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Statistical Word Learning in Children with Autism Spectrum Disorder and Specific Language Impairment

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Abstract

Background—Word learning is an important component of language development that influences child outcomes across multiple domains. Despite the importance of word knowledge, word-learning mechanisms are poorly understood in children with specific language impairment (SLI) and children with autism spectrum disorder (ASD). This study examined underlying mechanisms of word learning, specifically, statistical learning and fast-mapping, in school-aged children with typical and atypical development.

Methods—Statistical learning was assessed through a word segmentation task and fast-mapping was examined in an object-label association task. We also examined children's ability to map meaning onto newly segmented words in a third task that combined exposure to an artificial language and a fast-mapping task.

Results—Children with SLI had poorer performance on the word segmentation and fast-mapping tasks relative to the typically developing and ASD groups, who did not differ from one another. However, when children with SLI were exposed to an artificial language with phonemes used in the subsequent fast-mapping task, they successfully learned more words than in the isolated fast-mapping task. There was some evidence that word segmentation abilities are associated with word learning in school-aged children with typical development and ASD, but not SLI. Follow-up analyses also examined performance in children with ASD who did and did not have a language impairment. Children with ASD with language impairment evidenced intact statistical learning abilities, but subtle weaknesses in fast-mapping abilities.

Conclusions—As the Procedural Deficit Hypothesis (PDH) predicts, children with SLI have impairments in statistical learning. However, children with SLI also have impairments in fast-mapping. Nonetheless, they are able to take advantage of additional phonological exposure to

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Supporting information: Additional Supporting Information may be found in the online version of this article
Appendix A. Novel Objects
Appendix B. Model Summary for Research Question 3

boost subsequent word-learning performance. In contrast to the PDH, children with ASD appear to have intact statistical learning, regardless of language status; however, fast-mapping abilities differ according to broader language skills.

Keywords

Specific language impairment; autism spectrum disorder

Introduction

School-aged typically developing children learn as many as 12 words per day (Bloom, 2000). It is well understood that a rich lexicon is crucial for language development and greatly impacts academic learning (Durkin, Conti-Ramsden, & Simkin, 2012). However, children with language impairments show persistent deficits in word learning. Specifically, children with autism spectrum disorder (ASD) and specific language impairment (SLI) demonstrate word learning difficulties that are noticeable early in development and extend into the school-aged years (Kjelgaard & Tager-Flusberg, 2001; Rice & Hoffman, 2015). Given that language learning difficulties are associated with children with ASD and SLI, it is necessary to determine whether the nature of these language learning difficulties is different in each disorder. In order to test hypotheses of word-learning mechanisms that result in language learning difficulties in these populations, this study examined two word-learning mechanisms, statistical learning and fast-mapping, in school-aged children with ASD and SLI.

Statistical learning is a domain-general implicit learning mechanism whereby individuals exploit the statistical structure of input to facilitate learning (Saffran, Aslin, & Newport, 1996). In typically developing individuals, statistical learning serves as a language-learning mechanism for phonetic discrimination (Maye, Werker, & Gerken, 2002), word learning (Smith & Yu, 2008), and syntactic learning (Gomez & Gerken, 1999). Word segmentation tasks – in which learners are exposed to a continuous stream of speech containing words with only statistical cues to word boundaries – are commonly used to study statistical language learning. A commonly tracked statistical cue is transitional probability (TP), which is the likelihood of stimulus Y given stimulus X, as a function of the frequency of the co-occurrence of XY (i.e., frequency of XY| frequency of X [Saffran et al., 1996]). Learners appear to be sensitive to these kinds of co-occurrence statistics, and can use them to distinguish high-probability sequences (words in the fluent speech stream) from low-probability sequences.

Although segmenting words from fluent speech is important, it is not sufficient for word learning. To learn a spoken word, one must process phonological information, attend to relevant linguistic and nonlinguistic contextual cues, map meaning onto the phonological form, relate the new meaning to previous conceptual knowledge, retain the form-meaning association, and use the word appropriately (Nation, 2014). To better understand the role of statistical learning in word learning, Graf Estes and colleagues examined how infants establish connections between sounds and meanings (Graf Estes, Evans, Alibali, & Saffran, 2007). Specifically, they asked whether newly segmented sound sequences – discovered via statistical learning processes – were more easily mapped onto a referent than sound sequences that had not been previously segmented. They found that infants were able to map meanings onto high-TP words (TP = 1.0), but not the nonwords (TP = 0.0) or part-words (TP = 0.33), indicating that the output of statistical learning can support word learning in infants. There has been a call for research to explain how the output of statistical learning contributes to the process of linking knowledge of sound patterns to meaning in children with ASD and SLI (Arunachalam & Luyster, 2015; Nation, 2014).

Given the high co-morbidity of language impairments in ASD, it is particularly important to examine the link between statistical learning and fast-mapping in children with ASD and SLI. The Procedural Deficit Hypothesis (PDH) has been suggested to account for language impairments in both groups (Ullman & Pierpont, 2005; Walenski, Tager-Flusberg, & Ullman, 2006); however, others suggest that language deficits in children with ASD and SLI stem from distinct or partially non-overlapping mechanisms (Boucher, 2012; Williams, Botting, & Boucher, 2008). Importantly, procedural learning and statistical learning both fit under the umbrella of implicit learning. Implicit learning is the learning of information in an incidental form, without awareness of the newly-formed information. Although the declarative/procedural model distinctly links declarative abilities with vocabulary and procedural abilities with grammar within the language domain, it has been suggested that aspects of word learning also may be supported by the implicit system (Evans, Saffran, & Robe-Torres, 2009). A better understanding of the nature of procedural and declarative learning in children with ASD and SLI is necessary.

As will be outlined below, language deficits are apparent in children with ASD and SLI (Durkin et al., 2012; Kjelgaard & Tager-Flusberg, 2001). Additionally, both groups share risk factors spanning demographic, behavioral and neural (Tager-Flusberg, 2016). It is thus important to determine whether similar learning mechanisms account for language deficits within the two populations (Obeid, Brooks, Powers, Gillespie-Lynch, & Lum, 2016; Rice, 2016).

Specific Language Impairment and Autism Spectrum Disorders

Children with SLI have a primary deficit in language without hearing impairment, intellectual disability, or neurological impairments. Although grammatical skills are particularly poor in children with SLI, other abilities often are impaired. Notably, children with SLI have poorer word learning abilities relative to chronological age-matched peers (Kan & Windsor, 2010). Children with SLI have deficits in encoding phonological and semantic information about words (Alt & Plante, 2006). In addition, they have been found to demonstrate deficits in word-learning mechanisms like shape bias (Collisson, Grela, Spaulding, Rueckl, & Magnuson, 2015). As such, lexical-semantic weaknesses exist in both breadth and depth of word knowledge (Sheng & McGregor, 2010). Beyond language, children with SLI have deficits in working memory (WM) and processing speed (Gathercole & Baddeley, 1990; Leonard et al., 2007).

