Not all procedural learning tasks are difficult for adults with developmental language disorder

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This research was supported by funding by NSF 1724842 & NIH R01DC018410 to LAG, and NIH R01DC016813 & NIH R01DC018410 to LG.

Abstract

Purpose: The experiment reported here compared two hypotheses for the poor statistical and artificial grammar learning often seen in children and adults with developmental language disorder (DLD; also known as specific language impairment). The *procedural learning deficit hypothesis* states that implicit learning of rule-based input is impaired (e.g., Ullman et al., 2020), while the *sequential pattern learning deficit hypothesis* (e.g., Goffman & Gerken, 2019) states that poor performance is only seen when learners must implicitly compute sequential dependencies. The current experiment tested learning of an artificial grammar that could be learned via feature activation, as observed in an associatively organized lexicon, without computing sequential dependencies, and should therefore be learnable on the sequential pattern learning deficit hypothesis, but not the procedural learning deficit hypothesis.

Method: Adults with DLD and with typical language development (TD) listened to CVCV familiarization words from one of two artificial phonological grammars: Family Resemblance (2 out of 3 features) and a control (exclusive OR) grammar in which no learning was predicted for either group. At test, all participants rated 32 test words as to whether or not they conformed to the pattern in the familiarization words.

Results: Adults with DLD and TD showed equal and robust learning of the Family Resemblance grammar, accepting significantly more conforming than nonconforming test items. Both groups who were familiarized with the Family Resemblance grammar

also outperformed those who were familiarized with the OR grammar, which as predicted, was learned by neither group.

Conclusion: Although adults and children with DLD often underperform their TD peers on statistical and artificial grammar learning tasks, poor performance appears to be tied to the implicit computation of sequential dependencies, as predicted by the sequential pattern learning deficit hypothesis.

Introduction

Developmental language disorder (DLD; also known as specific language impairment) is classically characterized at younger ages by a morpho-syntactic deficit, evidenced by the inconsistent use of grammatical morphemes such as the English past tense (Leonard, 2014; Rice & Wexler, 1996). However, a number of studies suggest that aspects of phonology are also implicated in the disorder. Children with DLD have difficulty accurately producing phonemes in an articulation test (Alt, Plante, & Creusere, 2004; Deevy, Weil, Leonard, & Goffman, 2010; Gray, 2006). Children and adults with DLD have difficulty acquiring novel word forms (Alt & Plante, 2006; Benham, Goffman, & Schweickert, 2018; Goffman, Gerken, & Lucchesi, 2007; Graf Estes, Evans, & Else-Quest, 2007; Gray, 2005; McGregor et al., 2013). Perhaps relatedly, children and adults with DLD have difficulty with nonword repetition, especially of multi-syllable sequences (e.g., Archibald, Joanisse, & Munson, 2013; Coady & Evans, 2008; Dollaghan & Campbell, 1998; Graf Estes et al., 2007; Poll, Betz, & Miller, 2010).

Focusing for the moment on the observed phonological deficits seen in DLD, there are at least three possible explanations. One is that children and adults with DLD have less robust skills than typically developing (TD) peers at perceiving or remembering speech sound sequences (e.g., Ellis Weismer, Evans, & Hesketh, 1999; Leonard et al., 2007). A second possibility is that deficits in procedural memory make it difficult for children and adults with DLD to learn and use patterned or rule-governed parts of language including aspects of syntax, morphology and phonology (Ullman, 2001, 2004; Ullman & Pierpont, 2005). A third possibility is that a deficit in sequential pattern learning in children and adults with DLD makes it difficult to learn phonological, morphological, and syntactic sequences in which there is a dependency relation among elements in a sequence (Benham et al., 2018; Goffman & Gerken, 2019; Hsu & Bishop, 2014; Lukács & Kemény, 2014; Vuolo, Goffman, & Zelaznik, 2017).

The work here focuses on the latter two accounts, which have at least two key properties in common. First, both accounts propose that the syntactic and phonological deficits seen in children and adults with DLD reflect a single underlying mechanism. Second, both propose that this underlying mechanism is not specific to language, as evidenced by the fact that non-linguistic sequential processing is also affected in children with DLD (e.g., Clark & Lum, 2017; Lum, Conti-Ramsden, Morgan, & Ullman, 2014; Tomblin, Mainela-Arnold, & Zhang, 2007). There is also one important difference between the two accounts, and that difference drives the current work. The procedural learning deficit hypothesis adopts the view that there are at least two distinct memory systems, a procedural system that is slow and implicit and a declarative system that is fast and explicit. Ullman and Pierpont (2005, p. 403) say of the two systems with respect to language: ‘According to this view– referred to as the Declarative/Procedural (DP) model – idiosyncratic mappings are stored in a memorized “mental lexicon” that depends on declarative memory, whereas the learning and use of rule-governed computations involves a “mental grammar” that depends on procedural memory’. We have elsewhere (Goffman & Gerken, 2019; Plante, 2020) outlined problems with this particular pairing of dichotomies (fast~explicit; slow~implicit) as they apply to rapid rule learning in both human infants (e.g., Gerken & Knight, 2015) and some non-human animals (e.g., Smith et al, 2012). For present purposes, however, the important point is that, on the procedural learning deficit account any <u>rule or principle-governed input that</u>

is learned implicitly and that cannot be memorized or stored as chunks should be affected in DLD (e.g., Ullman & Pierpont, 2005). In contrast, the sequential pattern learning deficit hypothesis does not adopt the procedural~declarative dichotomy but rather focuses specifically on the learning of sequential dependencies. In general, these dependencies constitute a set that overlaps with the set that falls under the procedural learning umbrella, since not all rule or principle-governed input entails sequential dependencies, and not all sequential input is rule-governed (see footnote 1).

