Prediction and Word Learning in Young Autistic Children

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A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

(Communication Sciences and Disorders)

at the

UNIVERSITY OF WISCONSIN-MADISON

2024

Date of final oral examination: 6/21/2024

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Dedication

For Freddie James, my dissertation baby.

Acknowledgements

First, I would like to express immense gratitude to the children and families who participated in this research. This work is not possible without your time and commitment. We are so grateful that you have taken time out of your busy lives to support autism research.

I would like to acknowledge the funding sources that have supported this work. These include NIH grants NIDCD F31DC020902 (PI: Mathée-Scott), NIDCD R01 DC17974 (MPIs: Ellis Weismer & Saffran), and U54 HD03352 (core grant to the Waisman Center), the American Speech-Language-Hearing Foundation New Century Scholars Award and the Department of Communications Sciences and Disorders at UW-Madison.

I am eternally grateful to my mentor, Dr. Susan Ellis Weismer, who continued to work tirelessly to guide me, even in retirement. There is no one better to learn from in the field of child language than Susan. She is a steadfast leader, a brilliant scientist, a prolific writer, and most of all, an incredibly supportive person and mentor. Due to some unique circumstances, I know that I required more support than many, and Susan rose to the occasion every step of the way.

I would also like to thank my dissertation committee members, Dr. Jenny Saffran, Dr. Audra Sterling, and Dr. Haley Vlach. My introduction to child language research occurred 11 years ago, when I began working in Dr. Saffran's Infant Learning Lab. Her mentorship has guided my career and scientific development ever since. Similarly, Dr. Sterling has served as a mentor to me since I took her Child Language Disorders course, over 10 years ago. She has been an incredibly influential role model to me over the past decade and has provided invaluable mentorship and guidance over the past decade. I have learned so much from Dr. Vlach's lab meetings, courses, and our individual meetings. The way that she thinks about children's learning, cognition and memory has been highly influential in this dissertation work and my scientific development.

I would like to thank the members of the Language Processes Lab and Little Listeners research group. In particular, I would like to thank Kristine Millard, Kathryn Prescott, Heidi Sindberg, Martha Walters, and Lucia Stubbs for their help with data collection, their hard work and their expertise. I would like to thank the undergraduate and graduate research assistants whose help was essential in completing this work. In particular, I would like to thank Hannah Tauke, River Steen, and Morgan Kuckkahn for their hard work and dedication.

I would also like to thank some additional mentors who have helped shape my career and this dissertation. These include Dr. Courtney Venker, Dr. Caroline Larson, Dr. Ron Pomper, and Dr. Sara Kover.

On a personal note, I would like to thank my doctors, Dr. Brittany Galusha and Dr. Rebecca Sippel, who found and treated my thyroid cancer and allowed me to finish this dissertation and PhD in good health.

Finally, I express my deepest gratitude to my family. My husband, Kyle and my son, Freddie have kept me sane and grounded during this process. I owe so very much to my parents, Bettsy and Jamie, who always believed in my potential and gave me the firm foundation necessary to succeed in both my career and life. In particular, I extend my deepest appreciation to my mom, who drove two hours, back and forth, to Madison every week, over the past year, to provide childcare so that I could work on this dissertation. Without her sacrifices, throughout my entire life, but particularly over the past year, I would not have accomplished this dream. Mom, Dad, Kyle, and Freddie, I could not have done this without you.

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Abstract

The present dissertation tested prediction-based theories of autism spectrum disorder (ASD) in a word learning context. The predictive impairment in autism hypothesis has shown promise for explaining some phenotypic characteristics of ASD. The utility of this theoretical framework for explaining difficulty with language learning, however, remains largely unclear. Given that children learn words in their natural, often unpredictable environments, difficulty tracking unpredictable stimuli might have profound impacts on word learning. The present set of studies examined how difficulties aggregating unpredictable input might impact novel word learning in ASD. Thirty autistic and 31 non-autistic, younger, cognitive-ability-matched children participated in three eyegaze word learning tasks. Four novel words were taught, two with the same adjective at every exposure (predictable condition) and two with varied adjectives (unpredictable condition). In Study 1, we tested children's ability to anticipate the upcoming novel noun based on a preceding adjective and learn the label-object pairings. In Study 2a, we tested their ability to retain the words after a five-minute delay. In Study 2b, we tested children's generalization of the novel labels to shape-matched objects. Findings from Study 1 suggest that both groups were able to learn novel words taught in both predictable and unpredictable sentence contexts. However, groups differed significantly in their ability to predict upcoming novel words based on predictable adjectives. Autistic children looked significantly more to target during the anticipation window in the predictable condition, whereas the NT group did not show a significant difference in anticipation between the two conditions. Findings from Study 2a indicated that autistic children were able to retain the words above chance levels in the predictable condition, but not the unpredictable condition, whereas NT children did not demonstrate retention above chance in either condition. Study 2b revealed that children in both groups demonstrated generalization above chance levels in the predictable, but not the unpredictable condition. Individual differences related to performance on the aforementioned tasks were examined in Study 3. Overall, this work lends moderate support to prediction-based theories of ASD. This work also suggests that predictable sentence contexts may support autistic children's ability to learn, retain, and generalize new words.

Chapter 1: Introduction

Language and Word Learning in Autism Spectrum Disorder

Autism spectrum disorder (ASD) is a neurodevelopmental disorder characterized by social communication deficits and restricted and repetitive behaviors (*Diagnostic and Statistical Manual of Mental Disorders* 5th ed.; DSM–5; APA, 2013). Current estimates are that one in 36 children in the United States carries a diagnosis of autism, according to the CDC (Maenner et al., 2023). ASD is prevalent across all racial, ethnic, and socioeconomic groups. Deficits in social communication (e.g., difficulty with back-and-forth conversations, eye contact, nonverbal communication, and imaginative play) are inherent to the diagnosis of ASD. However, human communication involves the *form, content*, and *use* of language. Social communication, also referred to as pragmatic language, represents the *use* of language. The ASD diagnosis can be given with or without an impairment in structural language (APA, 2013). Structural language represents the *form* and *content* of language. In other words, structural language involves the sounds, words, and syntax of language.

ASD is characterized by broad heterogeneity, including considerable variability in structural language abilities (Delehanty et al., 2018; Ellis Weismer et al., 2010; Ellis Weismer & Kover, 2015; Koegel et al., 2020; Reindal et al., 2023). Although many autistic children demonstrate age-appropriate language abilities, prior research suggests that over a quarter of autistic children have minimal to no functional spoken language ability by the time they enter kindergarten (Tager-Flusberg & Kasari, 2013). Indeed, delays in language are among the most frequent early concerns noted by parents before receiving an ASD diagnosis (Coonrod & Stone, 2004). Thus, understanding the underpinnings of these early language delays might have important implications for beginning and targeting early interventions effectively. Importantly however, the mechanisms which underlie these delays and explain this vast heterogeneity remain a significant gap in knowledge.

In particular, the field presently lacks an understanding of the underpinnings of differences in structural language ability (i.e., vocabulary and syntax) in autism. Vocabulary (i.e., lexical knowledge) represents an important building block of the structural language system. As such, difficulty learning new words, retaining their meanings, and integrating them into a flexible vocabulary might contribute to downstream delays in structural language. Autistic children often demonstrate a puzzling early vocabulary phenotype in which comprehension (i.e., receptive vocabulary) is relatively more delayed than production (i.e., expressive vocabulary; Davidson & Ellis Weismer, 2017.) One hypothesis to explain vocabulary deficits in ASD is that autistic children might not learn new words in the same way that neurotypical (NT) children do.