Evans, Saffran, and Robe-Torres (2009) also identified deficits in statistical learning, with children with SLI requiring additional exposure to an artificial language before demonstrating above-chance learning of word boundaries. Under the PDH, statistical learning is crucial for learning rule-based features of language such as grammar and phonology (Ullman & Pierpont, 2005; but see Hsu & Bishop, 2014 for a nuanced interpretation of findings). Indeed, Hedenius et al., (2011) demonstrated that procedural learning abilities are associated with grammatical deficits in children with SLI. However, Evans and colleagues (2009) also identified an association between segmentation skills and vocabulary knowledge.

Autism spectrum disorder (ASD) is characterized by core deficits in social communication and by restricted interests and repetitive behaviors (American Psychiatric Association, 2013). Pragmatic deficits are a defining feature of ASD; however, some children also have structural language deficits, including grammatical and lexical deficits (McGregor et al., 2012). Specifically, some children have reduced breadth of word knowledge (Kjelgaard & Tager-Flusberg, 2001) and many children with ASD have limited depth of word knowledge (McGregor et al., 2012). Although children with ASD demonstrate use of learning mechanisms such as cross-situational learning (McGregor, Rost, Arenas, Farris-Trimble, & Stiles, 2013) and mutual exclusivity (de Marchena, Eigsti, Worek, Ono, & Snedeker, 2011), they have been found to not use others, like shape bias (Tek, Jaffery, Fein, & Naigles, 2008). Furthermore, studies have indicated that when children with ASD learn new words, they encode new phonological forms of words, but less-readily integrate phonological information (Henderson, Powell, Gareth Gaskell, & Norbury, 2014) and/or consolidate new word knowledge (Norbury, Griffiths, & Nation, 2010) over extended periods of time.

Given previous suggestions that the PDH may also explain deficits in children with ASD (Ruffman, Taumoepeau, & Perkins, 2012; Walenski et al., 2006), segmentation tasks also have been used to assess statistical learning in individuals with ASD. Scott-Van Zeeland and colleagues (2010) found that children with ASD failed to demonstrate neural evidence of statistical learning. However, Mayo and Eigsti (2012) found that children with ASD evidenced intact statistical learning abilities, but that they were not strongly associated with language abilities. Attention to phonological information and failure to integrate semantic information to support language development aligns with theories that suggest that children with ASD may have a featural/surface-biased information-processing style that may enhance processing of a single stimulus cue instead of focusing on multiple cues (Järvinen-Pasley, Wallace, Ramus, Happé, & Heaton, 2008).

Given the deficits in consolidating linguistic information observed in children with ASD and weak phonological representations or phonological WM observed in children with SLI, it is unclear whether these children are able to map meaning onto newly segmented words. Furthermore, the breakdown in mapping meaning to sound patterns may stem from different causes. Thus, a systematic comparison between children with ASD and SLI is needed to improve our understanding of the mechanisms that drive language impairment and to determine whether overlapping deficits contribute to the language deficits seen in both populations. Although researchers have begun to assess statistical learning in children with ASD and SLI separately, no study has evaluated the output of statistical learning – combining word segmentation and word learning – in either of these populations. Therefore, in the current study, we asked: Do children with ASD or SLI have deficits in 1) statistical learning, 2) fast-mapping, and/or 3) mapping of meaning onto newly segmented words, compared to typically developing children? In addition, we asked whether language abilities more strongly influence statistical learning and fast-mapping than diagnostic classification.

If atypical language development in ASD and SLI is derived from underlying impairments in statistical learning as proposed by the PDH, children in both diagnostic groups should demonstrate poor statistical learning. However, if children with ASD present with a surface-biased information-processing style, we would expect them to demonstrate intact statistical learning abilities. In addition, given word learning delays and difficulties with word meanings (McGregor et al., 2012), we hypothesized that children with ASD who also had a language impairment would demonstrate poor fast-mapping abilities. We also hypothesized that children with SLI would have poor fast-mapping abilities, given their known encoding deficits. Additionally, in reference to our third research question, if children were able to segment high TP words, we hypothesize that high TP words would be more readily mapped onto referents than low TP words. When comparing performance based on language impairment rather than diagnostic classification, we expect children with language impairment to have mixed profiles of statistical learning abilities. We predict that children with ASD and language impairment (ALI) will have better statistical learning abilities relative to the SLI group due to surface-level attention biases. We also predict that both language impaired subgroups would have deficits in fast-mapping. Lastly, we expect that difficulties mapping meaning to newly segmented words would be most apparent in the SLI group, relative to the subgroup with ALI. See Table 1 for an outline of the hypotheses.

Methods

Seventy-four school-aged children participated in the current study (TD $n = 26$, ASD $n = 25$, SLI $n = 23$). Given the importance of vocabulary knowledge in academic and social success in the school-aged years, we included children between the ages of 8 and 12 years. This age range also was similar to previous studies examining statistical learning abilities in children with ASD and SLI, which facilitates study comparisons. Participants lived in the greater Madison metropolitan area (USA) and were recruited from a larger two-year longitudinal study examining the relationship between language and executive functions conducted at the University of Wisconsin-Madison.

Standardized assessments were administered to measure language and cognitive skills in the first year of the larger study. Nonverbal cognitive abilities were assessed using the Perceptual Reasoning Index of the Wechsler Intelligence Scale for Children-IV (WISC-IV; Wechsler, 2003). The Peabody Picture Vocabulary Test-4 (PPVT-4; Dunn & Dunn, 2007) measured receptive vocabulary. The Clinical Evaluation of Language Fundamentals-4 (CELF-4; Semel & Wiig, 2003) was used to assess receptive and expressive lexical and grammatical skills. Children in all groups had WISC-IV standard scores above 85 (with the exception of two children with ASD who had scores of 79), and were monolingual American English speakers. Children with typical development (TD) obtained standard scores that were less than 1 standard deviation below the mean on the CELF-4 and had no history of special education services. Children with SLI scored 1.25 standard deviations below the mean on one or more of the composite CELF-4 measures or demonstrated at least a 14-point gap between one of the CELF-4 composite measures and nonverbal cognition, and had a history of or were currently receiving language therapy. Children in the ASD group had a documented community diagnosis of an autism spectrum disorder. Diagnoses were confirmed by an experienced psychologist; children with ASD had a score of 25 or higher on the Childhood Autism Rating Scale-2 (CARS-2; Schopler, Van Bourgondien, Wellman, & Love, 2010). To rule out ASD in the other groups, children with TD and SLI were required to score below the core autism cutoff score for on the Social Communication Questionnaire (SCQ; Rutter, Bailey, & Lord, 2003). Each child was required to complete the three experimental tasks and meet inclusionary criteria listed above to be included in the current study. Children were matched on chronological age ($p = .73$) and WISC-IV standard scores ($p = .72$); see Table 2 for participant characteristics.