The research presented here employs artificial grammar learning to contrast the procedural learning and the sequential pattern learning deficit accounts. There is a growing body of evidence that children and adults with DLD often perform relatively poorly in both statistical learning and artificial grammar learning experiments[1] (e.g., Evans, Saffran, & Robe-Torres, 2009; Grunow, Spaulding, Gómez, & Plante, 2006; Lukács & Kemény, 2014; Obeid, Brooks, Powers, Gillespie-Lynch, & Lum, 2016; Plante, Gómez, & Gerken, 2002). For example, in a statistical learning experiment, learners are familiarized with strings of nonwords such as *dutaba, tutibu, pidabu, patubi, bupada, and babupu* with no silence between words. At test, they must guess which new items were "words" during familiarization, a task thought to be accomplished through the use of high (often 100%) sequential dependencies between adjacent syllables in the familiarization words. Children with DLD perform more poorly on these tasks than do their peers with TD (e.g, Evans et al., 2009; Obeid et al., 2016). A similar requirement

[1] Here we use "statistical learning" to refer to those experiments in which the input stimuli are not generated by rules or principles but rather require learners use transitional probabilities for word segmentation. We use "artificial grammar learning" to refer to experiments in which the stimuli are generated by rules or principles and in which learners are tested for having learned those principles. Note that, because the stimuli in statistical learning experiments are not generated by rule, they may constitute an example of a sequential learning task, but not a procedural learning task, depending on the definition of the procedural system one adopts.

for detecting dependency relations can be seen in many artificial grammar learning experiments. In one such experiment, learners were exposed to strings of the form aXb cXd, in which the syllable that occurs in the third position (from either a *b*-set or *d*-set of syllables) is dependent on what occurs in the first position (from either an *a*-set or a *c*-set of syllables, respectively) (Gómez & Maye, 2005). Adult college students with DLD showed poorer learning of this language than did adults with TD (Grunow et al., 2006).

Note that all of these studies in which children or adults with DLD perform poorly would be considered procedural learning of rule-governed input by the procedural learning deficit hypothesis and sequential dependency learning tasks by the sequential pattern learning deficit hypothesis. How might we differentiate these two accounts? As noted above, the procedural learning deficit hypothesis predicts poor performance by participants with DLD for any learning study in which performance is dependent on implicitly detecting and using the underlying rule or principle-governed structure of the input. In contrast, the sequential pattern learning deficit hypothesis only predicts poorer performance by participants with DLD if the underlying structure requires detecting sequential dependencies in particular. Therefore, the latter hypothesis predicts TD-level performance in artificial grammar learning experiments that do not require detecting sequential dependencies.

Published experiments that involve the implicit learning of stress assignment rules of an artificial grammar appear to support the sequential pattern learning deficit hypothesis over the procedural learning deficit hypothesis. In two such experiments, participants heard a set of familiarization words created based on principles such as “stress heavy syllables” and “stress final syllables.” The principles were ranked with respect to each other, such that if two principles could be applied to the same input yielding different outcomes, the most important (highly ranked, e.g., “stress heavy syllables”) principle applied. Importantly, learning the principles did not entail detecting sequential dependencies among parts of the word (i.e., none of the rules had dependencies such as “stress the first syllable if the last syllable is heavy”). Children and adults with DLD showed significant learning and did not perform differently from TD peers (Bahl, Plante, & Gerken, 2009; Plante, Bahl, Vance, & Gerken, 2010). These results are consistent with the sequential pattern learning deficit hypothesis, because there were no sequential dependencies in the stimuli. The positive learning outcomes are not consistent with the procedural learning deficit hypothesis, because learning was implicit and stimuli were rule-governed. However, it is possible that prosodic patterns are somehow different from patterns in segmental phonology, as well as morphology and syntax. Therefore, it would be helpful to identify another case of phonological pattern learning that does not involve detecting sequential dependencies and on which children or adults with DLD can succeed at the same level as peers with TD.

To that end, the current research employs a segmental sound pattern (one involving consonants and/or vowels) that does not require sequential processing. Because this is a rule-generated, implicitly learned pattern, the procedural learning deficit hypothesis predicts poorer performance from adults with DLD than with TD. In contrast, the sequential pattern learning deficit hypothesis predicts that in this artificial grammar learning experiment, adults with DLD will show significant learning that does not differ from that seen in adults with TD. In our stimuli, participants listen to a set of familiarization nonwords that are in the form of $Consonant_1$, $Vowel_1$, $Consonant_2$, Vowel$_2$ ($C_1V_1C_2V_2$) strings. Each nonword must contain at least two out of the following three features: C_1 is voiced, C_2 is voiced, V_1 is front. Because not all words must contain the same features (e.g., one word can have C_1 voiced and C_2 voiced, and another can have C_2 voiced and V_1 front), this type of pattern—originally drawn from the visual domain-- is often referred to as having a Family Resemblance structure (Moreton & Pater, 2012; Shepard, Hovland, & Jenkins, 1961).

Family Resemblance patterns have been attested in phonological and morphological systems across human languages (Moreton & Pater, 2012; Moreton, Pater, & Pertsova, 2015). For example, parts of the English irregular past tense system can be described as a Family Resemblance pattern: Irregular verbs that contain /ɪ/ before a velar nasal (e.g., *ring, drink, swing*) become past tense by undergoing a vowel change (e.g., *rang, drank, swung*) in the past tense. Verbs that share a subset of these properties (/ɪ/, velar, nasal) also participate in the irregular past tense vowel change (e.g., *swim~swam, begin~began, hang~hung, dig~dug*) (Bybee & Moder, 1983). Adults have been shown to readily learn Family Resemblance patterns in artificial grammar learning experiments (Gerken et al., 2019; Moreton & Pater, 2012; Moreton et al., 2015).

The Family Resemblance pattern *can* be described as a set of sequential dependencies. For example, if C_1 is voiceless, then C_2 is voiced and V_1 is front, or if C1 is voiced, then either C2 is voiced or V_1 is front, or both, etc. However, this pattern can also be learned without reference to sequential dependencies via phonological feature activation (e.g., Moreton & Pater, 2012). The kind of feature activation that we have in mind can be seen in auditory word-form priming studies in which one word with featural but not full segmental overlap with a target word primes that target (e.g, Goldinger, Luce, & Pisoni, 1989). For example, presenting the auditory word *bull* causes a faster lexical decision for the target word *veer*. Note that *bull* and *veer* have no segments in common, but they do share place of articulation and voicing on C_1, contain back vowels, and share manner of articulation and voicing on C_2. One way that priming between *bull* and *veer* might occur is that, when a listener hears the word *bull*, the features of that word are activated, which in turn, activate the same features in other words and thereby activate those words. Thus, when *veer* is heard, it is already weakly activated, which allows a faster response than if the priming word had been featurally unrelated.

