2013): "The study demonstrates that verbal declarative memory deficits in SLI only occur when verbal working memory is impaired. Thus SLI declarative memory is largely intact and deficits are likely to be related to working memory impairments" (Lum et al., 2015).

1.3 Procedural Memory and Visual Implicit Learning

When the PDH has been tested in previous studies, the common cues used to test implicit learning in children with DLD were often auditory (Quam et al. 2021; Evans et al. 2009; Yu, 2020). One could question whether it is appropriate to use visual cues to test implicit learning in children with DLD, that visual cues do not elicit the type of procedural memory that drives language learning. It is important to note that the original PDH was formed and published in Ullman et al. (2005)'s study and tested again in Lum et al. (2011 & 2012)'s studies which tested procedural memory using a visuo-spatial serial reaction time test for implicit learning in visual and visuospatial domains (Ullman et. al., 2005; Lum et al., 2011, 2012). The assessment was a computer-based experiment which tasked children to press one of four buttons that were each associated with the location of a visual stimulant on the computer screen (Lum et al., 2012).

Lammertink et al. (2020) tests literacy skills in children with DLD using visual-statistical learning (VSL). Visual-statistical learning tests the child's ability to identify and learn sentence, sound, and word regularities in language (Lammertink et al., 2020). According to Lammertink et al. (2020), it is possible that "children with DLD are worse in detecting statistical regularities in linguistic materials than their typically developing peers, not because they are less sensitive to the statistical regularities, but because they have less expectations of the underlying structure due to their language deficit". Lammertink et al. (2020) go on to say that a study by Siegelman et al. published in 2018 (cited in Lammertink et al., 2020),found an impairment in visual-statistical learning in children with DLD. In fact, individuals with TLD have shown a higher performance than individuals with DLD, suggesting that individuals with DLD may show an impairment in finding and learning regular patterns from different language domains (Lammertink et al. 2020). Null results showed that there was no evidence that supported or contradicted the hypothesis that a VSL deficit in DLD had an effect on literacy skills (Lammertink et al. 2020). Lammertink et al. (2020)'s study also mentioned that though there was no obvious contrast between children with DLD and children with TLD, there is a possibility that the difference was small enough to not show up in the data analysis. The null results may suggest that further investigation may be necessary in this area.

West et al. (2017) conducted a study that addressed the reliability of the PDH by investigating the relationship between implicit/explicit learning and language, arithmetic attainment, and literacy in children. Results showed that explicit learning was correlated with attainment measures in the verbal-category. However, "no relationships between measures of implicit learning and attainment were found" (West et al., 2017). The author argues that since there is no reliable assessment for procedural memory, there is no ground to claim that "procedural learning deficits have any causal relationship with language learning disorders" (West et al., 2017). They also go on to point out that results from many studies are inconsistent and unreliable with small sample sizes, limited testing measures, and a small number of trials (West et al. 2017); further suggesting that the PDH (Ullman et al., 2005; Lum et al. 2011, 2012) may be problematic (West et al., 2017). Another (in progress) study from our own lab, described by Yu (2020), used both auditory and visual cues to test the procedural deficit hypothesis with preschool-age children with and without developmental language disorder. The study found that the one child with DLD showed higher accuracy scores for visual implicit learning than the children with TLD. Since there was only one participant with DLD due to restrictions with Covid-19, further testing is needed to continue this investigation (Yu, 2020).

Given these findings, despite the open question of whether other memory systems are involved in implicit learning or its impairment in DLD (Evans et al. 2009; Lammertink et al., 2020; Lum et al., 2013; Yu, 2020), there are questions as to whether the PDH has enough ground to claim that procedural memory is the main impairment in DLD (West, et al., 2017).

1.4 Current Study

Due to the restrictions of Covid-19, we were unable to test participants for a new study, so a previously collected set of data was analyzed differently to investigate an unforeseen observation/finding. The study involved testing implicit learning in 52 preschool-age children with and without DLD. This study was intended to test the PDH which posits that procedural memory, the basis of implicit learning, is the main impairment in DLD. The computer-based experiment was designed to test implicit learning through a sound-meaning-mapping task that used sound cues varied by pitch and duration. The sound cues were assigned to two different visual target items and the child would be asked to push one of two buttons that was associated with every sound. After gathering the data from each participant, an additional cue was discovered that impacted the results. There was a visual cue that presented a repeated pattern that the children were more attentive to than the sound cues. The "correct" visual target on the screen tended to flip from right to left instead of being more randomized. This thesis evaluates the sensitivity to both the sound and visual cues.