Indeed, researchers have established atypical or absent use of early word learning mechanisms such as the mutual exclusivity and shape biases (and difficulty with generalization of newly learned words in this population (Mathée-Scott et al., 2021; Tek et al., 2008; Tovar et al., 2020). However, the field presently lacks a comprehensive theoretical framework to explain these deficits. While some word learning mechanisms are impaired or absent, others appear to be a strength for autistic children, including relatively robust abilities to employ linguistic statistical learning (Haebig, 2015; Obeid et al., 2016; but see Hu et al., 2023; Scott-Van Zeeland et al., 2010) and utilize cross-situational word learning (Venker, 2019). At present, the underpinnings of these contradictory word learning findings in autism remain relatively unclear. Furthermore, the precise conditions that best support autistic children's ability to learn new words and flexibly integrate them into their vocabularies are not well understood.

Memory and Word Retention in ASD

Initial word learning is not enough to support overall vocabulary. Indeed, children learn words over extended timescales, spanning days, weeks, months and years. Children must integrate their exposures of word meanings across these timescales in order to build their lexicons. As such, memory plays a crucial role in extending word learning to word knowledge and functional use. Yet, much of the word learning literature to date focuses primarily on the encoding stage of word learning, often referred to as fast-mapping. However, it is crucial to look beyond this initial learning to fully understand the role of word learning differences in the overall development of structural language in autistic children. Indeed, children do not simply fast-map an object-label pairing and immediately retain, consolidate, and flexibly integrate it into their lexicon. This process takes course over longer periods of time. Additionally, this process likely does not occur uniformly for every child, nor for every word that a single child learns. Short- and long-term memory processes dynamically impact a child's memory for newly learned words throughout development. Additionally, it is important to consider the impact of a child's environment on these memory processes. As described by Storkel (2015), the input a child receives interacts with these memory processes to either help or hinder their memory for newly learned words. This interaction may be especially important for understanding the unique word-learning and memory processes that autistic children employ.

The role of memory and retention in word-learning has become increasingly understood in typical development. Vlach and colleagues (2012) have elucidated the importance of memory processes, (i.e., spacing effect, forgetting, consolidation, retrieval) in children's ability to retain and generalize newly learned words. Memory constraints in word learning have been studied in typical development as early as toddlerhood (Vlach & Johnson, 2013). Indeed, memory constraints appear to play an important role in word learning, particularly for generalization of newly learned words to other exemplars (Vlach, 2014). Crucially, the link between these memory processes and word learning has not yet been sufficiently explored in ASD. To date, these memory processes and their interaction with word learning abilities are not well understood in ASD. Hartley and colleagues (2019, 2020) have investigated retention of newly-learned words in school-age autistic children. Hartley (2019) found that autistic children demonstrated initial learning commensurate with receptive vocabulary-matched NT peers in a fast-mapping word learning task but displayed substantially decreased accuracy after a short delay (5 minutes). The conditions of the input that best support memory for words in autistic children is not well understood. A recent study by Carter and Hartley (2021) found that autistic toddlers retained label-object pairings better over a 5-minute delay when words were taught using color photographs (i.e., greater iconicity) than black-and-white cartoons. Future work will be necessary to further understand the type of input that best supports retention in this population. Namely, research investigating the types of linguistic input that best support memory for newly learned words in autistic children will be paramount.

Prediction-based Theories of ASD

Over the past decade, several research groups have advanced novel predictive coding theories of ASD, proposing that atypical predictive processing may explain the unique cognitive and behavioral features of ASD. Sinha and colleagues advanced existing predictive coding theories, proposing a Predictive Impairment in Autism (PIA) hypothesis, linking impaired prediction abilities to reduced contextual processing (Sinha et al., 2014). Sinha's research group updated their prior theoretical stance more recently, publishing a review in 2021, showing mixed evidence for prediction impairments across domains, but strong evidence for impairments in both the learning of predictive associations and the neural signaling of low-level prediction errors in ASD (Cannon et al., 2021). It should be noted that in Cannon and colleagues' (2021) review, the group updated their view of the use of the term "impairment" within their original theory. The theory itself uses this term, (i.e., PIA) but the authors noted in 2021 that "not all cognitive diversity associated with ASD necessarily results in functional impairment." Indeed, the updated findings reported in Cannon and colleagues' (2021) review reveal a more nuanced picture. That is, there are some contexts in which autistic children appear to demonstrate difficulty with predictive learning (e.g., predictions in the social domain), and others in which differences are not observed consistently (e.g., visual predictions in which antecedent-consequence patterns are constant). Additionally, there are other contexts in which Cannon and colleagues (2021) reported increased neural responsivity to predictive stimuli in autistic samples. As such, in keeping with these authors' updated terminology preferences, along with growing consensus among the autistic community that deficit-based language around ASD is stigmatizing (Bottema-Beutel et al., 2021) I will use the term "impairment" sparingly throughout this dissertation, as needed to refer to the PIA hypothesis. I will also use primarily identity-first language (e.g., "autistic children" rather than "children with autism") in accordance with Bottema-Beutel and colleagues' (2021) recommendations for avoiding ableist language.

Prediction and Language in ASD

To date, links between such prediction differences and language delays remain largely understudied. Understanding these links is a clear next step for scientific inquiry, as research suggests that language is processed incrementally, and requires that children track statistical probabilities in the input and generate ongoing predictions (Saffran, 2020). Incremental language processing has been studied in autistic children (Prescott et al., 2022; Venker et al., 2019), showing that autistic children who had weaker extant language abilities demonstrated less robust use of prior information from verbs to speed up processing of semantically constrained nouns. This suggests a possible link between predictive processing and language ability. The relationship between prediction deficits and language processing requires further inquiry to be fully understood. Moreover, there is a paucity of research to date on the role of prediction deficits in word learning. Therefore, the link between deficits in predictive associations (Cannon et al., 2021) and differences in word learning abilities in ASD (Tovar et al., 2020; Hartley et al., 2019, 2020) remains a significant gap in theoretical and clinical knowledge.

Autistic children have demonstrated robust abilities to employ statistical learning and utilize cross-situational word learning (Haebig et al., 2017; Venker, 2019). Importantly however, in their natural environments, autistic children face the added challenge of input that is inconsistent, imperfect, and unpredictable. While prior research has found links between predictability of stimulus presentations and word learning in NT infants (Benitez & Saffran, 2018) and in language processing in ASD (Prescott et al., 2022; Venker et al., 2019). To date, the impact of stimulus predictability on word learning in ASD is unknown. Based on predictive coding theory, one could hypothesize that disruptions in stimulus statistics (i.e., unpredictability) might disproportionately impede autistic children's learning (Sinha et al., 2014; Van de Cruys et al., 2013, 2014). Indeed, autistic individuals have demonstrated atypical neurological responses to predictive auditory and audio-visual stimuli (Font-Alaminos et al., 2020; Ruiz-Martínez et al., 2020; van Laarhoven et al., 2020). To date, however, there is a paucity of evidence on prediction in the linguistic domain (Ellis Weismer & Saffran, 2022). However, given that prediction-based theories of ASD, particularly Sinha and colleagues (2014) hypothesize that prediction deficits occur across domains in ASD (e.g., cognitive, linguistic, social) it stands to reason that language may be impacted by predictive coding deficits.