The latter example pertains to feature activation during word-form priming. But what about learning a phonological pattern like the Family Resemblance pattern? Such patterns must be induced over a set of familiarization words followed by a generalization test in which the participant has to determine if a new word fits the pattern. As in the example described above, the familiarization words all share at least two out of three of the features: C_1 voiced, V_1 front, C_2 voiced. As a listener who engages in lexical processing hears the familiarization words, the phonological features in those words are activated. Of course features in addition to the relevant ones (e.g., place of articulation, vowel height, etc.) will be activated as well, but across the set of familiarization words, if these other, irrelevant features are randomly distributed, the three relevant features (C_1 voicing, V_1 front, C_2 voicing) will be the most active. At test, the generalization words can be judged based on how many of the three most active features they contain. Words that contain zero or one of the active features are more likely to be rejected as fitting the familiarization pattern, whereas words that contain two or three active features are more likely to be accepted. Thus, the Family Resemblance pattern under consideration here is logically learnable via feature activation.

There is evidence that children and adults with DLD show relatively normal patterns of feature activation. The most direct kind of evidence concerns priming: Children with DLD show phonological priming effects with both phonologically related words (Seiger-Gardner & Schwartz, 2008) and phonologically related nonwords (Brooks, Seiger-Gardner, Obeid, & MacWhinney, 2015). Another type of evidence concerns factors that influence nonword repetition (for a review of many factors, see Szewczyk, Marecka, Chiat, & Wodniecka, 2018). As noted above, children and adults with DLD show particular difficulty with nonword repetition compared with their TD peers; this is not surprising, since nonword repetition is deeply sequential. However, nonwords share characteristics with words, and there is evidence that learners with DLD are influenced by featural overlap between nonwords and known words. For example, children with DLD and TD benefit from nonwords that are more similar to words in their language (Archibald & Gathercole, 2006; Graf Estes et al., 2007). When they make errors in nonword repetition, children with DLD and TD both generally substitute more frequently occurring phonemes for less frequently occurring phonemes, and their productions tend to be more phonotactically probable than the targets (Burke & Coady, 2015). Children with DLD produce nonwords with high phonotactic frequency more accurately than those with low phonotactic frequency (Coady, Evans, & Kluender, 2010; Munson, Kurtz, & Windsor, 2005). Munson and colleagues (2005) showed that children with DLD were actually more influenced by phonotactic frequency than their age-, but not their vocabulary-, matched peers. Finally, one study employing a lexical decision measure also showed that children with DLD were more influenced by the phonotactic probability of nonwords than were their TD peers (Quémart & Maillart, 2016). We will return to the question of sound-based lexical representations in DLD in the discussion, but for the present purpose, there appears to be sufficient evidence that adults with DLD may well be able to use feature activation to discern featural patterns among auditory nonwords.

Now consider a phonological pattern that is, on the surface, very similar to the Family Resemblance pattern. In one example of this phonological pattern, all nonwords are $C_1V_1C_2V_2$ strings which if C_1 is voiced then C_2 is voiced, OR if C_1 is voiceless, then C_2 is voiceless. This pattern is often referred to as an exclusive OR pattern (Moreton & Pater, 2012; Shepard et al., 1961), because it involves two sub-patterns (e.g., 2 voiced consonants OR 2 voiceless consonants). The fact that the OR pattern contains two sub-patterns prevents it from being learned via feature activation. This point can be illustrated by considering the feature activation pattern that results from just two familiarization nonwords: *bida* and *pɛta*. The first word activates a set of features including C_1 voiced and C_2 voiced, as well as irrelevant features such as C_1 labial or C_2 alveolar. After a number of familiarization words that fit the C_1 voiced and C_2 voiced pattern occur, the activation of the irrelevant features will cancel out, but the two relevant C_1 and C_2 voiced features will gain in activation. However, there is also a second pattern, the one in which C_1 and C_2 are both voiceless. Therefore, those features will also grow in activation, resulting in C_1 and C_2 each being equally activated for voiced and voiceless. Now consider what happens at test: A generalization nonword like *bota* has C_1 voiced and C_2 voiceless, thus not fitting the OR pattern. But based on feature activation, it should be incorrectly judged as fitting the pattern. The logical problem for OR patterns in a feature activation system is that feature activation is summed *across* familiarization words, whereas discovering the OR relation requires noting the *sequentially contingent* relation of two features *within* each word (both C's voiced OR both C's voiceless). Therefore, we suggest that Family Resemblance patterns can be learned without sequential processing via the feature activation that takes place automatically during lexical processing. However, OR patterns must be learned from implicitly noticing within-word sequential dependencies among features (Gerken et al, 2019).

Like the Family Resemblance pattern, the OR pattern is also attested in natural languages and is therefore learnable. In fact, it is more frequently attested than the Family Resemblance pattern (Moreton et al., 2015). Regular English past tense can be described as an OR pattern: Add /t/ if the verb stem ends in a voiceless segment other than /t/ OR add /d/ if the verb stem ends in a voiced segment other than /d/ OR add /əd/ if the verb stem ends in /t/ or /d/. However, while adults readily learn Family Resemblance patterns in artificial grammar studies, they fail to learn the OR pattern (Gerken et al., 2019; Moreton & Pater, 2012; Moreton et al., 2015). In contrast, 11-month-olds across several studies show robust learning of the OR pattern (Gerken & Knight, 2015; Gerken & Quam, 2017; Gerken et al., 2019). We will offer an explanation for the developmental differences observed in OR pattern learning in the discussion. For them moment, however, it is important to note that the procedural learning deficit hypothesis predicts that, because both the Family Resemblance and OR patterns are learned implicitly by the procedural system, neither should be learned by adults with

DLD. In contrast, the sequential pattern learning deficit hypothesis predicts differential learning of the Family Resemblance and OR patterns by both adults with DLD and TD. The two groups should show equal and robust learning of the Family Resemblance pattern and no learning of the OR pattern.

In summary, children and adults with DLD have difficulty learning some syntactic and phonological components of natural language. They also perform more poorly in most statistical learning and artificial grammar learning tasks. As discussed above, two hypotheses have been proposed to account for this array of observations: the procedural learning deficit hypothesis (Ullman, Earle, Walenski, & Janacsek, 2020; Ullman & Pierpont, 2005) and the sequential pattern learning deficit hypothesis (Benham et al., 2018; Goffman & Gerken, 2019; Hsu & Bishop, 2014). One way to differentiate these hypotheses is to identify a type of artificial grammar in which the stimuli are generated by a set of rules or principles and which can be learned implicitly but that do not involve implicitly tracking sequential dependencies among elements in a string. We contend that phonological Family Resemblance patterns constitute such an artificial grammar.