CHAPTER 2: Methods

2.1 Participants

The children who were involved in this study also participated in a separate experiment, an explicit sound-meaning-mapping task that was previously published by Quam, Cardinal, Gallegos, and Bodner (2021). The explicit-learning tasks mapping sounds to meanings are documented there (Quam et al., 2021). The test of implicit mapping of sounds to objects is reported here in addition to the participant information from the previous study with permission from the first author Carolyn Quam. Fifty-two children ages 4-5 years old were included in the study. Half of the participants were in the group with TLD and the other half in the group with DLD. Children were required to hear English in the home at least 70% of the time. This criterion is used in other studies involving monolingual children (Quam, & Swingley, 2014; Quam, Knight, & Gerken, 2017). To justify the use of a 70% English exposure criterion to be considered a monolingual speaker, we conducted an informal review of criteria reported in the literature. There are several studies testing monolingual participants that don't explicitly state the English exposure criterion they used (i.e., Werker et al., 1981; Werker & Tees, 1984; Polka & Werker, 1994; Shi & Werker, 2001; Kuhl et al., 2006; Kuhl et al., 2008; Kuhl et al., 2014; Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Gerken et al., 2015; Gerken & Quam, 2017). Other studies have used a minimum threshold as low as 67% exposure to English to be considered monolingual (Quam & Swingley, 2010). Some studies even share the same 70% minimum exposure threshold (Quam & Swingley, 2014; Quam, Knight, & Gerken, 2017), as well as 75% (Maye, Werker, & Gerken, 2002), 80% (Yeung & Werker, 2009; Yeung, Chen, & Werker, 2014; Fennell & Werker, 2003; Bosch & Sebastián-Gallés, 2003), and 90% (Sundara & Mateu, 2018;

Sundara et al., 2018; Narayan, Beddor, & Werker, 2010; Singh et al., 2018; Danielson et al., 2017; Dietrich, Swingley, & Werker, 2007; and Bruderer et al., 2015). There are also bilingual studies that use a minimum of 30% exposure of both L1 and L2 used in the home (i.e., Fennell, Byers-Heinlein, & Werker, 2007; Byers-Heinlein, Burns, & Werker, 2010; Hoff, Core, Place, Rumiche, Señor, & Parra, 2012). Given this, we've concluded that the 70% English exposure for monolingual speakers is considered a lower bound threshold for a monolingual inclusion criterion.

Participants were tested through summer language intervention camps and in home and laboratory environments in the Tucson area. Efforts were made to maintain SES-balanced groups; however, the group with TLD was significantly higher in maternal education than the group with DLD (See Table 1 for participant demographics; reprinted with permission from Quam, Cardinal, Gallegos, and Bodner (2021). We age-matched participants in the group with TLD to the group with DLD within 6 months of age. The inclusion criteria match the criteria used in Quam et al. (2021; as the same participants are included in both studies). All participants passed a hearing screening in both ears at 1,000, 2,000, and 4,000 Hz at a level of 20 dB. The children were required to receive a minimum score of 75 on the Kaufman Assessment Battery for Children (KABC-II) non-verbal subtest to make sure that the participants were at a typical cognitive level of development (Kaufman & Kaufman, 2004). Other experiments in this area testing for DLD (using the previous term SLI) have used a score of 75 on the KABC-II (e.g., Dailey, Plante, & Vance, 2013), though it is important to note that some studies involving SLI use a stricter criterion. To consider a participant to be included in the group with DLD, a score on the Structured Photographic Expressive Language Test--Preschool: 2nd Edition (SPELT-P2;

Dawson et al., 2005) must be lower than 87, which was a criterion established in the Tucson area (Greenslade, Plante, & Vance, 2009). The group with TLD was required to have a SPELT score that met or exceeded 87.

Table. 1 Demographic information and standardized test scores for preschoolers with and without DLD. Reprinted with permission from Quam et al. (2021).

Variable	**DLD (N = 26)**			**TLD (N = 26)**			
Race (Ns)							
Caucasian, White	15			20			
African American, Black	3			2			
Hawaiian, Pacific Islander	0			1			
American Indian, Native American, Alaska Native	0			1			
Asian American	0			1			
Multiple Races	4			1			
Unspecified	4			0			
Ethnicity (Ns)							
Hispanic	10			10			
Non-Hispanic	14			15			
Unspecified	2			1			
Gender (Ns)							
M	19			19			
F	7			7			
	Mean	***SD***	***Range***	***Mean***	***SD***	***Range***	***T-test***
Age (years; months)	4;11	4 mo.	4;2-5;7	4;9	4 mo.	4;0-5;10	t(50) = 1.40, *p* = .17
Mother's education level (years)	14.38	2.04	11-18	16.00	1.90	12-18	t(50) = 2.96, *p* = .005
KABC-II[a]	101.23	14.37	79-130	111.88	9.38	87-130	t(50) = 3.17, *p* = .003
PPVT-4[a]	96.92	12.98	72-118	113.81	12.58	86-132	t(50) = 4.76, *p* < .001
SPELT-P2[a]	73.27	10.05	41-86	112.54	8.16	100-132	t(50) = 15.47, *p* < .001

Note. KABC-II = Kaufman Assessment Battery for Children – Second Edition; PPVT-4 = Peabody Picture Vocabulary Test, Fourth Edition; SPELT-P2 = Structured Photographic Expressive Language Test—Preschool: 2nd Edition. [a]Standard scores with a mean of 100 and a standard deviation of 15. If a child's SPELT-P2 score fell below the cutoff of 87, we verified that this was still the case even when potentially articulation-based errors were counted as correct. (The Goldman-Fristoe Test of Articulation, 2nd Edition, was administered in cases of articulation concern.)