Hyperplasticity and Language Learning

One facet of the PIA theory that might have profound impacts for language is the hyperplasticity hypothesis. Herein, Sinha and colleagues (2014) propose that autistic children overweight recency, treating incoming environmental stimuli as new learning. This tendency to treat all or most environmental stimuli as new learning, and therefore disproportionally weight these experiences when integrating new knowledge with existing knowledge has been demonstrated in adults with ASD (Church et al., 2015). Recently, there has been mixed evidence regarding hyperplastic learning in linguistic contexts for autistic children. Mathée-Scott and colleagues, (under review) found that autistic children who were able to learn an original antecedent-consequence relationship demonstrated hyperplastic learning in a linguistically-relevant task (i.e., speaker dependent cues) relative to younger, NT children. That is, autistic children adjusted their looking behavior based on a newly introduced contingency, whereas NT children more heavily weighted their cumulative experience with the prior contingency. However, this pattern did not hold in a non-linguistic task. Conversely, Prescott and colleagues (under review) did not find evidence of hyperplastic learning in a linguistic context in which adjectives predicted upcoming nouns. As such, recent evidence paints a nuanced picture with several questions which remain unanswered. It appears that there may be some linguistic contexts in which autistic children are impacted by hyperplasticity of learning, and others in which they may not be.

Better understanding how hyperplasticity of learning might impact word learning in ASD may provide new clues into differences in word learning in this population. It is possible that exposure to unpredictable linguistic input might impact autistic children's ability to update prior linguistic statistics and integrate them with existing knowledge. Language unfolds in statistically constrained sequences, (Saffran, 2020) however most language input in the real world is not perfectly predictable or consistent. That is, children experience variation and unpredictability in the speakers, exemplars, words, and environmental and linguistic contexts in which they experience language. As such, unpredictable input might impact autistic children's ability to update prior statistics and integrate them with existing knowledge. If borne out in a word learning context, this may have important implications, particularly for generalization, which requires integration of new learning with prior experience.

Generalization of Word Knowledge

Generalization is thought to be a particular area of deficit in the language profiles of autistic children (Happe & Frith, 2006; Hartley & Allen, 2014). To understand the precise mechanisms underlying word learning in this population, it is paramount that researchers examine not only initial word learning, (fast-mapping) but also evaluate differences in autistic children's ability to generalize labels to objects in the same category. The hyperplasticity hypothesis (Sinha et al., 2014) may have important implications for generalization within word learning in ASD. The tendency to treat all or most environmental stimuli as new learning, disproportionally weighting these experiences when integrating new exposures with existing knowledge, may be advantageous in some contexts, but detrimental in others. In the context of word learning, treating stimuli disproportionally as novel may result in decreased ability to integrate current experiences with previous experience, thus potentially impacting one's ability to generalize object-label pairings across exposures. Indeed, prior research has established atypical use of the shape-bias to generalize labels to shape-matched objects in this population

(Tek et al., 2008; Tovar et al., 2020). In addition to evaluating retention of object-label mappings, Hartley and colleagues (2019) examined generalization of newly learned words in school-age autistic children, finding impaired generalization of fast-mapped words in autistic, school-aged children compared to NT peers matched on receptive vocabulary. However, Hartley and colleagues (2020) found similar retention and generalization of words learned via cross-situational word learning in receptive language-matched autistic and non-autistic children. Thus, to date, a significant gap in knowledge remains regarding the conditions under which words are best generalized in this population.

The Role of Individual Differences

ASD is a disorder characterized by extensive heterogeneity (Wolfers et al., 2019) particularly in the area of structural language (Koegel et al., 2020). As such, it has become broadly evident that investigating individual differences is crucial for understanding the underpinnings of language development and word learning in this population. For example, Hartley and colleagues (2020) investigated the role of individual differences in age, receptive vocabulary and nonverbal cognition on autistic and non-autistic children's ability to engage in cross-situational word learning. While individual differences in each of these variables appeared to have effects on accuracy and response time in both groups, the authors acknowledge that intercorrelations between these variables make conclusions about each of their individual contributions to word learning difficult to make. Similarly, Abdelaziz and colleagues (2018) examined potential individual differences related to the use of the shape bias in autistic children's word learning. Their conclusions were that no single account sufficiently explained shape bias performance. For example, vocabulary differences did not significantly account for performance. However, for children with low verbal ability and ASD, these authors did observe a positive association between initiation of joint attention and the use of shape bias. With respect to prediction abilities in ASD, individual differences may play an important role in disambiguating the picture. Cannon and colleagues' highlight in their (2021) review that the relationship between prediction differences and other phenotypic characteristics (e.g., ASD symptom severity/traits, genetic profiles, cognitive ability, language ability) remains largely unclear. These authors suggest that future research investigating the role of individual differences in explaining prediction differences will be crucial. Understanding the individual differences that contribute to prediction abilities will help to better inform the theory (i.e., PIA hypothesis) and will help to determine whether prediction-based theories can be applied to intervention contexts.

Clinical Implications

Understanding the underpinnings of autistic children's language and word learning is of great clinical significance. Improved understanding of what factors underlie language deficits in this population will allow for researchers and clinicians to design and target interventions earlier and more effectively. Central to this goal is better understanding how autistic children learn the labels for the objects in their environment, retain those labels, and generalize them, in order to integrate them into their vocabularies. To date, relatively little is known about the early dynamics of word learning processes in young autistic children. Thus, understanding the conditions under-which autistic children can best learn, retain, and generalize words (e.g., in predictable contexts, as hypothesized by PIA theory) is a clear area of clinical need. More specifically, generalization of learning has long been identified as an area of particular clinical concern for treating autistic children (de Marchena et al., 2015). In fact, early research on this phenomenon found that nearly half of autistic children demonstrated no transfer of skills from therapeutic contexts to another environment (Rincover & Koegel, 1975). Clinical research has continued to demonstrate difficulty with generalization across several domains in autistic children (Bellini et al., 2007). See Brown and Bebko (2012) and Wass and Porayska-Pomsta (2014) for reviews of more recent literature, describing a) the paucity of clinical studies that have evaluated generalization of skills beyond a period of a few months and to additional settings and b) the demonstrated difficulty with generalization of skills when it is explicitly evaluated in this population.

The Current Dissertation

The current dissertation aimed to advance the field's understanding of the contexts in which autistic children can best learn, retain, and generalize new words, which may have far-reaching clinical as well as theoretical significance. The mechanisms which underlie language delays in ASD remain a significant gap in knowledge. Researchers have established difficulty with generalization and atypical use of word learning mechanisms in this population (Hartley et al., 2020; Mathée-Scott et al., 2021; Tovar et al., 2020), but the field presently lacks a comprehensive theoretical framework to explain these deficits. This dissertation evaluates the utility of Sinha's (2014) PIA hypothesis in understanding word learning differences in ASD. To this aim, we investigated the impact of an unpredictable word learning environment on initial word learning, retention, and generalization in 2–4-year-old autistic children compared to cognitively matched, younger, NT peers, via three experiments.

Aims and Hypotheses

Aim I: To establish the impact of predictable and unpredictable presentations on initial word learning in autistic children compared to cognitively matched NT peers.

Study 1 employed an eyegaze paradigm to examine the pattern of word learning in autistic toddlers and their NT peers matched on nonverbal cognitive ability, when words were trained in predictable and unpredictable contexts. Two novel words were trained and tested in predictable sentence contexts, in which a predictable adjective (i.e., consistent across presentations) preceded the noun at each presentation (e.g., Training: "It's a *silly* modi;" Test: "Find the *silly* modi"). Two additional novel words were trained and tested in unpredictable sentence contexts, in which the adjective preceding the noun varied at each presentation (e.g., "It's a *funny/nice/pretty* toma").