The procedural learning deficit hypothesis predicts poor performance on implicitly learned rule-governed patterns, including the Family Resemblance pattern. Therefore, learning this pattern should be more difficult for adults with DLD relative to their TD peers. In contrast, the sequential pattern learning deficit hypothesis implicates learning only of sequential patterns. Since the Family Resemblance pattern can be learned from activating the set of features in the word and without detecting sequential patterns among the features, this hypothesis predicts that adults with DLD will show significant learning of a phonological Family Resemblance pattern and that their level of learning should not differ from adults with TD.

The experiment reported below also examines learning of a phonological OR pattern, which logically requires noting sequential dependencies. The OR pattern was included because the sequential pattern learning deficit hypothesis, but not the procedural learning deficit hypothesis, predicts better performance by adults with DLD on the Family Resemblance pattern than the OR pattern.

Method

The main goal of the experiment presented here was to determine if adults with DLD show significant learning of a phonological Family Resemblance pattern and show learning at the same level as adults with TD. Additional goals were to replicate previous findings with adults with TD that demonstrated differential learning of a Family Resemblance pattern and an OR pattern, and to determine if, contrary to the procedural learning deficit hypothesis, adults with DLD also show better learning for Family Resemblance than OR patterns.

Participants

Eighty adult college students (21 male, 40 with DLD) ranging in age from 18 to 26 participated in the experiment for course credit. All participants indicated that English was their native language. Forty participants were familiarized with a Family Resemblance pattern and 40 were familiarized with an OR pattern. For each phonological pattern, half of the participants were diagnosed as DLD and half as typically developing (TD). Participants were assigned, in alternating order to each condition, until the conditions were filled with 20 subjects each.

The referral pool consisted of individuals from the Psychology undergraduate experiment volunteer pool and from a campus program that provides services to students with language and learning disabilities. Members of the DLD group met the definition of the CATALISE group (Bishop, Snowling, Thompson, & Greenhalgh, 2016) for DLD as having a language disorder not due to another biological etiology. This is also consistent with how SLI has been operationally defined in the recent literature (Nitido & Plante, 2020 for a discussion) and with evidence supporting the notion that DLD represents a continuum of behavior rather than a dichotomy based on IQ cut points (Lancaster & Camarata, 2019). Two individuals with DLD and two in the TD group also reported a diagnosis of Attention Deficit Hyperactivity Disorder. However, the presence of this condition does not appear to impact the severity of DLD (Redmond, Ash, & Hogan, 2015). These four individuals had all been assigned to the OR condition. Participants also self-reported an absence of other disorders (i.e., sensory impairment, other neurological disorders).

All participants passed a pure-tone hearing screening and scored above 75 on the Test of Nonverbal Intelligence-IV (Brown et al., 1997). This test is scaled so that the normative test mean is 100, and standard deviation is 15. Language status was determined using the procedures of Fidler et al. (2011), in which performance on a battery of three measures were weighted and the weighted score was compared to a validated cut point that maximized sensitivity (80%) and specificity (87%) for the classification of individuals as having DLD or typical language skills. The weighting is scaled to a mean of zero with positive scores corresponding to positive for DLD and negative scores are consistent with typical performance for adults without the disorder. In addition, the Broad Reading subscale of the Woodcock–Johnson Psychoeducational Battery—Third Edition (Woodcock, McGrew, & Mather, 2001) was given to document reading levels, an additional language skill often impaired in the adult population. In particular, Letter-Word identification taps decoding, a phonological skill that is often implicated in adults with DLD. Finally, participants completed a nonword repetition task, as this measure specifically taps phonological skills. Nonwords were largely taken from Kamhi & Catts (1996), with five additional four-syllable words added to their original list of 15 nonwords. Table 1 displays the test scores for each set of participants in each condition.

TABLE 1

Materials

Materials were $C_1V_1C_2V_2$ non-words that were created using the schematic shown in Table 3. C_1's were b, g, v, z (voiced) and p, k, f, s (voiceless). C_2's were b, d, z, v (voiced) and p, t, f, s (voiceless). V_1's were ɛ, i (front) and o, u (back). Crossing the 8 C_1's, 8 C_2's, and 4 V_1's, with the provision that the same consonant could not occur in C_1 and C_2, yielded 192 CVCV non-words. The voicing of the first and second consonants and the frontness/backness of the first vowel were manipulated to generate eight different word templates (Table 2) – four of which were consistent with the Family Resemblance pattern and four of which were consistent with the OR pattern. Note in Table 2 that the Family Resemblance and OR patterns overlap for words with two voiced consonants. Therefore, two of the word templates were consistent with both patterns (2 voiced consonants), two were consistent with only the Family Resemblance pattern (1 voiced consonant and a front vowel), two were consistent with only the OR pattern (2 voiceless consonants), and two were not compatible with either pattern (1 voiced consonant and a back vowel).

TABLE 2

Test Words

From the set of 192, 32 words (4 from each of the 8-word templates shown in Table 2) were selected for test words. All of the test words had labial consonants (b, p, f, v) in both C_1 and C_2 positions, because the stimuli were designed to also be used in a production experiment in which lip movements are monitored using articulatory motion capture technology (not reported here). Half (16) of the test words were consistent with the Family Resemblance pattern and a partially overlapping set of 16 were consistent with the OR pattern (see Table 2). One half of the test words (those with 2 voiced consonants) were the same for the Family Resemblance and the OR conditions. During pilot testing, we eliminated two test words because they were similar or identical to English words, leaving 30 test words total.

Familiarization Words

Familiarization stimuli were constructed from the pool of CVCV nonwords, excluding test words. After elimination of those words that were similar or identical to English or common Spanish words, two familiarization lists of 76 words each were created, one containing a randomly ordered set of words that are consistent with the Family Resemblance pattern and the other containing a randomly ordered set of words that are consistent with the OR pattern. One half of the familiarization words (those with

2 voiced consonants) were the same for the Family Resemblance and OR conditions. 250 msec pauses were placed between words in each list.

Procedure

Stimuli were delivered via computer using Direct RT software. Participants were told that they would hear some words and that later they would be tested on what they had learned about these types of words just by hearing the words. Critically, they were not given any instruction on what to listen for in the set of words, only that they should listen. After the familiarization phase, participants were asked to respond, via key press, to test words. They were told that the words they had heard conformed to a set of rules and asked to respond "yes" if the test word also conformed to these rules or "no" if it did not. All test items reflected generalization of the "rules" of the familiarization set to new items. Participants did not receive feedback concerning the accuracy of their responses.