Ethical Considerations

Parents provided informed written consent and children provided verbal assent. The study was approved by the university's Institutional Review Board.

Experimental Procedures

Participants completed three experimental tasks over two visits. Task order was counterbalanced across participants. Half of the participants completed the segmentation and fast-mapping tasks during visit 1 and the combination task during visit 2, and the other half of the participants completed the combination task during visit 1 and the segmentation and fast-mapping tasks during visit 2.

Statistical learning

A word segmentation task was used to assess statistical learning. Children were assigned to one of two artificial languages (Graf Estes et al., 2007; Experiment 1). Each artificial language consisted of four disyllabic novel words (Language A: /time/, /mɑno/, /dobu/, /pigɑ/; Language B: /nome/, /mɑti/, /gɑbu/, /pido/) that were repeated in random order without pauses or other acoustic cues to word boundaries. A female American English speaker recorded each syllable with all possible co-articulatory contexts. The syllables were later concatenated to create the artificial language containing the appropriate coarticulatory versions for each syllable at a rate of approximately 200 syllables/minute. The only reliable cue for segmentation of words was the statistical structure of the artificial language (within-word TP = 1.0, across-word TP = 0.33). While listening, children watched a silent nature slide-show for 4.75 minutes, presented using E-Prime software. Children were informed that they were going to listen to a “Martian language” and their job was to sit and listen. After the exposure phase, children completed a practice phase with commonly-known disyllabic real words and disyllabic novel words following American English phonotactics. Then, a 32-item two-alternative forced-choice (2AFC; word vs. nonword) test phase was administered. During the 2AFC, children were presented with two auditory stimuli – a word and nonword (a pair of syllables that never occurred together in the speech stream; TP = 0.0) from the artificial language. Items that were words for participants who heard Language A were nonwords for participants who heard Language B, and vice versa. During the 2AFC test, the first stimulus played while the number 1 appeared on the left side of the computer screen and as the second stimulus played the number 2 appeared on the right side of the screen. After both items had been presented, a question mark appeared in the center of the screen to prompt the child to select the stimulus that sounded like the “Martian language” by pressing the button-box key with either the number 1 or 2 above it.

Fast-mapping

A fast-mapping task assessed word learning abilities. Four novel words (/timo/, /bole/, /deno/, /pɑdu/) were paired to two-dimensional novel objects with a solid color. During teaching, each novel object was displayed and its corresponding auditory label was presented within a 2 second teaching trial. Each object-label pair was presented individually three times in a non-sequential pseudo-randomized order. In the test phase, two objects appeared at opposite sides of the bottom of the screen. An auditory cue directed the child's attention to one of the two images (e.g., “Find the __.” “Where's the __?”). Each object-label association was tested in four test trials, yielding a total of 16 test trials. The task was presented using Matlab and lasted 4.5 minutes. A video camera recorded the child's face. To derive the eye-gaze data and examine learning from the eye-gaze test phase, trained coders analyzed the videos offline using Looking-While-Listening (LWL) coding procedures (Fernald, Zangl, & Marchman, 2008). After the eye-gaze test phase completed, a second test phase ensued. The examiner showed the child a piece of paper with one of the four object images in each corner and asked the child to point to the object that she named (e.g., “Find the ___.” “Where's the ___?”). The examiner recorded in writing the child's response for each of the four labels.

Mapping meaning to sounds

A combination task (Graf Estes et al., 2007) was designed to investigate children's ability to map meaning onto newly segmented words. The task included an artificial language presentation phase, word-learning phase, and test phase. A new artificial language – different from the one used in the segmentation task – was created with the same statistical structure used in the segmentation task, using a new set of syllables (Language 2A: /pɑtu/, /midɑ/, /gine/, /bodu/; Language 2B: /tune/, /pɑgi/, /mipo/, /dɑdu/). Children were randomly assigned to one of the two artificial languages. The same methods were used to create the artificial language for the combination task as the segmentation task. The labels for the word learning phase of the combination task came from artificial language that was presented in the artificial language exposure phase of the combination task. Two of the four words in the artificial language, with TPs of 1.0, served as the labels in the subsequent fast-mapping phase. The other labels consisted of two nonwords that were comprised of non-sequential syllables from the artificial language, yielding a TP of 0. Items that were words for participants who heard Language 2A were nonwords for participants who heard Language 2B, and vice versa. The stimuli in the fast-mapping task and combination task did not differ in phonotactic probability ($p = 0.686$).

During the exposure phase, children watched a silent nature movie while listening to the new artificial language for 4.75 minutes. Afterwards, children were taught four object-label associations (i.e., 2 “words” and 2 “nonwords” from the combination task's artificial language; /midɑ/, /bodu/, /pɑgi/, /tune/) individually, three times each in a pseudo-randomized order. The two-dimensional objects had novel and distinct shapes and were different colors (relative to each other, and the objects from the fast-mapping task; see Online Supplementary Material: Appendix A). In the eye-gaze test phase, children viewed two yoked images with either the objects that corresponded to words from the artificial language, or the objects that corresponded to nonwords. Each label was tested 4 times in a pseudo-randomized order ("Find the ___." "Where's the ___?"). The combination task was presented using Matlab. After the eye-gaze test phase completed, the examiner administered the pointing test phase. The examiner showed the child a form with each of the four object images in a corner and asked the child to point to the object that she named (e.g., "Find the ___." "Where's the ___?"). The examiner recorded in writing the child's response for each of the four labels. The data from the eye-gaze test phase were coded offline by trained coders using LWL procedures.

Eye-gaze data

Inter-coder reliability was high (above 97.0% for frame and shift agreement, with ICCs > .890). Eye-gaze data tasks were cleaned at trial and child levels. Children were required to look towards the target or distractor image for at least 50% of the test window and contribute at least 2 trials in each condition. Five additional children participated in the current study but did not pass eye-gaze cleaning criteria in at least one of the eye-gaze tasks and were therefore excluded from the study because they did not contribute data for all three tasks (3 TD, 1 ASD, 1 SLI).

Results

Our first research question asked whether children with ASD and SLI have deficits in statistical learning relative to typically developing children. The mean scores on the segmentation task were 62.7% (*SD* = 14.3%) for the TD group, 63.9% (*SD* = 12.6%) for the ASD group, and 53.7% (*SD* = 11.6%) for the SLI group (see Figure 1). A mixed-effect logistic regression model tested for group differences while accounting for random variation at the child level. The random effect allowed children to vary, rather than fixing them at the same intercept value. The TD group served as the reference group. Because differences between the ASD and SLI groups are also interesting, the "linearHypothesis" function from the "car" package in R was used to test such contrasts (Fox, Friendly, & Weisberg, 2013). The TD and ASD groups performed significantly better on the segmentation task than the SLI group (TD vs. SLI group: *Estimate* = -0.41; *Std. Err* = 0.16; $z = -2.58$; ASD vs. SLI group: *Estimate* = -0.45; *Std. Err* = 0.16; $z = -2.79$). The ASD and TD groups did not differ significantly from each other (*Estimate* = 0.04; *Std. Err* = 0.16; $z = 0.24$). Additionally, each group was separately tested against chance performance (50%). The TD and ASD groups performed significantly above chance ($t[25] = 4.55$, $p < .001$; $t[24] = 5.51$, $p < .001$, respectively); however, the SLI group did not ($t[22] = 1.52$, $p = .14$). Given that the experimental tasks were administered on two schedules to control for order effects, we tested for differences in task performance according to order in which the task was administered. There was no effect of visit order on performance on the segmentation task.