Two dependent measures were used to evaluate learning in this task. Anticipatory eye movements (AEM's) were used to assess whether children correctly predicted the noun based on the preceding adjective. Proportion of looking to target was used to assess accuracy as a measure of word learning. Growth curve analyses were used to evaluate the impact of condition (predictable versus unpredictable) and group (ASD versus NT) on looking behavior.

Hypotheses: We predicted that due to difficulty encoding unpredictable stimuli, autistic children would demonstrate poorer prediction and disproportionately disrupt word learning in the unpredictable condition compared to NT peers.

Aim II: <u>To establish the impact of predictable and unpredictable presentations on retention and generalization of word learning over a 5-minute delay in autistic toddlers compared to cognitively matched NT peers.</u>

Study 2a employed eyegaze methods to evaluate autistic children's ability to retain novel object-label mappings learned in predictable and unpredictable sentence contexts, as compared to their NT peers.

Study 2b tested generalization of labels to shape-matched objects. Immediately following the retention trials, children saw eight trials testing generalization. For each of the four objects initially taught, children saw two trials testing whether they would generalize the label to shape-matched objects. Shape-matched images were created using Photoshop, changing the color of the object presented. We chose to evaluate shape-match generalization given that autistic children have demonstrated atypical use of the shape-bias mechanism for generalization (Tek et al., 2008, Tovar et al., 2020). As such, understanding the input that best supports autistic children's ability to engage in shape-based generalization is paramount.

In Studies 2a and 2b, proportion of looking to target was used to assess accuracy on retention (Study 2a) and generalization (Study 2b) trials. Growth curve modeling was used to evaluate the impact of condition and group on looking behavior at delayed test (Study 2a), and to shape-matched objects (Study 2b).

Hypotheses: We predicted that due to difficultly integrating unpredictable input, autistic children would show decreased retention of the label-object pairings for objects taught in the unpredictable condition compared to NT peers. We predicted that autistic children would show poorer generalization of words in the unpredictable condition compared to NT peers due to a tendency toward hyperplasticity, characterized by difficulty integrating unpredictable stimuli with prior learning.

Aim III: To evaluate the extent to which child characteristics predict individual variability in word learning performance following predictable and unpredictable presentations in autistic children.

To evaluate the role of individual differences, we used standardized measures of cognition, autistic traits, and structural language, modeled as concurrent predictors of performance on the tasks from Studies 1 and 2a/2b. We fit linear models for which the dependent variable was average accuracy in each condition and experimental window.

Hypotheses: We predicted that difficulty with learning, retaining, and generalizing words presented via unpredictable stimuli (e.g., performance on Studies 1, 2a and 2b) would be associated with structural language ability (receptive and expressive language), given that prior work has found links between extant language ability and use of word learning mechanisms (Mathée-Scott et al., 2021) as well as incremental language processing (Prescott et al., 2022) in autistic children. According to Cannon and colleagues (2021) there has been limited research to date that has explored links between prediction and other individual differences, including cognitive ability and autistic traits. No clear links to individual differences in autistic traits or nonverbal cognition have been demonstrated for real word comprehension (Venker et al., 2013), nor the use of the shape bias (Abdelaziz et al., 2018). As such, we predicted that individual differences in non-verbal cognition and autistic traits would not sufficiently explain differences in task performance on the present studies.

Overview

The present dissertation aimed to address important gaps in the prior literature on word learning in ASD. To date, the field lacks a theoretical basis for understanding differences in the use of word learning mechanisms by autistic individuals, as well as a clear understanding of the mechanisms underlying the heterogeneity in language outcomes across the autism spectrum. Understanding what precise conditions best support word learning in this population will have important implications, both theoretical and clinical. To this end, the present dissertation aimed to evaluate the utility of prediction-based theories in explaining some of the differences in word learning patterns among autistic individuals. The present dissertation aimed to answer four research questions:

First, we asked whether autistic children were able to learn words more robustly when the input was presented in predictable versus unpredictable sentence contexts, compared to their NT peers.

Second, this project aimed to evaluate whether the predictability of the word learning input would support autistic and non-autistic children's ability to retain object-label pairings after a short delay (5 minutes).

Third, we evaluated whether autistic and non-autistic children were able to generalize words learned from predictable and unpredictable sentence contexts to shape-matched objects at delayed test.

Finally, this project aimed to explore the individual differences that contribute to performance on the word learning tasks, including cognitive ability, language ability and autistic traits.

This line of inquiry will lead to greater understanding of the heterogeneity observed in language and word learning in this population. This dissertation will explore these research questions across six subsequent chapters. Chapter 2: "General Methods," will describe the methodological approach taken for each of the three experimental tasks. Chapter 3: "Word Learning from Predictable and Unpredictable Input in Autistic and Non-autistic Children," will report findings from Study 1. Chapter 4: "Retention and Generalization of Object-Label Pairings Learned from Predictable and Unpredictable Input in Autistic and Non-autistic Children," will report findings from Study 2a and 2b. Chapter 5: "Individual Differences in Prediction and Word Learning among Autistic and Non-autistic Children," will explore the findings relevant to Aim III. Finally, Chapter 6: "General Discussion," will synthesize the preceding findings from each aim, their clinical and theoretical implications, and discuss future directions related to this work.

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Chapter 2: General Methods

General Procedure

The present dissertation involved three experimental eyegaze tasks (Study 1 and Study 2a/2b) along with a series of developmental assessments (see *Assessment Measures*, below). Developmental assessment data will be analyzed alongside performance on the experimental tasks to evaluate the role of individual differences (Study 3). The present studies were administered to participants who were recruited for a larger study within Dr. Ellis Weismer's laboratory (Little Listener's Project, Ellis Weismer and Saffran, MPIs, https://littlelisteners.waisman.wisc.edu/). The larger study protocol involved two timepoints, approximately one year apart (Time 1 and Time 2). Enrollment for both time points of the parent project was ongoing at the time this dissertation project was conducted. Thus, participants being tested at either timepoint of the parent project were eligible to participate in the present dissertation studies. However, each individual participant only was administered the present studies at Time 1 or Time 2. Time 1 visits involved two in-person visits and one virtual visit conducted via secure WebEx conference. This visit was conducted virtually due to the COVID-19 pandemic. Due to decreased task demands for the second timepoint, Time 2 visits involved one in-person visit. However, the parent project administered developmental assessments via telehealth at Time 2 as well, in order to be consistent with the procedure at Time 1. Telehealth sessions were recorded for scoring purposes. The order of experiment presentation was counterbalanced across participants, including counterbalancing of day of administration for those children participating at Time 1 across two days. Written informed consent was provided by a legal guardian prior to the start of the first visit at each timepoint. Families received financial compensation and children received a book as a thank you for their participation. The laboratory team included two licensed psychologists who completed autism diagnostic measures, and three certified speech-language pathologists (including the author) who administered language and cognitive assessments (see *Assessment Measures*). The team also included a research specialist who helped with recruitment and administration of eyegaze tasks. This protocol was approved by the Institutional Review Board at the University of Wisconsin-Madison.