Participants were excluded from the study if they had any potential or predetermined speech, cognitive, or sensory impairments. Participants who showed signs of attention deficit (hyperactivity) disorder but who were not diagnosed were only exempted from the study if the tasks could not be finished. The research speech-language pathologist suspected that two participants in the group with TLD did not show typical language development, and so excluded these participants from the study. This was due to their SPELT-P2 scores being borderline passing, in addition to evidence of language impairment in their language samples. Due to technical complications with the PsychoPy program, experimental data were lost for two children with TLD, so these children were excluded from the study. If there were reports or concerns of any possible articulation difficulties by a teacher, parent, laboratory staff, or school speech pathologist, the Goldman-Fristoe Test of Articulation-- 2nd Edition (GFTA-2; Gokman & Fristoe, 2000) was administered. Children with DLD who completed the GFTA-2 (n=17) had standard scores varying from 50 to 105. For children with TLD who completed the GFTA-2 (n=3) the standard scores were from 75 to 101. The SPELT-P2 score was confirmed to still be below 87 for children in the group with DLD, and at or above 87 for the children in the group with TLD, when any possible articulation errors were counted as correct. As anticipated, the groups with DLD and TLD had notably different scores on the SPELT-P2. They also differed on the PPVT-4 and KABC-II.

2.2 Stimuli

We used the KlattGrid speech synthesizer (Klatt & Klatt, 1990; Weenink, 2009) in the Praat program (Boersma & Weenick, 2008) to synthesize isolated vowel sounds. Synthesized sounds were used to control acoustic parameters for establishing a predictable sound-category structure. All pitch-differentiated sounds were 0.6 seconds in duration and had an average intensity of 70 decibels (dB). Duration-differentiated sounds were also 0.6 seconds in duration, on average (but varied). Pitch was decreased by 75% at the tail end of each sound to make the stimuli more naturalistic and less robotic sounding. Matlab was utilized to amplitude ramp the last 10 milliseconds of each sound file so the sound file didn't stop suddenly at the end.

The sound categories varied by pitch or duration. Two dimensions were used to define the two sound categories: short duration v. long duration, or low pitch v. high pitch. The categories each contained three distinct sounds, equating to six sounds for the pitch-category and six sounds for the duration-category. (See Figure 1.) The Bark Scale was used to evenly space out stimuli for pitch (Zwicker, 1961). Trial tests demonstrated that participants had a higher sensitivity to pitch than duration. Due to this, differences in duration stimuli were compressed within-category and the distance between categories was heightened. A simulation of an /u/ vowel was set for the second-formant frequency for pitch-distinguished sounds (8.9 Barks, or 1254 Hertz). An /i/ vowel was mimicked for the duration-distinguished sounds (13.9 Barks, or 2988 Hertz). The first, third, fourth, and fifth formant frequencies were calibrated to 448, 2722, 4019, and 4898 Hertz for all sounds (4.1, 13.3, 15.6, and 16.8 Barks).

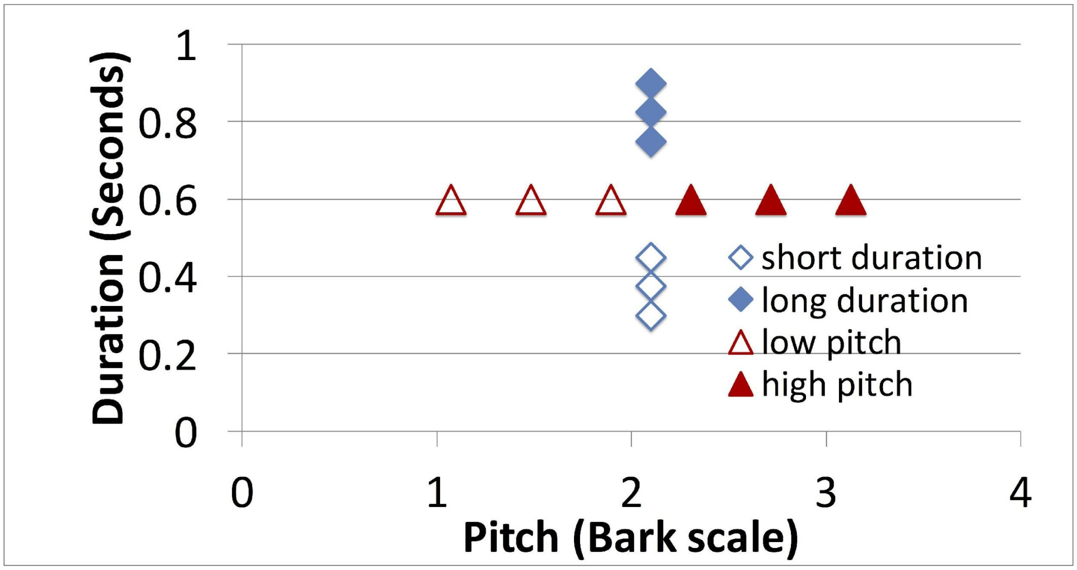

Figure. 1 Sound categories. Reprinted with permission from Quam et al. (2021).