Growth curve analyses (GCA) were employed to analyze eye-gaze data collected during the fast-mapping and combination tasks (Mirman, 2014). Looks to the target image during the test window (200 – 1800ms) served as the outcome variable, and are analogous to accuracy (proportion of looking to the target) in traditional ANOVA analysis procedures. Mean proportion of looks to the target were transformed into empirical log odds (Elog). Linear, quadratic, and other higher-order polynomials were included in the model to accurately represent the shape of the data. Linear time (i.e., slope) is similar to the traditional latency measure, reaction time, and indicates the rate of change in looking to the target versus the distractor during the test window. As before, the TD group was the reference group. Therefore, the intercept reported in the current analyses represents the average overall looking to the target image (similar to average proportion of looks to the target in the test window in ANOVA procedures) for the TD group. Lastly, degrees of freedom are difficult to estimate for mixed-effects models; therefore, a z-distribution was used to evaluate the significance of the t-values ($t >= +/- 1.96$ was considered significant at the .05 level).

To address the second research question, which asked whether children with ASD and SLI have deficits in fast-mapping, we analyzed the eye-gaze data from the fast-mapping task. Main effects included linear, quadratic, and cubic orthogonal time terms, group, and group by orthogonal time term interactions. Random effects were included to allow children to vary by the orthogonal time terms. The random slope GCA model yielded a significant effect of intercept (*Estimate* = 0.63; *SE* = 0.12; $t = 5.45$) and linear time (*Estimate* = 2.06; *SE* = 0.52; $t = 3.96$), indicating that children increased their looks to the target during the test window and spent more time looking at the target than the distractor. Additionally, TD and ASD groups looked to the target image significantly more than the SLI group (*Estimate* = -0.41; *SE* = 0.17; $t = -2.43$, *Estimate* = -0.37; *SE* = 0.17; $t = -2.16$, respectively). None of the interactions between group and time terms were significant. Performance did not differ according to visit order. Figure 2 depicts the average group looking behavior.

Pointing data from the fast-mapping test phase yielded accuracy scores of 2.8 (*SD* = 1.4) for the TD group, 2.8 (*SD* = 1.4) for the ASD group, and 2.0 (*SD* = 1.0) for the SLI group, out of a possible total of 4 points. The pointing data were evaluated using linear regression (which is relatively robust to violations of statistical assumptions) and non-parametric analyses. Since results were equivalent only regression findings are presented. Analysis of the pointing data from the fast-mapping task revealed similar findings to the eye-gaze data; although all groups performed significantly above chance, the TD and ASD groups had significantly higher pointing accuracy relative to the SLI group (*Estimate* = -1.30; *SE* = 0.57; $t = -2.28$, *Estimate* = -1.38; *SE* = 0.59; $t = -2.36$, respectively), but the TD and ASD groups did not differ (*Estimate* = 0.08; *SE* = 0.57; $t = 0.89$).

The third research question asked whether children are able to map meaning onto newly segmented words. In the model of the eye-gaze data from the combination task, the intercept and linear time were significant (*Estimate* = 1.68; *SE* = 0.14; $t = 4.81$, *Estimate* = 1.86; *SE* = 0.65; $t = 2.87$, respectively), indicating that children increased their looks to the target image and spent more time looking at the target than the distractor across the test window. There were no significant main effects of group or condition indicating that, overall, the groups spent a similar amount of time looking to the target and that looking to the target was similar for word and nonword trials. However, there was a three-way interaction of cubic time, condition, and SLI group (*Estimate* = -1.41; *SE* = 0.64; *t* = -2.22), indicating that children with SLI had a different trajectory of looking in the word condition, with looks to the target object, then away, and then back to the target. See appendix B for the full model results. As with the eye-gaze data, the pointing data revealed that there were no significant group differences in pointing accuracy for the combination task, *p*s >.10, and that all groups had above-chance pointing accuracy. Mean pointing scores on the combination task were 3.2 (*SD* = 1.4) for the TD group, 2.9 (*SD* = 1.5) for the ASD group, and 2.6 (*SD* = 1.4) for the SLI group. When testing for visit order effects, we found that children had higher proportion of looks to the target image and higher pointing accuracy when completing the combination task during the second visit; however, after controlling for visit order, we continued to see similar performance across the groups (i.e., a lack of a group effect). Figure 3 depicts group performance.

Our fourth research question asked whether statistical learning and fast-mapping abilities were more strongly related to child language characteristics than diagnostic group classification. As an initial step, we examined correlations within each group between performance on the experimental tasks and standardized language assessments (see Table 3). Only the ASD group exhibited significant correlations between performance on the experimental measures and language assessments. Given the heterogeneity in language abilities in children with ASD, we also examined correlations when the TD and SLI groups were combined into a non-ASD group, to have similar ranges in language assessment scores. Despite the increased range of performance with this non-ASD group the only significant correlation was between fast-mapping performance and receptive vocabulary on the PPVT-4 ($r = .405$). Nevertheless, the somewhat larger amount of variability in the ASD group may have influenced this pattern of correlations. It is noteworthy that nonverbal cognition scores were not significantly correlated with performance on the experimental tasks for any group (*p*s > .05).

To further examine our fourth research question, we classified our participants based on language abilities. Children with ASD were sub-categorized according to the CELF-4 standard scores. Thirteen children with ASD were classified as having a language impairment (ALI). These children had a CELF standard score that was at least 1.25 standard deviations below the mean, with the exception of two children who had greater than 1 standard deviation below the mean and were receiving special services for language or reading. The children in the language impairment (LI) classification consisted of children in the SLI and ALI groups; they were matched on PPVT-4 standard scores ($p = .84$) and CELF-4 Core Language standard scores ($p = .54$). The children classified as having normal language abilities consisted of children in the TD group and the ASD group with normal language (ALN); they also were matched on PPVT-4 ($p = .41$) and CELF-4 ($p = .82$) scores. In order to examine whether child language characteristics more strongly influenced statistical learning and word learning, relative to diagnostic group classification, we compared the groups within each of the language classifications on the experimental measures. In addition, we compared performance between the ALN and ALI groups, who by the nature of their language groupings differed on PPVT and CELF-4 standard scores, *p*s < .001.