Eyegaze Task Procedure

Eyegaze experiments (Study 1 and 2a/2b) followed standard procedures for Looking-While-Listening studies (Fernald et al., 2008). The experiments were administered in-person at the Waisman center in a child-friendly, sound-attenuated booth. The booth contained a chair, two floor lamps, a 55-inch television screen, a speaker, and a camera. A Canon video camera was mounted below the screen to record children's eye movements at a frame rate of 30 Hz for later offline coding (see *Data Coding and Processing*). Auditory stimuli played at a level of 65 dB from a speaker that was mounted below the screen. A trained experimenter (either the author or another trained laboratory member) administered the experiments via a PC computer, situated just outside the experimental booth, using E-Prime software (Version 3.0, Psychology Software Tools, Inc, 2016). The eye-gaze tasks lasted approximately two to five minutes. During the experiment, children sat on their caregiver's lap, or independently if they preferred, on a chair in the experimental booth, approximately 60 cm away from the television screen. If the caregiver was in the booth, they were asked to wear opaque glasses to prevent their gaze from influencing their child's looking behaviors. Caregivers were also asked to refrain from talking to their child, particularly to refrain from restating any of the words heard in the experiment, or from directing their child's attention in any way during the experiment.

Participants

A total of 72 children, 37 one- and two- year-old neurotypical (NT) children and 35 two-, three-, and four-year-old autistic children, were recruited to participate in the present dissertation research. In order to facilitate group matching based on cognitive abilities while allowing for a representative range of abilities within the autistic group, including those with possible concomitant intellectual disability, the NT group that was enrolled was younger than the ASD group (see *Group Matching*). Children in the NT group were screened for ASD using an appropriate measure and method based on their age at the time of participation. NT children participating at Time 1 fell within the age range of the Modified Checklist for Autism, Revised with Follow-Up (MCHAT-R/F; Robins et al., 2009). Thus, parents of those children completed this measure and children included in this group had scores in the "Low-Risk" (0-2) range. Children who participated in the present studies at Time 2 had received a score of "Low-Risk" on the MCHAT-R/F at their first visit (Time 1) but had aged out of this measure at Time 2. Thus, scores within the normal range on all other developmental assessments, described further below, along with parental report of typical development and clinical judgement by trained laboratory clinical staff (clinical psychologists and speech-language pathologists) was used to determine eligibility for inclusion in the NT group at Time 2. Children recruited for the ASD group received a comprehensive evaluation to confirm ASD diagnosis at both timepoints, via telehealth, by an experienced licensed psychologist (see *Autism Diagnostic Measures*).

Assessment Measures

Full Group Assessment Measures

Participants in both groups received a battery of assessments to evaluate their overall development, as well as to facilitate group matching and individual differences analyses. The Preschool Language Scales, 5e (PLS-5; Zimmerman, Steiner, & Pond, 2011) was administered to assess receptive and expressive language. Participants completed the cognitive subtests of the Developmental Assessment of Young Children, 2e (DAYC-2; Voress & Maddox, 2012) and the Developmental Profile 4 (DP-4; Alpern, 2020), Parent Interview Form, in order to evaluate early nonverbal cognitive abilities. These scales were chosen as most of the items were designed to minimize the influence of language on the assessment of cognitive skills. Raw scores from the DAY-C cognitive subtest were used for participant matching. All parents filled out an electronic version of the Vineland Adaptive Behavior Scales, 3e (Vineland-3; Sparrow, Cicchetti, & Saulnier, 2016), Comprehensive Parent/Caregiver Form. This measure evaluated children's adaptive skills, daily living skills, socialization, and motor skills. Additionally, all parents completed a background form, administered online via Qualtrics survey software. This background form was intended to provide information related to participant demographics, medical and intervention history, and any concerns parents had regarding any area of their child's development.

Autism Diagnostic Measures

To confirm a diagnosis of ASD, based on Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5; APA, 2013) participants recruited for the ASD group and their parents completed a battery of assessments administered by a licensed psychologist. DSM-5 criteria and review of all assessment data leading to a confirmation of the diagnosis of ASD was required for final inclusion in the ASD group. These measures were conducted via telehealth due to the larger research project occurring during the COVID-19 pandemic. Measures included the

Autism Diagnostic Interview-Revised (ADI-R), Toddler Research Version (Rutter et al., 2003); Brief Observation of Symptoms of Autism (BOSA; Lord et al., 2020); and Childhood Autism Rating Scale, 2e (CARS-2; Schopler et al., 2010). The CARS-2 provided a measure of autistic traits, sometimes referred to as autism symptom severity (Bottema-Beutel et al., 2021). The BOSA is a measure, adapted from the Autism Diagnostic Observation Schedule, Second Edition (ADOS-2; Lord et al., 2012), which was designed to be administered via telehealth. The administration of the BOSA via telehealth has been demonstrated to be effective for diagnosing ASD in preschool-aged children (Martin et al., 2022).

Group Matching

We used standard distribution matching procedures (Kover & Atwood, 2013) to match autistic and NT groups on cognitive ability. We quantified group differences using two-sample, two-tailed *t*-tests and have reported Cohen's *d* (effect size) and *p*-values (see Table 3.1 and Table 4.1). We chose cognitive ability as our matching variable given that the theoretical framework underlying our hypotheses (i.e., PIA hypothesis; Sinha et al., 2014) posits that prediction-based differences are domain-general. Additionally, we wanted to include autistic children with a wide range of language abilities to have sufficient range of abilities to evaluate individual differences in extant language as they relate to task performance (see Chapter 5: "Individual Differences in Prediction and Word Learning among Autistic Children"). Cognitive abilities were measured by raw scores from the DAY-C Cognitive Domain. We sampled participants for the NT group who were slightly younger than the ASD group for matching purposes. This allowed for a broader subset of autistic children, including those with possible concomitant intellectual disability, to be included in the sample. We made this decision in order to facilitate individual differences analyses across a wide range of abilities, and to be more representative of the true population of ASD (Thurm et al., 2021).

Experimental Tasks

Study 1: Word Learning from Predictable and Unpredictable Sentence Contexts

Study 1 was intended to test two research questions: 1) whether autistic and non-autistic children could predict upcoming novel words based on predictable adjectives and 2) whether autistic and non-autistic children learned words equally well when they were taught in predictable and unpredictable sentence contexts. In this experiment, four novel words were taught across two blocks. Two words were taught in predictable sentence contexts, in which the adjective that preceded the noun (e.g, "silly modi") was consistent across presentations (i.e., predictable condition). Two words were taught in unpredictable sentence contexts, in which the preceding adjective changed at every presentation (i.e., unpredictable condition). In each block, children first saw a set of training trials, followed by a set of test trials. In order to familiarize children with the task, an image of a familiar object was presented on the screen (e.g., cow) accompanied by auditory stimuli naming the object (e.g., "It's a cow"). Following the two familiarization trials, children saw eight training trials teaching them two novel words (e.g., four presentations of each word). One word (predictable condition) was always accompanied by the same adjective across four presentations (e.g., "It's a silly modi"). The other word (unpredictable condition) was accompanied by a different adjective across each of the four presentations. A testing block immediately followed the first training block. During test trials, children were presented with images of two objects accompanied by auditory stimuli naming one of the objects, along with an adjective that either facilitated prediction of the noun (predictable condition) or did not (e.g., unpredictable condition). Target objects were presented alongside their yoked pair (i.e., the other object taught during training). Each word was tested twice. There were also four familiar word trials interspersed during testing. These trials were used to confirm that children engaged with the task appropriately, based on demonstrating looking to target above chance for words they would be expected to know. The second block of training and test trials followed the same structure as the first block. Children were trained and tested on two additional novel words, one with predictable adjectives and one with unpredictable adjectives. Targets from each condition and target location (i.e., right or left side of the screen) were pseudorandomized and counterbalanced across two orders of the experiment.