Results

A 2 x 2 x 2 Diagnosis (DLD vs TD) X Pattern Type (Family Resemblance vs. OR) X Consistency (consistent vs. inconsistent with the familiarization pattern) ANOVA was performed on the mean number of accept ("yes" the test item was a member of familiarization words) responses made by participants for consistent and inconsistent test items (see Fig. 1). There was a significant main effect of Consistency, $F(1,76) = 36.16$, $p < .0001$; Mean (SD) consistent = 10.98 (3.11), inconsistent = 8.91 (3.37), $h_p^2 = .33$. The main effects of the between-subject variables were not significant, Diagnosis $F < 1$, $h_p^2 = .03$; Mean (SD) DLD = 9.88 (3.11), TD = 10.01 (2.36); Pattern Type, $F(1,76) = 2.06$, $p = .16$, $h_p^2 = .01$; Mean (SD) Family Resemblance = 9.50 (3.12), OR = 10.39 (2.26). Importantly, as predicted by the sequential pattern learning deficit hypothesis, there was a significant Consistency X Pattern Type interaction, $F(1, 76) = 22.14$, $p <$ $.0001$, $h_p^2 = .21$. The nature of this interaction is clear in Fig. 1, where the consistent minus inconsistent acceptance difference is larger for the Family Resemblance group than for the OR group, and this is true for participants with DLD and with TD. For the latter group, the difference in acceptance for consistent vs. inconsistent test items is near chance (0). None of the other interactions approached significance (Diagnosis x Consistency, $F < 1$; Diagnosis X Pattern Type, $F < 1$; 3-way interaction $F < 1$).

FIGURE 1

The sequential pattern learning deficit hypothesis predicted that adults with DLD would learn the Family Resemblance pattern and that they would do so to the same level as adults with TD. Therefore, although the ANOVA showed no interactions with Diagnosis, separate t-tests were performed on the four groups (DLD Family Resemblance; TD Family Resemblance; DLD OR; TD OR) independently. Adults in the DLD Family Resemblance group significantly differentiated consistent from inconsistent test items (mean (SD) consistent = 11.45 (3.97), inconsistent = 7.72 (4.36); $t(19) = 5.12$, $p < .0001$, Cohen's $d = 1.15$). Replicating previous findings (e.g., Gerken et al., 2019), adults in the TD Family Resemblance group significantly differentiated consistent from inconsistent test items (mean (SD) consistent = 11.28 (2.95), inconsistent = 7.57 (2.81); $t(19) = 4.75$, $p < .0002$, Cohen's $d = 1.06$). Both the DLD and TD groups who were familiarized with the Family Resemblance pattern showed large to very large effect sizes for discriminating consistent from inconsistent test items.

As noted in describing the design of the stimuli (see Table 2), four test item types were consistent and four were inconsistent with the familiarization items. For participants who were familiarized with the Family Resemblance pattern, both the DLD group and the TD group accepted all four consistent test item types at a higher rate than all four inconsistent test item types (see Fig. 2). In short, participants with DLD and TD both showed robust learning of the Family Resemblance pattern and they did so at comparable levels.

FIGURE 2

Neither adults with DLD or TD distinguished consistent from inconsistent test items for the OR pattern (DLD mean (SD) consistent = 10.52 (2.85), inconsistent = 9.85 (2.35); $t(19) = 1.08$, $p = .29$, Cohen's $d = .24$; TD mean (SD) consistent = 10.68 (2.66), inconsistent = 10.50 (2.78); $t(19) = 0.30$, $p = .77$, Cohen's $d = .07$). Both the DLD and TD groups who were familiarized with the OR pattern showed small effect sizes for discriminating consistent from inconsistent test items.

Unlike the robust discrimination of consistent vs. inconsistent test items seen for the Family Resemblance pattern, the DLD group accepted only one (CC, see Fig 3) of the 4 consistent test item types at a higher rate than all four inconsistent test item types. The TD group's most accepted test item type (CV, see Fig. 3) was actually inconsistent with the familiarization words. As noted above, both groups showed a near-0 difference between consistent and inconsistent test items (see Fig. 1).

FIGURE 3

Discussion

The results from the experiment were remarkably clean. Briefly summarizing, adults with DLD showed significant learning of the Family Resemblance pattern, and they did so to a comparable level as adults with TD, as evidenced by similar means for consistent vs. inconsistent test items across the two Diagnosis groups, by similar large to very large effect sizes for t-tests comparing consistent and inconsistent test items, and for accepting all consistent test items at a higher rate than all four inconsistent test items. The strong performance of adults with DLD on the Family Resemblance pattern is consistent with their strong performance in an earlier study of stress pattern learning (Bahl et al., 2009). Thus, the current study, coupled with the earlier one on stress pattern learning, suggests that adults with DLD show a varied topography of strengths and weaknesses in artificial grammar learning studies—one that does not cleave neatly to the procedural-declarative dichotomy. We will return to the causes of these strengths and weaknesses below.

In contrast to strong performance on learning the Family Resemblance pattern, adults with DLD and TD who were familiarized with the OR pattern failed to show learning and showed significantly poorer performance than adults who were familiarized with the Family Resemblance pattern. The failure of adults with TD to learn the OR pattern replicates previous studies (Gerken et al., 2019; Moreton & Pater, 2012; Moreton et al., 2015). The differential performance of adults with DLD on the Family Resemblance vs. OR patterns conceptually replicates other research on artificial grammar learning by these adults (e.g., stress pattern learning vs. sequential dependency learning, respectively). Below, we discuss why adults with TD and DLD might have failed to learn the OR pattern and if they failed for the same reason.

Implications for Accounts of DLD

Although there are a number of accounts of DLD, we focused here on two: the procedural learning deficit hypothesis (e.g., Ullman et al., 2020) and the sequential pattern learning deficit hypothesis (Benham et al., 2018; Goffman & Gerken, 2019; Hsu & Bishop, 2014). These two accounts both treat the morpho-syntactic and phonological weaknesses observed in DLD as arising from a single underlying mechanism, and both propose that this underlying mechanism is not specific to language. Given the similarities between these two accounts, the main goal of the research presented here was to compare the performance of adults with DLD and TD on an artificial grammar pattern that can be learned without requiring the detection of contingency relations in a sequence; this pattern should be learnable on the sequential pattern learning deficit hypothesis, but not on the procedural learning deficit hypothesis. In the Introduction, we described one type of previous artificial grammar learning study involving stress assignment principles that also does not require detecting a contingency in a sequential pattern (Bahl et al., 2009; Plante et al., 2010). In two studies using this grammar, adults and children with DLD performed on par with their peers with TD. The comparable behavior of DLD and TD participants in these studies stands in contrast to the more usual finding in statistical learning and artificial grammar learning experiments, in which DLD participants significantly underperform their peers with TD. However, as we noted in the Introduction, stress assignment may be unique in some way, raising the need for a more typical artificial grammar learning study that might differentiate the two hypotheses under consideration.