2. 3 Apparatus and Procedure

The PsychoPy program (Pierce, 2007) was used on a Mac Mini computer with a connected Dell monitor, Apple mouse, Apple keyboard, and KidzGear headphones to conduct the experiments. The children started with a sound-discrimination task of duration and pitch. The participants were to then complete separate computer-based tasks created to simulate implicit or explicit learning of the matching of sounds to objects.

2.4 Sound-Discrimination task

Participants began with a sound discrimination test at the beginning of each session of the experiment. This was done to establish the minimum sensitivity to either duration or pitch of the participants. All participants were tested on sound discrimination of both pitch and duration, before both the implicit and explicit sound-meaning-mapping tasks which is reported in a previous study (Quam, Cardinal, Gallegos, & Bodner 2021). About half of the participants in the groups with DLD and TLD were involved in a previous explicit-learning experiment which is reported in the previous study (Quam, Cardinal, Gallegos, & Bodner 2021).

There were 12 trials in the sound discrimination task. Each trial contained a pair of sounds taken from a continuum of 6 sounds (varied by either duration or pitch). Figure 1 shows the spectrum of the 6 sounds for both pitch and duration. Of the two sounds, one was an end-point sound from the continuum (Figure 1). The second sound was either the same sound or was acoustically different by a distance of 1-5 notches on the continuum. Two trials were conducted for each pair (ie. 1-5 notches apart or undifferentiated). Children heard 2 sounds in each trial, each sound played 1 second from the other. The children were tasked to first listen to the sounds and then state whether those sounds were the same or different. There were 6 different trial orders used, and each participant was given a different trial order for duration v. pitch.

The sound discrimination task required the participants to decipher whether there was a distinction between two sounds. They would indicate their response by saying either "same" or "different" based on their perception of any possible differences. To determine the sensitivity to sound differences, the responses were adapted into D' scores (see Quam et al., 2021, for the conversion process). There were two relationships that we were interested in: (1) How did the likelihood of responding "different" differ between the groups with TLD and DLD or between pitch and duration cues? (2) Did the participant's sensitivity to acoustic differences increase as the space between two sounds increased?

2. 5 Implicit sound-meaning-mapping task

Participants took part in an implicit sound-meaning-mapping task following the sound discrimination task (for either duration or pitch). The same six sounds from the discrimination task were used in the implicit task to map the sounds to certain objects. Fifty percent of participants from both groups with DLD and TLD were tasked with mapping pitch-differentiated sounds to objects while the other half of both groups were instead tasked with mapping duration-differentiated sounds to objects. Participants were tested this way to counterbalance the order in which the tasks were done (implicit v. explicit tasks) and how they were paired with cues (pitch v. duration).

The design purpose for the implicit sound-meaning-mapping task was to support children's attending to sounds and their ability to decipher implicitly their connections to objects. There were a number of conditions employed to elicit implicit learning (See Table. 2 for comparison between the implicit and explicit side of this study).

Table. 2: Comparison of the explicit and implicit experimental designs of the study (Adapted from Yu, 2020 & Quam et al., 2021 with permission from Dr. Carolyn Quam, PhD).

Study	Quam et al. (2021)	Quam et al. (In Prep.)
Implicit/Explicit	Explicit	Implicit
Stimuli	Sound categories	Sound categories
Instructions	Children are told the monster wants them to learn the sounds for her toys"	Children are told to give the monster his food or drink as fast as they can

Length of training	Training phase contains 24 trials before evaluation of performance	Training phase contains 48 trials
Children's responses	Children's responses are direct interpretations of sounds	Children are not required to interpret sounds, as they can wait and respond based on the object that appears on the screen
Contingency/Feedback	Feedback is contingent on the child's response	No feedback is provided

Firstly, the experimenters oriented the children to the procedure of the computer-based task. During the training phase of the experiment, the children were introduced to a monster named "Leonard" who appeared in the middle of the screen. They were informed of how Leonard used certain sounds to communicate what he wanted. Then the experimenter showed them Leonard's favorite food and drink which showed up on both sides of Leonard on the screen (drink on the left and food on the right). (See Figure 2.) The children were told that Leonard had a "special sound" for his food and his drink. The keyboard in front of them had two buttons with images velcroed to the left and right arrow keys matching the food and drink image on the screen (left arrow key for drink and right arrow key for food). Then the participants were informed that Leonard would use the sounds when he wanted his favorite food or his favorite drink. The experimenter explained how the images velcroed to the buttons on the keyboard were the same as the images on the screen. As a part of the orientation phase, rather than listening to Leonard's sounds, children heard the experimenter say "[Leonard] is hungry for more food! What [button] do you press?" and "[Leonard] is thirsty! What [button] do you press?". This was done to allow the children to practice pressing the arrow buttons on the keyboard to match the images of

Leonard's food and drink they saw on the monitor. It was important for the experimenter to make sure that the children understood how to press the correct button to match the correct image before proceeding to the training phase.