Two dependent measures were used to evaluate learning in this task. Anticipatory eye movements (AEM's) were used to assess whether children correctly predicted the noun based on the preceding adjective during an anticipatory window. Proportion of looking to target during a noun recognition window was used to assess accuracy as a measure of word learning. Growth curve analyses were used to evaluate the impact of condition (predictable versus unpredictable) and group (ASD versus NT) on looking behavior (see *Analytical Approach*).

Study 2: Retention and Generalization of Words Learned from Predictable and Unpredictable Sentence Contexts

Study 2a was designed to evaluate autistic children's ability to retain novel object-label mappings learned in predictable and unpredictable sentence contexts after a short delay, as compared to their NT peers. After a 5-minute delay following the administration of Study 1, each of the object-label pairings taught in Study 1 were tested again for retention. During this retention period, the experimenter set a visual timer for 4 minutes. Children played just outside of the experimental booth with a set of toys that were chosen to require minimal verbalization for engagement (e.g., marble run or pinwheel toy). After four minutes, the experimenter let the child know that it was time to return to the experimental booth to "watch another movie." The experimenter started the delayed test experiment upon the child's return to the booth (Study 2a). It should be noted that it is possible that some children took longer to transition back into the booth, and thus may have experienced a delay slightly longer than five minutes.

As in Study 1, the delayed test block started with two familiar trials to re-familiarize children to the experiment. Following these trials, each of the four novel objects taught in Study 1 were tested twice. The structure of test trials was the same as in Study 1, except that there were no adjectives in the cue sentence (e.g., "Find the modi"). We chose to exclude adjectives from the delayed test as we wanted to evaluate children's retention of the nouns rather than their retention of the adjective that predicted them. The order of presentation of the nouns was pseudorandomized across two orders of the experiment.

Study 2b was designed to test children's generalization of labels to shape-matched objects. We chose to evaluate shape-match generalization given that autistic children have demonstrated atypical use of the shape-bias mechanism for generalization (Tek et al., 2008, Tovar et al., 2020). As such, understanding the input that best supports autistic children's ability to engage in shape-based generalization is theoretically and clinically significant. Immediately following the retention trials, children saw eight trials testing generalization. For each of the four objects initially taught, children saw two trials testing whether they would generalize the label to shape-matched objects. Shape-matched images were created using Photoshop, changing the color of the object presented.

In Studies 2a and 2b, proportion of looking to target during the noun recognition window was used to assess accuracy on retention (Study 2a) and generalization (Study 2b) trials. Growth curve modeling (see *Analytical Approach*) was used to evaluate the effect of condition and group on looking behavior at delayed test (Study 2a), and to shape-matched objects (Study 2b).

Stimuli

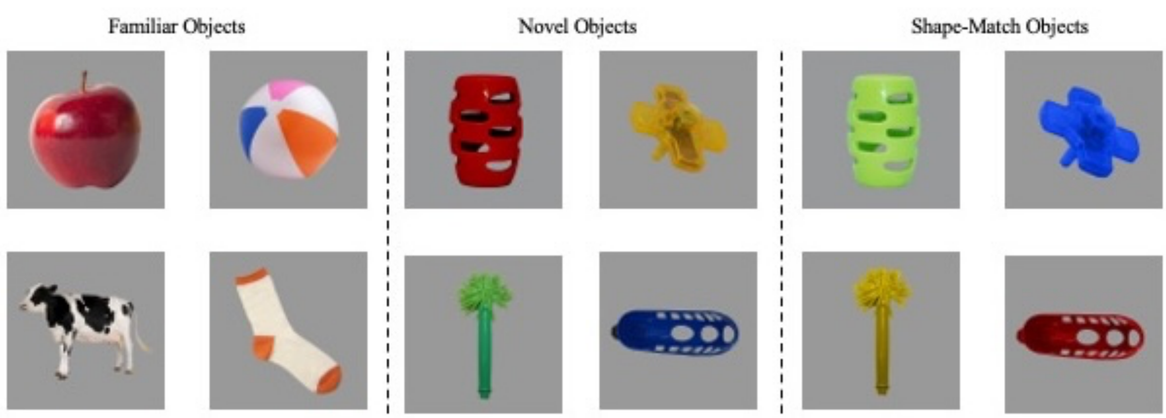
Stimuli for all three experiments consisted of still images and pre-recorded sound tokens. Auditory stimuli were recorded by a speaker of the local dialect and were normed to the same volume (65 dB) using Praat software (Boersma, 2001). Praat software was also used to norm the tokens of each noun, adjective and carrier phrase to the same duration for each category, such that the timing of carrier phrases, adjectives and nouns were time-locked for purposes of analyses. Tokens were recorded as sentences and then spliced for time-locking. Thus there was coarticulation in the stimuli. To examine the impact of coarticulation on the adjective stimuli, we conducted a perceptual stimuli test. See Appendix A for the stimuli, instructions, and results of this test. Three research assistants who were unaware of the correct answers participated. None of the three participants were able to correctly predict the upcoming phoneme for any of the four adjective tokens tested. Specific trial timing for each experiment will be described in the subsequent chapters.

Adjectives and familiar nouns were chosen based on local norms from unpublished data from autistic toddlers (N=129) from Dr. Ellis Weismer's lab. Adjectives (*nice, pretty, cute, funny, happy, silly)* were selected to have unambiguous meanings that are positive, but do not provide explicit facilitation of noun identification (i.e., do not describe the color, shape, or function of the object). Novel nouns were chosen from the Novel Object and Unusual Name (NOUN) database (Horst & Hout, 2016). Each noun was a 2-syllable CVCV word (/modi/, /bosə/, /pibu/, /tomə/). A web-based phonotactic probability and neighborhood density calculator was used to confirm that the novel words were distinct, phototactically probable (in English) novel nouns, given that dense neighborhoods and common sound sequences facilitate word learning in young children (Vitevitch & Luce, 2004; 2016). Assignment of novel labels and objects to predictable and unpredictable conditions was counterbalanced across two orders of each experiment.

Visual stimuli were created using Photoshop software, (Adobe Inc., 2019) adapting images taken from the NOUN database for novel objects (Horst & Hout, 2016) and prototypical images of objects taken from prior lab projects for familiar objects. Each novel object was edited to appear within a gray box background. See Figure 2.1 for the full set of visual stimuli. Shape-matched objects for Study 2b were created by changing the color of the original object using Photoshop software (Adobe Inc., 2019).

Figure 2.1

Full Set of Visual Stimuli



Data Coding and Processing

After the eyegaze experiments were completed, a video recording of each child's face (for coding of looking behavior) was exported, without sound, using FinalCut Pro software

(Apple). These videos were saved on a secure laboratory server to be coded offline at a later time, by trained research assistants. We chose to use offline hand-coding rather than automatic eye tracking because prior research completed by our research group suggests that hand-coding results in less data loss for autistic children (Venker, Pomper, et al., 2019). Coding was completed using Peyecoder software (Olson et al., 2020) on laboratory Mac computers, following established laboratory procedures. Peycoder allows the coder to indicate where the child was looking (i.e., right image, left image, center image, shifting between images, or off screen) for each 33 ms video frame. Coders were unaware of the target location during coding. To evaluate inter-coder reliability, a second research assistant independently coded 20% of videos for each experiment. Coder agreement will be reported for each experiment in the subsequent chapters. After the data was coded, it was processed using Peyecoder software, (Olson et al., 2020) which converted coded eyegaze data into comma-separated value files for analysis in R (version 4.0.2, R Core Team, 2021) and R Studio software (version 2022.02.3+492, R Studio Team, 2020) in which look location for every 33ms frame was reported for further analysis.