First, we examined statistical learning abilities in children with LI. The mean scores on the segmentation task in the LI groups were 61.1% (*SD* = 9.51%) for the ALI group and 53.7% (*SD* = 11.6%) for the SLI group. A mixed-effect logistic regression revealed that the ALI group performed significantly better on the segmentation task than the SLI group (*Estimate* = -0.31; *Std. Err* = 0.15; *z* = -2.11). As before, each group was separately tested against chance performance (50%). The ALI group performed significantly above chance (t[12] = 4.19, p = .001), but, the SLI group did not (t[22] = 1.52, p = .14). Next, we examined statistical learning abilities in children with normal language abilities. The mean scores were 66.9% (*SD* = 15.1%) for the ALN group and 62.7% (*SD* = 14.3%) for the TD group. The mixed-effect logistic regression model revealed that performance on the segmentation task did not differ between the ALN and TD groups (*Estimate* = -0.19; *Std. Err* = 0.24; *z* = 0.41). Both groups performed significantly above chance (50%, ALN t[11] = 3.88, p = .003; TD t[25] = 4.55, $p < .001$). Lastly, a mixed-effect logistic regression model revealed that performance on the segmentation task did not differ between the ALN and ALI groups (*Estimate* = 0.28; *Std. Err* = 0.23; *z* = 1.25).

To determine whether fast-mapping differences were observed in our language groups, we analyzed eye-gaze data from the fast-mapping task. As before, main effects included linear, quadratic, and cubic orthogonal time terms, group, and group by orthogonal time term interactions. Random effects allowed children to vary by the orthogonal time terms. The random slope GCA model comparing fast-mapping performance between the ALI and SLI groups yielded a significant effect of intercept (*Estimate* = 0.31; *SE* = 0.10; *t* = 3.15) and linear time (*Estimate* = 1.24; *SE* = 0.45; *t* = 2.73), indicating that children with LI increased their looks to the target during the test window and spent more time looking at the target than the distractor. There were no significant group differences and none of the interactions between group and time terms were significant. Comparison of the pointing data, however, revealed that the ALI group had significantly higher pointing accuracy than the SLI group, $p < .05$. The random slope GCA model comparing fast-mapping performance between the ALN and TD groups revealed a significant effect of intercept (*Estimate* = 0.70; *SE* = 0.10; *t* = 6.93) and linear time (*Estimate* = 2.31; *SE* = 0.46; *t* = 5.01), indicating that children increased their looks to the target during the test window and spent more time looking at the target than the distractor. The groups did not significantly differ and there were no interactions between group and time terms. Furthermore, there were no significant differences in pointing accuracy between the ALN and TD groups, p = .96. Lastly, the random slope GCA model comparing fast-mapping performance between the ALN and ALI groups revealed a significant effect of intercept (*Estimate* = 0.78; *SE* = 0.14; *t* = 5.57) and linear time (*Estimate* = 2.55; *SE* = 0.68; *t* = 3.78). Although the ALN group spent slightly greater amount of time looking to the target image relative to the ALI group, the groups did not significantly differ (*Estimate* = -0.37; *SE* = 0.19; *t* = -1.92). There was a significant interaction of cubic time and group (*Estimate* = 1.09; *SE* = 0.55; *t* = 1.97), indicating that the ALI group had a different trajectory of looking, with looks to the target image, then away, and then back to the target. The ALN and ALI groups had similar pointing accuracy on the fast-mapping task, p = .98.

Finally, we compared performance on the combination task to examine whether the ability to map meaning onto newly segmented words differed among children with similar language abilities. In the LI comparison model, there were significant effects of intercept (*Estimate* = 0.40; *SE* = 0.09; *t* = 4.47), linear time (*Estimate* = 1.76; *SE* = 0.49; *t* = 3.62), and quadratic time (*Estimate* = -1.22; *SE* = 0.39; *t* = -3.10), indicating that the children with LI increased their looks to the target image, plateaued in looks to the target image, and spent more overall time looking at the target than the distractor across the test window. There were no significant main effects of group or condition indicating that, overall, the LI groups spent a similar amount of time looking to the target and that looking to the target was similar for word and nonword trials. However, there again was a three-way interaction of cubic time, condition, and SLI group (*Estimate* = -2.80; *SE* = 0.73; *t* = -3.85), indicating that children with SLI had a different trajectory of looking in the word condition, with looks to the target object, then away, and then back to the target. In addition, pointing accuracy did not differ between the ALI and SLI groups, *p* = .72.

In the comparison model including the ALN and TD groups, there were significant effects of intercept (*Estimate* = 0.73; *SE* = 0.10; *t* = 7.15), linear time (*Estimate* = 2.36; *SE* = 0.38; *t* = 6.22), and quadratic time (*Estimate* = -0.65; *SE* = 0.26; *t* = -2.50), indicating that the children with normal language abilities increased their looks to the target image, plateaued in looks to the target image, and spent more overall time looking at the target than the distractor across the test window. There were no significant main effects of group, condition, or interactions across group, condition, and time, indicating that the ALN and TD groups spent a similar amount of time looking to the target and that looking to the target was similar for word and nonword trials. There also were no differences in pointing accuracy between the ALN and TD groups, *p* = .65. Lastly, comparisons of the ALN and ALI groups on the eye-gaze test phase of the combination task revealed significant effects of intercept (*Estimate* = 0.78; *SE* = 0.17; *t* = 4.63) and linear time (*Estimate* = 2.85; *SE* = 0.68; *t* = 4.17), indicating that the children with ASD increased their looks to the target image and spent more overall time looking at the target than the distractor across the test window. Additionally, there was a significant effect of group, with the ALN group looking more to the target image during the test window than the ALI group (*Estimate* = -0.54; *SE* = 0.23; *t* = -2.29). There were no significant main effects of condition, or interactions across condition and time. However, there was a three-way interaction across cubic time, condition, and group (*Estimate* = -1.73; *SE* = 0.86; *t* = -2.01), indicating that the ALI group had a different trajectory of looking behavior with looks to the target image in the word condition, to looks away, and then looks back to the target towards the end of the trial. The pointing data revealed that the ALN group had marginally higher accuracy relative to the ALI group, *p* = .08.

Discussion

This study examined word-learning mechanisms in order to better understand the nature of language impairments in children with ASD and SLI. We found that children with SLI had deficits in statistical learning whereas children with ASD did not. Additionally, we found that children with SLI have deficits in fast-mapping. Fast-mapping abilities were mixed in children with ASD. Children with ASD with normal (structural) language abilities (ALN) had intact fast-mapping abilities, but children with ASD with language impairment (ALI) demonstrated subtle weaknesses in fast-mapping, evidenced by the eye-gaze data, but not the pointing data. These findings suggest that when language impairments co-exist with ASD, the nature of the word learning difficulty is different than when language impairment occurs without ASD.