The results from participants in the Family Resemblance group supported the predictions of the sequential pattern learning deficit hypothesis, but not the procedural learning deficit hypothesis. We suggest that the Family Resemblance pattern can be learned via feature activation and therefore does not require detecting contingencies between elements in a sequence. On the account proposed here, participants with DLD and TD both learned the Family Resemblance pattern via feature activation. However, as discussed in the introduction, the OR pattern *cannot* be learned via feature activation. Rather, it requires learners to detect sequential dependencies between C_1 and C_2. In contrast with the sequential pattern learning deficit hypothesis, the procedural learning deficit hypothesis predicted poorer performance by our participants with DLD than those with TD on both the Family Resemblance and OR patterns, because both patterns are rule-generated, and both are learned implicitly.

We contend here that the Family Resemblance pattern falls squarely in the domain of procedural learning as that construct has been employed to explain DLD (e.g., Ullman et al., 2020), as well as how it has been used in related literatures. Indeed, on a somewhat different view of the procedural learning system than the one espoused by Ullman and colleagues, only the Family Resemblance pattern and not the OR pattern are learned via the procedural system, because the former involves integrating over stimulus dimensions (e.g., Ashby & Maddox, 2005; Smith et al,, 2012). The Family Resemblance pattern is generated by rule and is learned implicitly, and therefore fits the definition of a procedural task given by Ullman and Pierpont (2005). One possible objection to our contention that the Family Resemblance pattern should be learned by the procedural system as it is defined under the procedural learning deficit hypothesis concerns our suggestion that the Family Resemblance pattern is learned via feature activation within the form-based lexicon. Thus, it might be possible for proponents of the procedural learning deficit hypothesis to claim that, because feature activation occurs in the lexicon, it is outside the domain of procedural learning.[2] We offer three arguments against this claim. First, our interpretation concerns the word-form lexicon, not the semantic lexicon or arbitrary associations between forms and referents. Only the latter two are thought to implicate declarative memory (Ullman & Pierpont, 2005). Second, adults appear to have implicit (and not explicit) access to various grammar-governed regularities of the word-form lexicon that seem to reflect just the sort of rules that the procedural learning account of DLD was created to address. For example, neither /bw/ nor /dl/ occur at the beginning of English words, yet /bw/ is an accidental gap and /dl/ is a grammatically-driven gap, according to the Obligatory Contour Principle (e.g., Frisch, 2004). English-speaking adults distinguish these forms, treating the accidental gap as more acceptable than the ungrammatical gap (e.g., Moreton, 2002). Such results suggest that implicit, abstract grammatical principles of the sort that are the focus of the procedural deficit account can arise from word-forms in the lexicon. Finally, the learning of stress assignment principles described in the Introduction also appear to fit the definition of procedural learning. They are rule-governed, implicit, and do not involve memorized, idiosyncratic mappings (Ullman & Pierpont, 2005). Yet, they are learned by both children and adults with DLD at the same level as their TD peers, and they do not appear to be learned via feature activation. Thus, the emerging range of observations about when children and adults with DLD succeed vs. fail to learn various linguistic patterns appears to be more consistent with the sequential pattern deficit hypothesis than the procedural deficit hypothesis. It is in the sequential dependencies that the learner breaks down.

[2] We are grateful to an anonymous reviewer for pointing out this issue.

Implications for Typical and Atypical Language Development

The current study replicates previous work in which adults are not able to learn an OR pattern in the lab (Gerken et al., 2019; Moreton & Pater, 2012; Moreton et al., 2015). In contrast, as noted in the Introduction, 11-month-olds are readily able to learn the OR pattern (Gerken & Knight, 2015; Gerken & Quam, 2017; Gerken et al., 2019), even from just four familiarization words (Gerken & Knight, 2015). One study directly compared adult and infant learning of the same OR pattern (the OR pattern employed here); 11-month-olds learned the pattern but adults did not (Gerken et al., 2019). Elsewhere, we have offered a possible explanation for the developmental difference in OR pattern learning (Goffman & Gerken, 2019): As learners become increasingly exposed to the lexical properties of their language, and adept at lexical processing, lexical processing becomes increasingly automatic and obligatory. As a result, learners become increasingly good at detecting Family Resemblance patterns and increasingly poor at detecting OR patterns. By adulthood, Family Resemblance patterns, which can be learned from feature activation in the lexicon, can be learned, but OR patterns, which cannot be learned via the lexicon, cannot (Gerken et al., 2019; Goffman & Gerken, 2019). We are currently testing this hypothesis in our lab by comparing the performance of infants, toddlers, and preschool aged children of different ages and lexicon sizes on Family Resemblance vs. OR patterns. We predict a developmental increase in the ability to learn Family Resemblance patterns and a concomitant decrease in ability to learn OR patterns.

The developmental account offered here raises an important question about whether young children (or infants) with DLD *could* learn the OR pattern. There are two possibilities. On the sequential pattern learning deficit hypothesis, the OR pattern reflects exactly the type of contingent sequence learning that is weak in DLD. Therefore, we expect that young children with DLD would not be able to learn this pattern as well as their peers with TD. If DLD is characterized by a specific difficulty with sequential patterns, the adults with DLD in our study would have *never* been able to learn the OR pattern because of their weakness in sequential processing. In contrast, adults with TD were able to learn OR patterns as young children until their lexical processing bias became too strong. The second possibility is that adults with DLD were at some point in their infancy or childhood able to learn the OR pattern and have lost that ability do to a developmentally increasing bias to engage in lexical processing of speech that is comparable to the time course over which this happens with typically-developing children. If this is the case, young children with DLD may be able to learn the OR pattern early in development. We are testing this possibility in our labs.

What is the Nature of the Lexicon in DLD?