Analytical Approach

All analyses were conducted using R (version 4.0.2, R Core Team, 2021) and R Studio software (version 2022.02.3+492, R Studio Team, 2020). For each study, a series of growth curve mixed effects regression models were fit to evaluate looking behavior. We used growth curve modeling (Mirman, 2017) in congruence with similar prior work (Mathée-Scott et al., 2021; Venker et al., 2019). In each model, the dependent variable was accuracy (log transformed) during the experimental window. The experimental window for each study differed slightly based on trial timing. In Study 1, we first assessed whether children learned the predictive adjective-noun relationship by analyzing anticipatory shift data during the anticipation window (400ms before and after noun onset, 800ms total) as in prior research (Prescott et al., 2022; Venker, Edwards, et al., 2019). The proportion of looks to target during this window were measured by number of frames (33ms) coded as target divided by total number of frames in the analysis window. A growth curve linear mixed effects model, using the lme4 package in R, was fit for each condition, including random effects for subject and fixed effects for the intercept and diagnostic group. To measure word learning accuracy, we then modeled eyegaze behaviors during the noun recognition window (300-1800ms after noun onset) as in prior work (Venker, 2019). The dependent variable was the empirical logit of looking to the target object over time, as in prior studies in our research group (Pomper et al., 2021; Mathée-Scott et al., 2021).

In Study 2a and 2b, additional growth curve linear mixed effects models were fit for each condition, in which the dependent variable was the empirical logit of looking to the target object over time. For these studies, given that there was no predictive adjective, there was only one analytical window, for noun recognition, which was set to 300-1800ms after noun onset in accordance with prior work in our research group (Pomper et al., 2021; Mathée-Scott et al., 2021).

For Study 3, we evaluated the role of individual differences on performance in Studies 1 and 2. For each group, we evaluated the role of individual differences in age, language ability, cognitive ability, daily living skills, and autistic traits (in the ASD group only) on performance in Study 1, Study 2a and Study 2b. We separately examined this for each condition (predictable and unpredictable) and each experimental window (anticipatory window and noun recognition window) in the case of Study 1. We fit a series of linear regression models for each condition of each experiment for both groups. In these models, the dependent variable was average accuracy, including each of the above individual differences variables as independent variables.

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Chapter 3: Word Learning from Predictable and Unpredictable Input in Autistic and Non-autistic Children

Introduction

Word Learning in Autism Spectrum Disorder

There is considerable variability in structural language abilities of children on the autism spectrum (Delehanty et al., 2018; Ellis Weismer et al., 2010; Koegel et al., 2020). Although many autistic children have age-appropriate language ability, research suggests that over a quarter of children with ASD have minimal to no functional spoken language ability by the time they enter kindergarten (Tager-Flusberg & Kasari, 2013). The mechanisms which drive this variability in language outcomes remains largely unknown. One such mechanism might be the pathways by which autistic children learn new words. There is variability across studies on the word learning profiles of autistic children. There is evidence of atypical or absent use of early word learning mechanisms such as the mutual exclusivity and shape biases and difficulty with generalization of novel words (Mathée-Scott et al., 2021; Tek et al., 2008; Tovar et al., 2020). However, whereas some word learning mechanisms are impaired or absent, others appear to be a strength for autistic children, including relatively robust abilities to employ linguistic statistical learning (Haebig, 2015; Obeid et al., 2016; but see Hu et al., 2023; Scott-Van Zeeland et al., 2010) and employ cross-situational word learning (Venker, 2019). Hartley, Bird and Monaghan (2019) found that autistic, school-age children performed similarly to receptive vocabulary matched, neurotypical (NT) peers on a cross-situational word learning accuracy task. However, autistic children in that study were significantly slower to identify correct referents as compared to the NT group. These authors suggest that this difference points to potential differences in the mechanisms that support word learning in autistic children. Presently, the underlying mechanisms that contribute to word learning performance, and to the variable findings in the present literature, are not fully specified.

Impact of Sentence Context

One area of word learning in ASD that has received scant attention to date is the role of sentence context during exposure. Children and adults use a variety of cues to aid in disambiguating labels and referents. Some such cues have been explored in ASD, including word learning mechanisms such as the mutual exclusivity and shape bias, as well as cross-situational word learning. In their natural language environments, however, children are exposed to words within sentence contexts in addition to in isolation. Koehne and Crocker (2015) found that NT adults prioritize cues from sentence contexts over cross-situational cues when learning novel words. Children employ a strategy known as syntactic bootstrapping to leverage the information within the syntax of a sentence to map words to meaning, particularly for learning the meanings of verbs (Fisher et al., 2020; Gleitman, 1990). Shulman and Guberman (2007) found that preschool-aged autistic children demonstrated commensurate syntactic bootstrapping abilities as language-matched NT peers. Beyond syntactic bootstrapping, the impact of the sentence context during word learning has received scant attention in ASD.

Predictability of Input

The role of prediction differences in ASD is has been an emerging area of inquiry over the past decade (Cannon et al., 2021; Evers et al., 2014; Gomot & Wicker, 2012; Sinha et al., 2014). The impact of prediction difference on language and word learning differences in ASD is unclear to date. Prediction differences show some promise for explaining differences in language in autistic children, as language unfolds in predictable sequences (Ellis Weismer & Saffran, 2022). Prior research with NT infants has found links between predictability of stimulus presentations and word learning in NT infants (Benitez & Saffran, 2018) and in language processing in ASD (Prescott et al., 2022; Venker et al., 2019). To date, the impact of stimulus predictability on word learning in ASD is unknown. Early research from Yoder and colleagues (Yoder et al., 1995) investigated the effectiveness of "verbal routines" for increasing mean length of utterance in children with developmental delays. While this intervention strategy was not framed around any prediction-based theory, indeed they were described by Yoder and colleagues (1995) as having "a predictable and recognizable sequence" in order to support children's semantic networks and memory for words. These authors also suggest that the predictability of verbal routines might reduce the information processing load required to engage in linguistic interactions. To date, the use of verbal routines with autistic children has not been evaluated empirically. While the present study does not aim to evaluate the verbal routine intervention in ASD, there are some similarities between this previously validated intervention strategy and the manipulation tested in the present study – the impact of predictable sentence contexts on word learning.

The Current Study

The present study aimed to evaluate the impact of the predictability of the sentence context on word learning in autistic and NT peers, matched on cognitive ability. Thus, we employed established eyegaze methods to answer two research questions:

1) First, do autistic and non-autistic children differ in their ability to predict upcoming novel words based on a predictable (based on input during training) preceding adjective?

2) Second, are autistic and non-autistic children able to learn novel words equally well when they were taught in predictable and unpredictable sentence contexts?

Methods

General Procedure

The present experiment was administered alongside a battery of developmental standardized assessments and other eyegaze experimental tasks within the parent study. See *Chapter 2: General Methods* for additional details regarding general procedure, standardized assessments, and group matching. The order of task administration was counterbalanced across participants. Written informed consent was given by a parent or guardian at the start of the visit.