To address our first research question, we examined statistical learning abilities. Statistical learning, measured through a word segmentation task, was impaired in the SLI group but unimpaired in the ASD and TD groups. Our findings were similar to those of Evans et al. (2009) and Mayo and Eigsti (2012), despite notable differences in the artificial languages used. In the current study, the artificial language consisted of four disyllabic words (Graf Estes et al., 2007). In contrast, Evans and colleagues and Mayo and Eigsti used an artificial language with six tri-syllabic words. Given the reported deficits in phonological WM in children with SLI, a reduction in syllable length in words and number of words in the language could have possibly lowered phonological WM demands and improved segmentation performance. However, most of the children with SLI in the current study were unable to sufficiently grasp the statistical structure of the language to demonstrate above-chance test performance.

Poor word segmentation performance in the SLI group may have resulted from difficulties in implicitly tracking the statistical regularities, due to processing constraints (Leonard et al., 2007). Alternatively, children with SLI may have weak phonological representations, making it difficult to differentiate words from near neighbor nonwords in the 2AFC test. Indeed, previous research suggests that children with SLI have underspecified phonetic representations (Edwards & Lahey, 1996). Additionally, children with SLI have difficulties dismissing alternative candidates during language processing tasks (McMurray, Munson, & Tomblin, 2014). With our knowledge of these other deficits in children with SLI, it is important to note that impaired implicit learning in children with SLI has been observed across a variety of linguistic and nonlinguistic tasks (Hsu, Tomblin, & Christiansen, 2014; Obeid et al., 2016; Tomblin, Mainela-Arnold, & Zhang, 2007). Thus, it seems likely that reduced performance may point to a specific deficit in statistical learning abilities in children with SLI, though other deficits may compound this weakness.

In contrast to the SLI group, the ASD group demonstrated intact statistical learning, even in the presence of concomitant ASD and language impairment. Mayo and Eigsti (2012) reported similar findings from their experiment, which used a more complex artificial language. However, these findings differed from the neural data presented by Scott-Van Zeeland and colleagues (2010). Furthermore, although Mayo and Eigsti (2012) failed to find an association between word segmentation performance and vocabulary abilities, Scott-Van Zeeland et al. (2010) reported a relationship. In the current study, we demonstrated an association between word segmentation abilities and PPVT-4 and CELF-4 Core Language standard scores in our ASD group. However, although the ALI subgroup had slightly lower word segmentation accuracy relative to the ALN subgroup, both subgroups segmented at above-chance levels. This finding suggests that statistical learning abilities may be relatively robust to language impairments in children with ASD. This may potentially be due to enhanced attentional biases for local processing seen in many children with ASD (Happé & Frith, 2006; Järvinen-Pasley et al., 2008; Mottron, Dawson, Soulières, Hubert, & Burack, 2006). Jeste and colleagues (2014) found that individuals with low nonverbal cognition and

ASD demonstrate neural evidence of visual statistical learning, though such skills were rather heterogeneous in this group.

Statistical learning abilities may be generally preserved in individuals with ASD despite heterogeneity in cognitive and linguistic skills. Like Mayo and Eigsti (2012) suggest, statistical learning abilities may not play a strong role in linguistic deficits seen in children with ASD. The suggestion that implicit learning deficits do not cause language impairments counters theories proposed in the Procedural Deficit Hypothesis (Ullman & Pierpont, 2005; Walenski et al., 2006). Instead, difficulties in consolidation may present greater challenges to language learning in children with ASD (Henderson et al., 2014; Norbury et al., 2010). Although the current study included children with ASD with varying language abilities, all of our participants were able to produce sentence-level language. Future work examining the relationship between statistical learning and language abilities in children with ASD is warranted in children with more substantial linguistic limitations.

Our second research question asked whether children with ASD and SLI have deficits in fast-mapping abilities. We measured fast-mapping using a task in which each object-label association was presented only three times. Children with SLI performed significantly worse than children in the TD and ALN groups. These findings are consistent with prior evidence suggesting that children with SLI typically require additional exposure in order to learn new words (Kan & Windsor, 2010). It is possible that in the current experiment, children with SLI were unable to form stable phonological representations of new words during the teaching phase. It is also possible that children with SLI have deficits in declarative memory, contrary to the PDH claims. Lum, Ullman, and Conti-Ramsden (2015) recently suggested that declarative memory is only impaired in children with SLI if children have concomitant WM deficits. Phonological WM and nonverbal WM skills were not measured in the current study; therefore, this claim cannot be directly addressed. However, future studies should examine cognitive predictors of fast-mapping in children with SLI.

Unlike our findings from the word segmentation task, language status may have influenced fast-mapping abilities. Children in the ALI subgroup and SLI group performed similarly on the fast-mapping task when measured using eye gaze, but children with ALI had significantly higher pointing accuracy than the SLI group. It has been suggested that children with ASD have relative strengths in object-label associative learning (Preissler, 2008). Additionally, children with ASD may be particularly good at learning the sound structure of language, such as the phonological structure of words (Järvinen-Pasley et al., 2008; Norbury et al., 2010). The current findings support this claim for children with ASD who have normal language abilities. However, the picture is more complex with our ALI group. It is possible that performance on the eye-gaze test phase of the fast-mapping task may have been driven by attention mechanisms (Nation, Marshall, & Altmann, 2003; Norbury, 2005) and that simple object-label associative learning in a fast-mapping study may be mostly preserved even in children with comorbid ASD and language impairment. However, children with ASD with comorbid language delays have been found to have deficits in fast-mapping relative to mental-age expectations (McDuffie, Kover, Hagerman, & Abbeduto, 2013). McDuffie et al. also found associations between fast-mapping and concurrent vocabulary knowledge in children with ASD and language impairments. As previous studies have suggested, child characteristics in children with ASD may influence the strength of associative learning in children with ASD and we will explore this in future studies.

Our third research question asked whether the output of statistical learning facilitates word learning. The results were somewhat mixed. Children with SLI demonstrated greater learning in the combination task than the fast-mapping task. As depicted in Figures 2 and 3, the proportion of looking to the target was higher in the combination task relative to the object-label association task. In addition, the children in the ALI subgroup did not differ from the SLI group. However, although pointing accuracy did not differ, the children with ALI spent less time looking to the target image relative to the ALN group in the combination task, which may be explained by attention differences in the two subgroups during the eye-gaze test phase. The analyses also revealed that, in contrast to our predictions, children did not learn words more easily than nonwords in the combination task. However, as indicated by the interaction across the SLI group, condition, and cubic time, children with SLI shifted from the target to the distractor and then back to the target in the word condition. Additionally, despite the lack of a main effect of condition, the correlation analyses revealed a significant association between performance on the segmentation task and combination task in the TD and ASD groups. The current study was the first to examine the link between the output of statistical learning (i.e., identifying boundaries to word forms) and subsequent mapping of word forms to referents in children with atypical development. Contrary to our hypotheses, the lack of a condition effect in the combination task and the lack of a significant correlation between segmentation performance and performance on the combination task in the SLI group indicate that there is no support for the idea that exposure to word forms with high transitional probability in a word segmentation task facilitates subsequent word learning in school-aged children.