Figure 2. Leonard with his favorite drink (left side) and his favorite food (right side).

As a part of the training phase of the experiment (see Figure 3), the children were instructed that once they saw the drink or the food "magically appear" on the screen, to press the button that matched the image "as fast as [they] can" to give the item to Leonard. In the training phase, a sound would play and the child would choose whether Leonard was hungry or thirsty. The training phase of this experiment was comprised of 2 blocks of 24 trials (48 total trials) which were designed so that the sound would play and then the image would magically slide in from the left or the right side depending on which sound played–regardless of whether the child pressed the correct button or not (or pressed the button at all). There was no explicit instruction given as to which sound-category (long duration v. short duration or high pitch v. low pitch) went with which target image (food or drink). The appearance of the object after the sound served as a highly implicit or indirect form of feedback for the training phase of the experiment. Again, this feedback was not contingent on the child's response. There was no explicit feedback given to any of the children's answers.

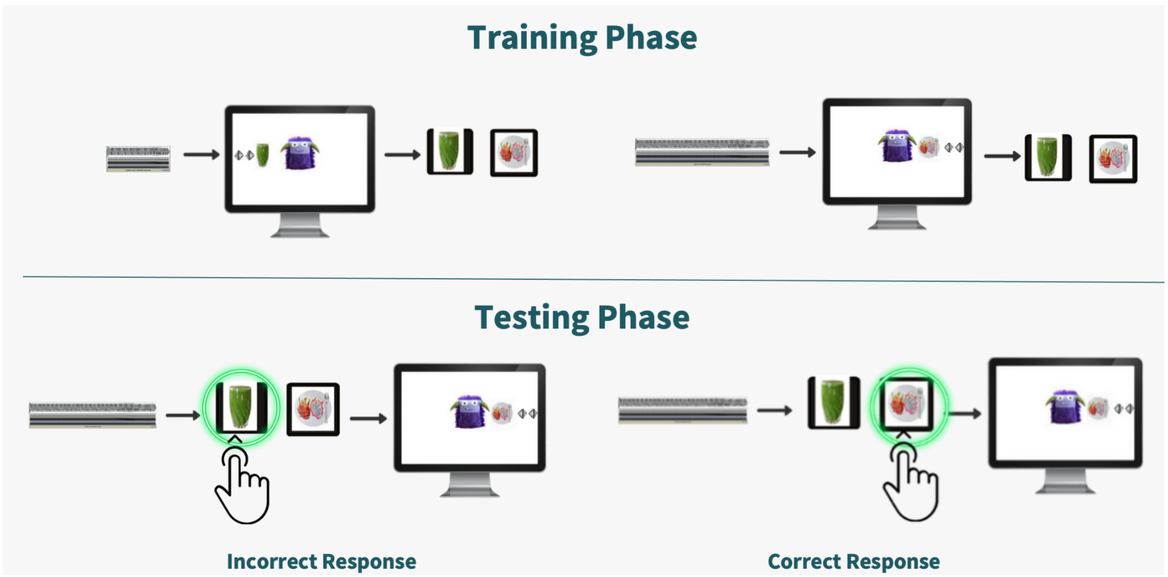

Figure 3. Training & Testing Phase Example: The training phase shows the drink "magically appearing" from the left side of the screen after a short-duration sound is made and the food "magically appearing" from the right side of the screen when a long-duration sound is made. The testing phase shows what an incorrect selection would look like (on the left side) where the drink is being selected for a long-duration sound instead of a short-duration sound and a correct selection (shown on the right side) where the food is selected for the long-duration sound.

The testing phase (Figure 3) included 1 block of 24 trials. The trials were similar to the training phase. However, the biggest difference was that the image only appeared after the child pressed the button. Once the child selected their response to the sound, the correct corresponding image would "magically" appear from the right for food (long duration or high pitch) or from the left for drink (short duration or low pitch) despite whether the child's answer was correct or not. The responses of the participants were determined based on the correctness of the answer for each sound, one object was associated with 3 short-duration and low-pitch sounds, and the other object corresponded to 3 long-duration and high-pitch sounds. The proportion of correct answers was calculated for the test block for each participant. The successfulness of the participants' sound-meaning-mapping skills were based on these accuracy scores. After the experiment was completed, each child was given a production task. The experimenter would ask each child, "Now, can you tell me what sound Leonard makes when he wants his food/drink?" This was done just to further depict whether the child showed learning of the sounds.