As discussed in the Introduction, phonological deficits are an increasingly acknowledged component of DLD (e.g., Alt et al., 2004; Archibald et al., 2013; Benham et al., 2018). Yet, the sequential pattern learning deficit hypothesis, which was supported by the experiment presented here, depends on adults with DLD having a relatively normally organized form-based lexicon. It is in this lexicon that features of incoming nonwords are activated, allowing non-sequential, feature-based patterns, like the Family Resemblance pattern, to be detected. How can we reconcile apparent phonological deficits with a relatively normally organized lexicon? We have already noted that children and adults with DLD show phonological priming effects (Brooks et al., 2015; Seiger-Gardner & Schwartz, 2008). They are also influenced by many of the same factors as their TD peers in nonword repetition, new word learning, and lexical decision. These factors include word-likeness (Archibald & Gathercole, 2006; Graf Estes et al., 2007), phoneme frequency, and phonotactic probability (Burke & Coady, 2015; Coady et al., 2010; Munson et al., 2005; Quémart & Maillart, 2016). Nevertheless, there is ample evidence that the phonological representations of children and adults with DLD are somehow weaker or less well specified than the representations of their TD peers (Alt & Plante, 2006; Archibald et al., 2013; Coady & Evans, 2008; Dollaghan, 1998; Edwards & Lahey, 1998). These less robust representations might be sufficient for feature activation of the type implicated by the sequential pattern learning deficit hypothesis and the experiment presented here. However, these representations might not be sufficient for tasks such as word learning or lexical decision, in which an actual item in the form-based lexicon must be uniquely accessed and integrated with its counterpart in the semantic lexicon (e.g., Jones & Brandt, 2018; Storkel, Maekawa, & Hoover, 2010). In short, despite having weaker phonological representations, children and adults with DLD may be able to use their form-based lexicons to identify some types of phonological patterns, some of which have parallels in morphosyntax, and thereby compensate for their difficulties with sequential pattern learning of the type used here. Clearly more research on the specific nature of word-form representations is needed before we can predict how much compensation can be attained.

Conclusion

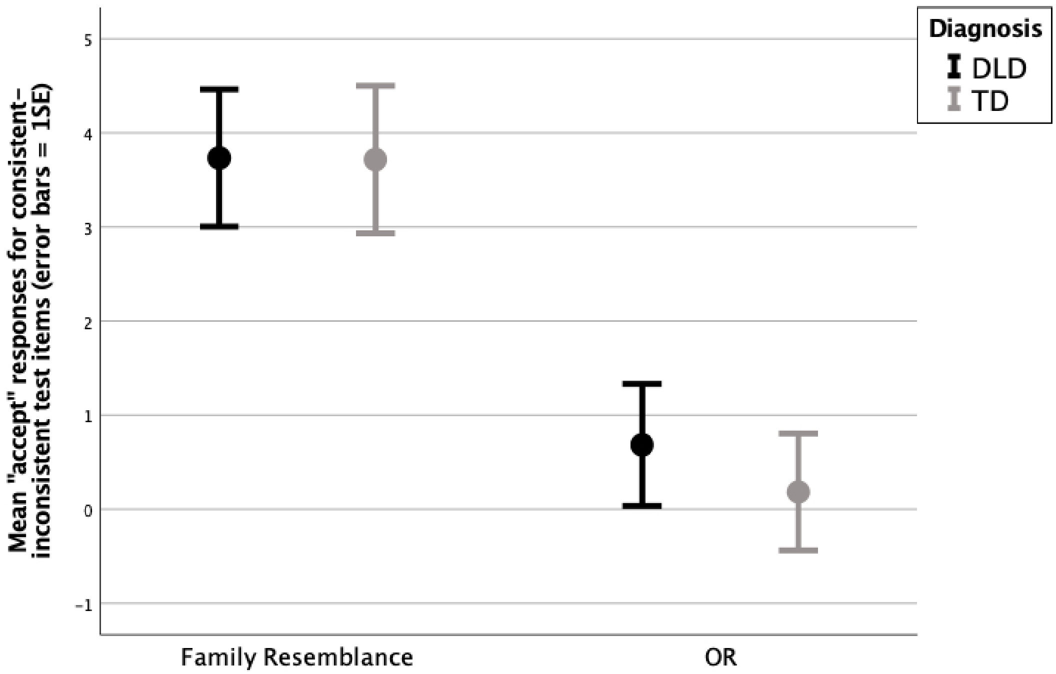
The fact that adults with DLD showed very robust learning of an artificial grammar involving a Family Resemblance phonological pattern supported the sequential pattern learning deficit hypothesis over the procedural deficit hypothesis. This finding suggests that any adequate account of DLD needs to view artificial grammar learning as a multi-factored problem that can showcase both strengths and weaknesses. Hopefully this observation will lead to new, more nuanced, approaches to artificial grammar and statistical learning by children and adults with DLD.

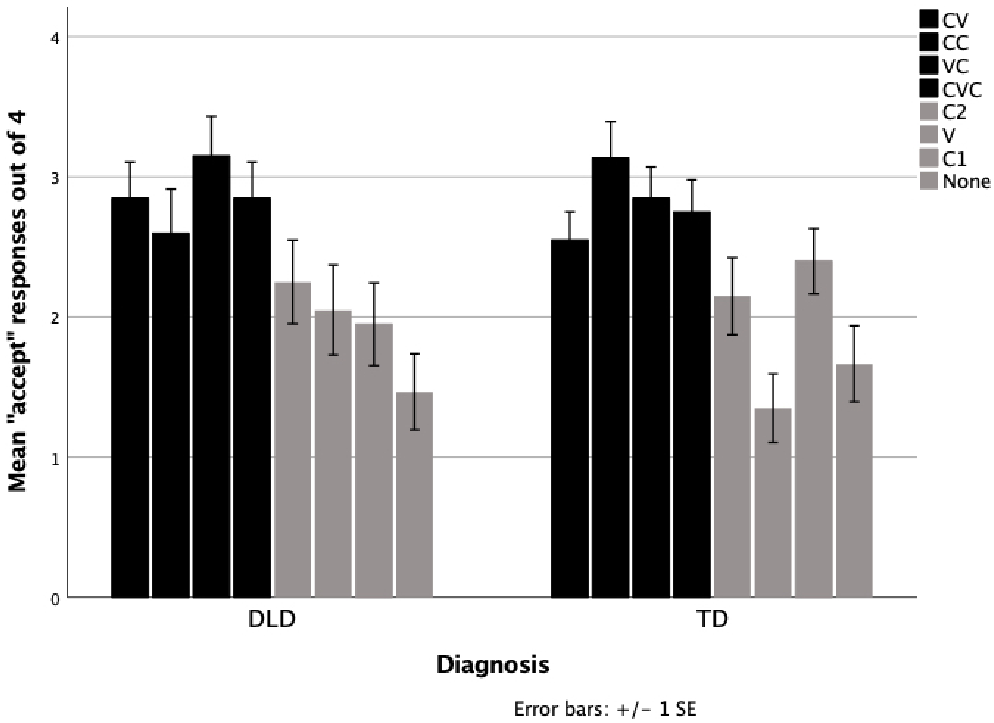
	Family Resemblance Condition						OR Cond		
	TD			DLD			TD		
Tests	Mean	SD	Range	Mean	SD	Range	Mean	SD	Range
TONI-IV	94.9	7.8	84 - 110	96.8	10.8	77 - 119	99.9	10.4	84-110
Language Identification Battery	-0.9	0.7	-2.08 - -0.02	1.1	1.5	0.16 – 6.66	-1.0	0.6	-2.24 - -0.04
W-J Broad Reading	111.2	12.5	85 - 113	96.5	7.5	86 - 114	109.0	11.0	85 - 113
W-J Passage Comprehension	104.3	9.7	86 - 118	94.9	7.1	77 - 107	100.2	8.5	86 - 118
W-J Letter-Word Identification	102.1	7.7	93 - 133	90.9	6.7	71 -99	101.9	8.4	93 -116
W-J Reading Fluency	113.4	13.0	77 - 140	100.6	10.3	55 - 98	111.9	14.5	77 - 140
Nonword Repetition	15.2	2.9	11 - 20	12.5	3.2	7 - 18	14.4	2.6	11 - 20