The most surprising finding in the current study was that, unlike the fast-mapping task, children with SLI did not perform significantly worse than the other groups in the combination task. It is possible that the statistical structure of the words taught during the teaching phase of the combination task slightly enhanced learning in the SLI group. Alternatively, the SLI group's overall increase in looking to the target in word and nonword trials may be explained by the artificial language exposure phase wherein children received additional exposure to the phonemes that subsequently appeared in the words and nonwords during the object-label associative learning phase. Building on phonological explanations, exposure to the artificial language may have helped the children with SLI to develop more robust phonetic representations (Edwards & Lahey, 1996). The more stable phonetic representations may have allowed children with SLI to develop stronger representations of labels during the teaching phase. Furthermore, the more stable phonetic representations may have been easier to map to visual referents and to be differentiated from distractor images during the test phase. Dismissing alternative candidates in lexical processing tasks can be difficult for children with SLI (McMurray et al., 2014). Alternatively, attention during the teaching phase may have been primed because of the pre-exposure of the phonemes in the artificial language.

Previous language-learning studies in children with SLI have utilized therapy strategies that provide targeted input to facilitate language development. Such therapeutic strategies include auditory bombardment (Alt, Meyers, & Ancharski, 2012), recast intervention (Hassink & Leonard, 2010), and focused stimulation (Ellis Weismer, Venker, & Robertson, 2016). Additional work is needed to understand the types of exposure that facilitate word learning. For example, is exposure to the sounds/syllables of words that will be taught as effective in enhancing word learning as exposure to the novel words in isolation before object-label associations are presented? The results from this study indicate that children with SLI have deficits in statistical learning and fast-mapping; however, the link between these deficits and their problems in word learning is unclear. Our data suggest that children with SLI may require additional phonetic input to enhance learning. In contrast, children with ASD, as a group, did not display significant deficits in these learning mechanisms. Although the current study did not address slow mapping or long-term word learning, practitioners may need to address this component of the learning and consolidation process with children with ASD who have language deficits.

Conclusion

Statistical learning and fast-mapping are impaired in children with SLI, relative to their age- and cognition-matched peers with ASD and TD. In addition to previously suggested deficits in procedural learning in the Procedural Deficit Hypothesis, declarative learning, measured through the fast-mapping task, also seems to be impaired in children with SLI. In contrast, children with ASD demonstrated intact statistical learning, despite heterogeneity in language abilities. Fast-mapping abilities varied slightly according to language abilities in children with ASD. This finding counters suggestions that language impairments in children with ASD stem from deficits in procedural learning.

The current study provides an initial step in examining whether the output of statistical learning relates to subsequent word-learning opportunities. Children with SLI demonstrated increased looking to the target and higher pointing accuracy in the combination task and no longer differed from the TD and ASD groups, suggesting that the SLI group benefitted from the artificial language exposure before word learning in the combination task. However, improvements in performance seemed to only partially be attributed to the condition (words vs. nonwords), suggesting that the additional exposure to the phonemes in the artificial language also may have facilitated word learning in children with SLI. Finally, this study underscores the importance of examining language abilities in children with ASD and taking this child characteristic into account when setting appropriate therapeutic goals and approaches.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Key Points

- This study examined word-learning mechanisms – statistical learning and fast-mapping – in school-aged children with SLI and ASD. We also examined whether children map meaning onto newly segmented words to clarify the relationship between these two mechanisms.
- Children with SLI displayed poorer statistical learning than children with ASD and TD.
- Children with SLI and, to some extent, children with ASD with language impairment evidenced poorer fast-mapping than TD and ASD peers with normal language.
- There was some evidence that word segmentation abilities are associated with word learning in school-aged children with TD and ASD, but not SLI.
- Clinical implications include the need to directly address language goals in some children with ASD and to provide additional phonetic input to children with SLI.

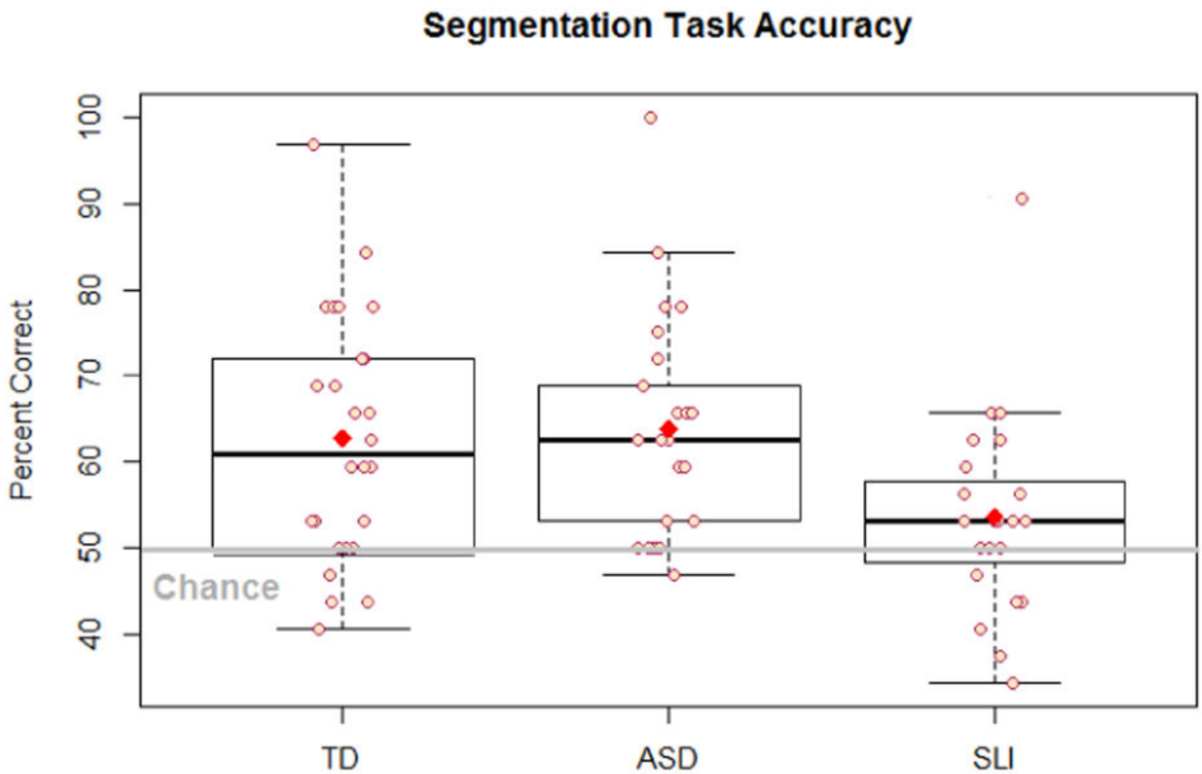

Figure 1.
Child accuracy on the segmentation task. Red diamonds represent group means.