2.6 Statistical design

All of the discrimination data in the methods and results section are identical to the previously published explicit counterpart of this study and have been recorded there (Quam et al. 2021). As in Quam et al. (2021), multivariate (MANOVA) approach was utilized instead of an univariate analysis of variance (ANOVA) in order for inferential statistics on two sets of data (sound-meaning-mapping and discrimination data) to be conducted. The test statistic that was run for this experiment was the Wilks' lambda (K) due to its relevant history in randomized trials (Bodner, 2018). Quam et al. (2021) ran inferential statistics on scores for sound-discrimination; readers can refer to that paper for more details. The use of MANOVAs over ANOVAs is explained in the published explicit study (Quam et al. 2021). Bonferroni corrections were utilized for numerous t-tests following the original MANOVAs; this was done to reduce the risk of Type I error introduced by multiple comparisons being conducted.

CHAPTER 3: Results

The first MANOVA was intended to code the data so that the correct response aligned with the sound cues like the original experimental design intended. By doing this, we would then be able to determine whether the participants were following the sound cues to depict the correct answer or if they were relying on the alternation pattern. The MANOVA was used to measure the effect of the within-subject factor Alternation Type (alternating trial vs. repeating trial) and between-subject factors Group (DLD vs. TLD), Cue (pitch vs. duration), and First-Administered Task (explicit first vs. implicit first). Results showed a significant main effect of Alternation Type, $F(1,44) = 106.41$, $p < .001$, revealing that the Alternating Trial produced higher scores than scores from the Repeating Trial. After this discovery, we wanted to evaluate any possible interaction between Alternation Type and relevant between-subject factors. The MANOVA showed a significant four-way interaction between Alternation Type, Group, Cue, and First-Administered Task, $F(1,44) = 12.42$, $p = .001$, however, a greater quantity of participants (statistical power) would be required to meaningfully analyze this four-way interaction (subgroups in the interaction ranged from n = 4 to n = 9). Results conveyed a significant three-way interaction between Alternation Type, Group, and Cue, $F(1,44) = 4.93$, $p = .032$. To investigate the 3-way interaction of Alternation Type, Group, and Cue, paired *t* tests were conducted to analyze the accuracy differences between Alternating and Repeating Trails for four subgroups (DLD-duration, DLD-pitch, TLD-duration, TLD-pitch). Using the Bonferroni method, we divided the *p*-value threshold ($p = .05$) by a dividend of four ($p = .0125$) to detect significance of the 4 subgroups that were tested. The paired t-tests conveyed a significant preference for alternating over repeating trials for all four subgroups: DLD-duration (repeating trials mean = 30.91%, *SD* = 20.69%, alternating trials mean = 61.99%, *SD* = 18.12%), paired $t(12) = 3.69$, $p = .003$; DLD-pitch (repeating trials mean = 37.01%, *SD* = 18.89%, alternating trials mean = 67.91%, *SD* = 19.22), paired $t(12) = 4.90$, $p < .001$; TLD-duration (repeating trials mean = 34.13%, *SD* = 14.82%, alternating trials mean = 64.59%, *SD* = 15.3%), paired $t(12) = 4.47$, $p < .001$; and TLD-pitch (repeating trials mean = 26.72%, *SD* = 17.67%, alternating trials mean = 76.2%, *SD* = 19.12%), paired $t(12) = 6.71$, $p < .001$. The significant interaction seems to be driven by the stronger alternation effect for the TLD children learning pitch categories (See Figure. 4). The mean difference between repeating and alternating trials for the TLD-pitch subgroup was 49.47%, in contrast to the other three subgroups which had a mean difference of about 30%.

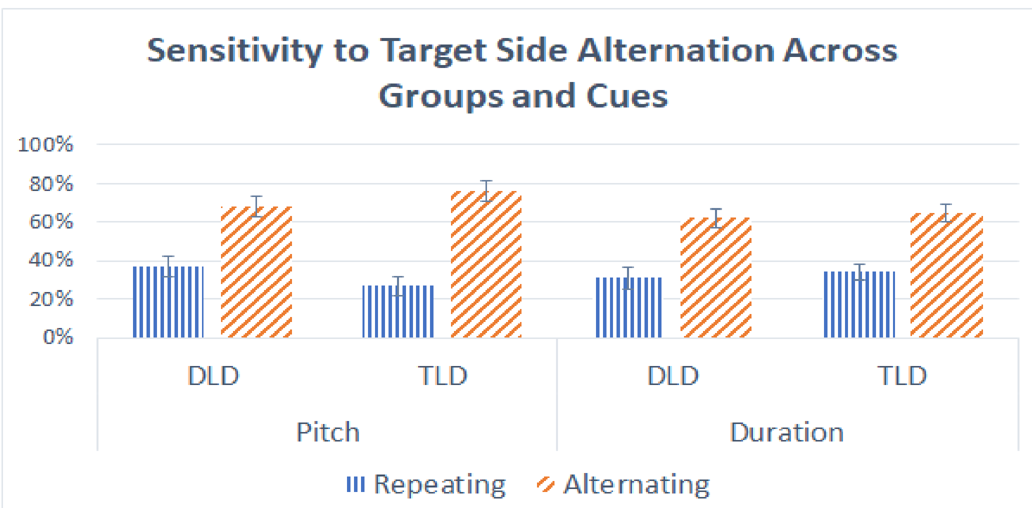

Figure 4. Sensitivity to target-side alternation across groups and cues.