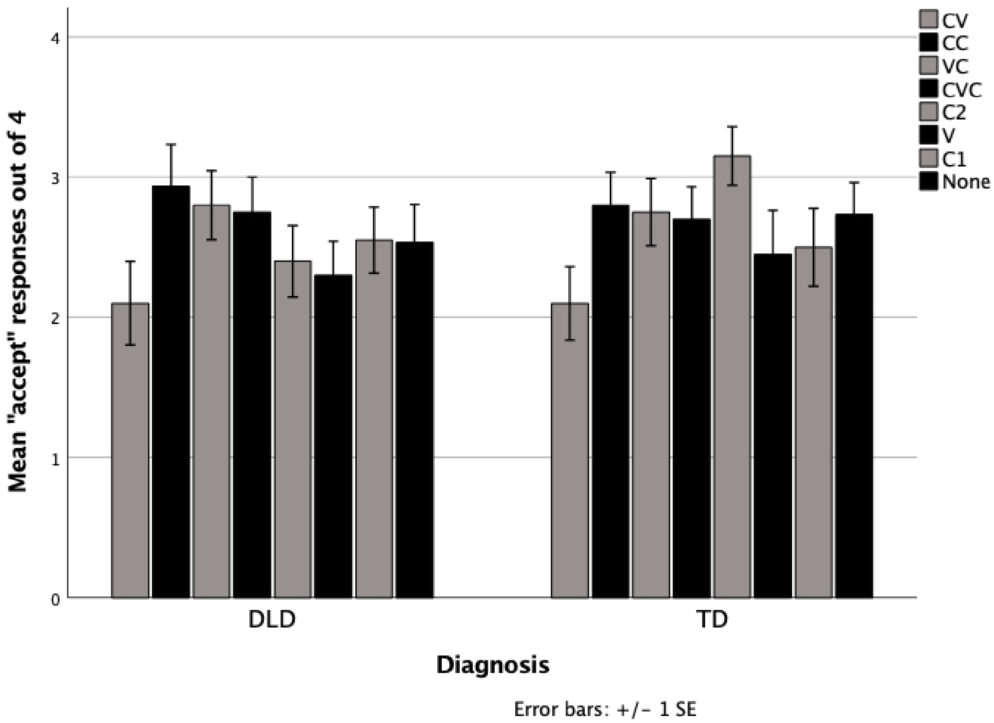
Table 1. Test scores for participant groups in each experimental condition. The Test of Nonverbal Intelligence-IV Edition (TONI-IV) and the Woodcock-Johnson (W-J) subtests and Broad Reading Scale have a normative mean of 100 and SD of 15. The Language Identification Battery (Fidler et al., 2011) produces weighted scores with positive numbers (>0) indicating DLD status and negative numbers indicating TD status. The Nonword Repetition task scores are number correct out of 20 total.

Stimulus Description C_1	V_1	C_2	Short Description used in Figs. 2-3, (C indicates a voiced consonant and V indicates a front vowel)	Consistent with Family Resemblance pattern?	Consistent with OR pattern?
+	front	-	CV	yes	no
+	back	+	CC	yes	yes
-	front	+	VC	yes	no
+	front	+	CVC	yes	yes
+	back	-	C2	no	no
-	front	-	V	no	yes
-	back	+	C1	no	no
-	back	-	NONE	no	yes

Table 2 – (adapted from Gerken et al., 2019). Schematic of 8 word templates used in the experiment. For C_1 and C_2, + indicates *voiced*, - indicates *voiceless*. The Family Resemblance pattern requires at least 2 of these 3 features must be present: C_1 voiced, C_2 voiced, V_1 front (2 above). The OR pattern requires that C_1 and C_2 must have the same voicing.


Mean "accept" responses for consistent-inconsistent test items (error bars = 1SE)
5
4
3
2
1
0
-1
Family Resemblance
OR
Diagnosis
DLD
TD


Mean "accept" responses out of 4
0
1
2
3
4
DLD
TD
Diagnosis
Error bars: +/- 1 SE
CV
CC
VC
CVC
C2
V
C1
None



Mean "accept" responses out of 4
0
1
2
3
4
DLD
TD
Diagnosis
CV
CC
VC
CVC
C2
V
C1
None
Error bars: +/- 1 SE

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Figure Captions

Figure 1, mean acceptance rates (SE) for test items that were consistent minus inconsistent with familiarization stimuli. Maximum possible score is 16 (16 – 0). 0 is chance level performance.

Figure 2, mean acceptance rates (SE) for test items consistent (black) vs. inconsistent (gray) with Family Resemblance pattern familiarization items. For more information about the test items, see Table 2.

Figure 3, mean acceptance rates (SE) for test items consistent (black) vs. inconsistent (gray) with OR pattern familiarization items. For more information about the test items, see Table 2.

The authors declare that there is no conflicts of interest.