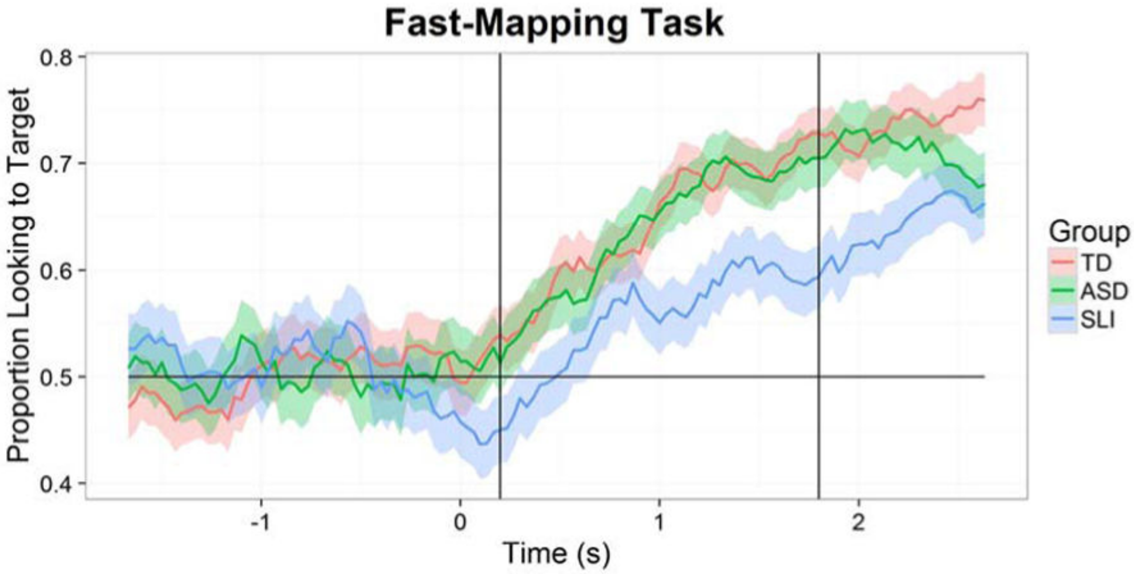

Figure 2.
Eye-gaze behavior on the fast-mapping task.

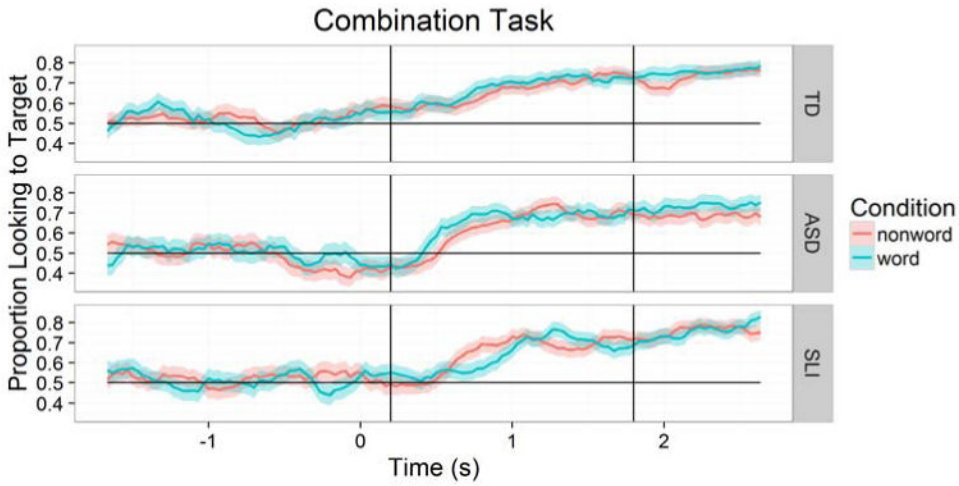

Figure 3.

Eye-gaze behavior on the combination task.

Table 1

Outline of Hypotheses

Task	Hypotheses	
Word Segmentation Task	TD & ASD[1] > SLI	TD = ALN; ALI > SLI; ALN = ALI[1]
Fast-Mapping Task	TD & ASD > SLI	TD = ALN; ALI = SLI; ALN > ALI[2]
Combination Task	TD & ASD > SLI; Word > Nonword	TD = ALN; ALI > SLI; ALN = ALI

Note

[1]Following work by Järvinen-Pasley, Wallace, Ramus, Happé, and Heaton (2008).

[2]Following work by McGregor, Berns, Owen, Michels, Duff, Bahnsen, and Lloyd (2012). TD = typical development, ALN = ASD with normal language, ALI = ASD with language impairment.

Table 2

Participant Characteristics

	TD (n = 26, 13 females)		ASD (n = 25, 3 females)		SLI (n = 23, 12 females)		Group Comparisons
	Mean	SD	Mean	SD	Mean	SD	
Chronological Age	10.38	(1.28)	10.13	(1.36)	10.28	(1.18)	TD = ASD = SLI
WISC-4[1]	104.50	(9.06)	103.65	(16.63)	102.35	(10.88)	TD = ASD = SLI
CELF-CL[2]	103.69	(12.37)	88.35	(20.21)	81.91	(14.23)	TD > ASD* = SLI[4]
PPVT-4[3]	110.96	(17.02)	106.27	(18.90)	94.22	(13.77)	TD = ASD > SLI*

Note.

[1] Perceptual Reasoning Index Standard Score

[2] Core Language Standard Score,

[3] Receptive Vocabulary Standard Score

[4] ASD vs. SLI $p = .101$

* $p < .05$

Table 3

Group Correlations

	Segmentation Task[1]	Fast-Mapping Task[2]	Combination Task[2]	PPVT-4[3]	CELF-CL[4]
Typical Development					
Segmentation Task		.207	.418*	-.072	-.172
Fast-Mapping Task			-.235	.360†	.016
Combination Task				.172	.219
ASD					
	Segmentation Task[1]	Fast-Mapping Task[2]	Combination Task[2]	PPVT-4[3]	CELF-CL[4]
Segmentation Task		.261	.445*	.469*	.466*
Fast-Mapping Task			.444*	.566*	.507*
Combination Task				.541*	.581*
SLI					
	Segmentation Task[1]	Fast-Mapping Task[2]	Combination Task[2]	PPVT-4[3]	CELF-CL[4]
Segmentation Task		.108	.051	.170	.165
Fast-Mapping Task			.249	.229	.159
Combination Task				.365†	.113

Note.

[1]Percent accuracy

[2]Mean proportion of looks to the target

[3]Receptive Vocabulary Standard Score

[4]Core Language Standard Score

† $p < .1$

* $p < .05$.