A second MANOVA with the same data was coded differently to determine whether the participants were paying any attention to the sound cues above and beyond attention to the alternation pattern. The MANOVA was recoded so that the "correct" response was alternating back and forth from the previous trial. This means that if the last trial response was a right target, then the next "correct" response would be a left target. Our goal for making the alternation pattern the primary target in this MANOVA was to be able to investigate whether children showed any additive sensitivity to the sound cues. The within-subject factor was set to Sound Convergence (sound conflicts v. converges with the alternation pattern) and the between-subject factors Group (DLD v. TLD), Cue (pitch v. duration), and First-Administered Task (explicit first v. implicit first).

Within-subject results did not meet the threshold for statistical significance. This suggests that while the children may not have ignored the sounds entirely, the alternation pattern cue was more influential/distracting than the sound cues. Results showed a significant 3-way interaction between Cue, Group, and First-Administered Task, $F(1,44) = 12.418$, $p = .001$. Due to limited statistical power in this experiment (again, subgroups ranged from n = 4 to n=9), the 3-way interaction cannot be meaningfully investigated at this time. The between-subject results showed no statistical significance for Cue, $F(1,44) = 3.72$, $p = .06$, despite the trend for higher pitch accuracy ($M = 70.95$, $SD = 13.69$) than duration ($M = 64.42$, $SD = 13.72$). However, there was a significant interaction between Cue and Group, $F(1,44) = 4.93$, $p = .032$.

To investigate the interaction, we conducted two unpaired *t*-tests to compare sensitivity to pitch v. duration within the TLD and DLD groups separately. The unpaired t-tests would show whether either group (TLD or DLD) was more sensitive to the alternation pattern when they were learning pitch cues v. duration cues. Using the Bonferroni method, we divided the *p*-value threshold ($p = .05$) by a dividend of two ($p = .025$) to correct for the conduction of two tests.

First we interpreted whether the sensitivity to the alternation pattern heightened when children with DLD were learning the pitch cue v. the duration cue. For children with DLD, there was no difference in attention to the alternation pattern that was shown in pitch (Mean = 66.47%, *SD* = 12.42) v. duration (Mean = 64.22%, *SD* = 15.17), unpaired $t(24) = .415$, two-sided $p = .682$. The group with TLD also did not show a significant difference for attention to the alternation pattern in pitch (Mean = 75.42%, *SD* = 13.9) v. duration (Mean = 64.62%, *SD* = 12.72), $t(24) = 2.068$, two-sided $p = .05$. However, the significant interaction appears to have been driven by the greater magnitude of advantage for pitch over duration in the group with TLD (mean difference, 10.80%) than in the group with DLD (mean difference, 2.25%). This means that the group with TLD appears to have been somewhat sensitive to the sounds, in the sense that hearing pitch-differentiated sounds seemed to boost their attention to the alternation cue.

CHAPTER 4: Discussion

This study was investigating the procedural deficit hypothesis (PDH), which states that procedural memory, the basis of implicit learning, is the core impairment in DLD (Ullman et al., 2005). This investigation tested implicit learning in preschool children with and without developmental language disorder. We originally hypothesized that children with DLD would not show learning of implicit categories and children with TLD would, supporting the PDH. The results from the study show that the participants with TLD and DLD produced higher scores by following the alternation pattern. Our hypothesis was correct about the group with TLD, however, the children in the group with DLD still attuned to the visual alternation pattern despite–as for children with TLD–showing less attention to the sound cues. Figure 4 shows how both groups with TLD and DLD showed a higher attention to the alternation pattern v. the repeating pattern in both the pitch and duration conditions (especially for children with TLD in the pitch condition). After analyzing the data to consider both sound and visual cues as an index of procedural memory, we concluded that children with DLD did show implicit learning of visual cues, defying the PDH.

In the first MANOVA, groups with DLD and TLD for pitch and duration all showed a significant preference for the alternating trial over the repeating trial. Children overall had high levels of attention to the alternation pattern, but children with TLD learning pitch had a significantly higher mean difference between alternating vs. repeating trials than any other subgroup (See Figure 4). While it is not clear what is driving this effect, it is possible that the group with TLD was affected by the sound cue in some manner, in a manner that heightened their sensitivity to the alternation pattern. However, this analysis is highly speculative and its nature is unclear. According to Quam and Swingley (2010), toddlers were found to respond more to the target when pitch changes were introduced in the test phase. They theorize that the pitch contour in this study may have increased attentiveness in the participants and therefore increased their responsiveness to the target (Quam & Swingley, 2010). In our data, we speculate that pitch-differentiated sounds in this experiment may have heightened the children's attention and utilization of the alternation pattern.

After our findings from our first MANOVA, we could assume that the participants had a strong sensitivity to the alternation pattern, so we wanted to see whether sound convergence had any effect above and beyond alternation (whether or not the children were sensitive to whether the sounds converged or conflicted with the alternation pattern). From the results in the second

MANOVA, we determined that sound convergence didn't seem to have much of an effect on the participant's attention to the alternation pattern. It is not that the children paid no attention to the sounds, it is more so that the alternation pattern had a much stronger pull. The only tentative evidence we have around the role that the sound cues played is that there seemed to be an advantage for children with TLD when learning pitch because their mean difference for attention to the alternation pattern was much higher when partnered with the pitch-differentiated cue v. the duration-differentiated cue compared to the children with DLD. (See Figure 4). Since the study was not designed to tease out whether the children were paying more attention to the sounds v. the alternation pattern, it is difficult to determine whether the sounds had a part to play in the children's learning.

Another plan is to analyze the non-alternating trials on their own to see if participants show sensitivity to sounds when they don't converge with the alternation pattern. In a newer version of this study described by Yu, results found that TLD children showed higher levels of implicit learning in the pitch condition than in the duration condition, when the alternation pattern was removed (Yu, W. 2020). This does suggest that children may be more sensitive to pitch differentiated sounds v. duration differentiated sounds (see also Quam et al., 2021). This could be why the group with TLD was able to use pitch differentiated sounds in some way to attune to the visual cue better than in other conditions.

Auditory domains are the most common cue utilized in studies testing the PDH. Some have even argued that visual procedural learning is not underpinned by the same procedural-memory system that underlies language learning (Gómez, personal correspondence). However, some evidence suggests that procedural memory can be expressed through learning tasks including visual, visuo-spatial, and auditory/verbal (Lum et al., 2013). Lum et al. (2013)'s meta-analysis even notes that there are no specific assessments available to test procedural memory systems. So, they describe how other experimenters have used assessments testing implicit learning in several domains including visual, visuo-spatial, and auditory/verbal (Lum et al., 2013). In Lum's (2012) later work readdressing the role of procedural memory in the PDH, procedural memory was tested with a visuo-spatial serial reaction time test. This test involved a computer-based program asking participants to select one of four buttons that each aligned with the location for a visual stimulus on a computer screen (Lum et al, 2012). Using visual domains to test procedural memory in participants to directly support the PDH in this study suggests that a visual cue is a viable method of testing implicit learning and testing the PDH in children with DLD. In fact, the procedure of selecting buttons that are associated with a visual cue in this visuo-spatial test that was conducted to support the PDH in Lum's work is very similar to the process that is involved in our implicit study.

While we were originally testing implicit learning through auditory cues, children with DLD showed implicit learning through the additional visual cue (alternation pattern). This study was reproduced without the alternation pattern to evaluate implicit learning in children with and without DLD in auditory and visual categories. According to Yu (2020), one child with DLD showed implicit learning in auditory and visual categories (Yu, 2020). When this experiment was reproduced without the visual cue, results showed implicit learning of auditory cues in children with TLD (Yu, 2020). Due to COVID-19, there was only one child with DLD that was tested. Further research is necessary for investigating whether this trend of implicit learning in DLD continues. This may suggest that the PDH may need further investigation. The experiment described by Yu (2020) is still currently on hold due to COVID-19. The long-term plan is to test 25 more participants with DLD, however, due to COVID-19, it is unknown when this data will be collected. In the short-term, we plan to combine the findings for children with TLD in Yu's (2020) master's thesis with the data from this current thesis and submit them for publication; since the study described by Yu (2020) clearly displays that children with TLD are capable of learning the sound-meaning-mapping relationships when the alternation pattern was taken out of the experiment.

CHAPTER 5: Conclusion

This study was intended to test children's implicit learning through matching sounds to meaning, hypothesizing that results would support the procedural deficit hypothesis (Ullman et al. 2005, Lum et al., 2011). While the additional visual cue alternating back and forth may not have been foreseen, the children certainly took to it quickly and displayed another way in which to look at implicit language learning and procedural memory using visual cues. After analyzing the data, it was clear that the alternation pattern took a stronghold on the children's attention. It was not that the children paid no attention to the sound cues, it was just that the alternation pattern had a much stronger pull. Despite this, it was interesting that children with TLD showed higher accuracy in identifying the alternation pattern in the pitch condition v. the duration condition. This is something that might be worth investigating further. When we tested to see if the sound cues converged with the alternation pattern in some way, null results were found. However, we found that children with TLD had a much higher mean difference of attention to the alternation pattern in the pitch condition over the duration condition compared to the children with DLD.

Overall, groups with TLD and DLD showed learning of visual cues in the pitch and duration conditions. We argue that while auditory tasks are most common for testing implicit language learning, the visual cue in this experiment was learned implicitly and thus the findings indicate intact implicit learning in DLD, despite the claims made in the PDH (Ullman et al., 2005; Lum et al., 2011, 2012, 2013, 2015). More research is necessary to investigate this finding further.

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