Participants

Participants were 30 autistic children (7 female) and 31 NT children (13 female). Participants in the ASD group had diagnoses of ASD consistent with DSM-5 criteria confirmed by diagnostic assessments administered by clinical staff in the research group (see *Chapter 2: General Methods*). ASD participants were 27-50 months old ($M=40.0$, $SD=7.3$) and NT children were 19-39 months old ($M=27.1$, $SD=6.4$). The ASD group was significantly older than the NT group ($p<.001$). This age difference allowed for group matching on a measure of cognitive ability while allowing for inclusion of autistic children with co-occurring cognitive delays (see *Chapter 2: General Methods*). See Table 1 for participant characteristics and group comparisons. Participants were recruited from the local area via a research registry at the Waisman Center, local parent groups and early intervention providers. Participants resided in monolingual, English-speaking households and were reported to have no known hearing or vision impairments. Self-reported maternal education in the ASD group ranged from 11 to 19 years ($M=14.03$ years) and 14 to 24 years in the NT group ($M=17.42$ years).

Eyegaze Task

The eyegaze experiment (Study 1) was designed to test children's ability to learn novel words taught in predictable and unpredictable sentence contexts, as well as their ability to anticipate upcoming novel nouns based on a predictable versus unpredictable preceding adjective. To test these research questions, participants were taught four novel words across two blocks. In each block, one word was taught alongside a predictable adjective, and one was taught with varied (i.e., unpredictable) adjectives. Thus, across the two blocks, two words were taught in predictable sentence contexts, in which the adjective that preceded the noun (e.g, "silly modi") was consistent across presentations (i.e., predictable condition). Two words were taught in unpredictable sentence contexts, in which the preceding adjective changed at every presentation (i.e., unpredictable condition).

Task Structure

Each block began with a set of 10 training trials intended to teach children the novel words. Following this, children saw a set of eight test trials. Each training block began with two familiarization trials in which an image of a familiar object was presented on the screen (e.g., sock) accompanied by auditory stimuli naming the object (e.g., "It's a sock"). Eight training trials immediately followed these familiarization trials, teaching two novel words (e.g., four presentations of each word). One word was always accompanied by the same adjective across each of the four presentations (predictable condition). The other word was accompanied by a different adjective across each of the four presentations (unpredictable condition).

A block of eight test trials immediately followed the training block. During test trials, children viewed images of two objects, accompanied by auditory stimuli. The auditory stimuli prompted children to look at the target object and included a preceding adjective that either facilitated prediction of the noun (predictable condition) or did not (unpredictable condition). Target objects were presented alongside their yoked pair (i.e., the other object taught during training). Each word was tested twice. Interspersed throughout these novel object test trials were four familiar word trials. These trials presented two target objects (e.g., shoe and apple) which were likely to be known by children in this age range (Ellis Weismer, 2014). Familiar word trials were included to maintain and confirm children's engagement in the task.

The second block of training and test trials followed the same structure as the first block. Thus, children were presented with 10 training trials (two familiar, eight novel) teaching two additional novel words in sentence contexts (one predictable, one unpredictable). Targets from each condition and target location (i.e., right or left side of the screen) were pseudorandomized and counterbalanced across two orders of the experiment. See *Chapter 2: General Methods* for additional detail regarding visual and auditory stimuli.

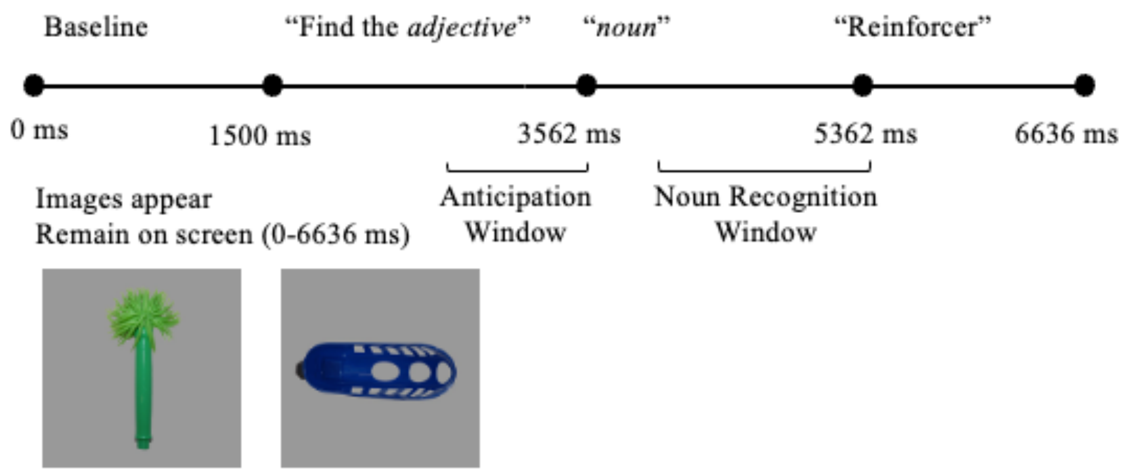
Data Processing and Cleaning

Children's looking behavior was coded offline by trained research assistants, following established procedures within Dr. Ellis Weismer's laboratory. Peyecoder software (Olson et al., 2020) was used for data coding. For each 33 ms video frame, coders indicated whether the child was looking at the center, left or right image, off screen, or shifting between images. Hand-coding methods were selected rather than automatic eye tracking because prior research suggests that this method is preferable for individuals with neurodevelopmental disorders as hand-coding results in more data retention (Venker, Pomper, et al., 2019). Coders were unaware of the target location as videos were coded without sound. To assess inter-coder reliability, 20% of videos were coded independently by a second coder. Frame agreement (the mean proportion of frames on which coders agreed) was 98% for the NT group and 98% for the ASD group. Shift agreement (the mean proportion of shift frames on which coders agreed) was 89% for the NT group and 90% for the ASD group.

We analyzed two distinct experimental windows to answer each research question. First, we assessed anticipation of the upcoming noun based on predictable versus unpredictable adjectives. To examine this, we chose a window of 200 ms after adjective onset to noun onset (2700-3562 ms after trial onset). To answer our second research question, evaluating whether children looked to the correct target image when the noun was named, we chose an analytical window of 200-1800 ms after noun onset. See Figure 3.1 for trial timing. Each window accounts for the time it takes children to execute a saccade (Canfield et al., 1997; Matin et al., 1993). Consistent with prior research (Mathée-Scott et al., 2021; Venker, Edwards, et al., 2019) we excluded test trials in which children attended to the screen for less than 50% of the analytical window. After this cleaning criterion was applied, children must have contributed at least four useable test trials for their data to be included (out of 16 possible). There was more data loss for the autistic group than the NT group. Autistic children contributed an average of 9.33 useable test trials, whereas NT children contributed an average of 11.97 trials. Three autistic children were excluded from final analyses because they did not contribute enough test data (minimum four trials). After these children were excluded, we re-evaluated whether our groups remained sufficiently matched. Indeed, a Welch two sample t-test confirmed that the groups included in the final analyses ($N = 27$ ASD; $N = 31$ NT) were still matched on our measure of cognitive ability ($t = -0.29$, $p = .655$).

Figure 3.1

Study 1 Trial Timing



Note. Schematic of trial timing. Time is represented in milliseconds (ms) from trial onset. The anticipatory adjective window was 200 ms after adjective onset to noun onset (2700-3562 ms after trial onset). The noun recognition window was 200-1800 ms after noun onset (3762-5362 ms after trial onset).

Results

One dependent measure (proportion of looks to target) within two distinct experimental windows, was used to evaluate both anticipation and learning in this task. Proportion of looks to target versus nontarget during the anticipatory window (200 ms after adjective onset until noun onset) was used to assess whether children correctly predicted the noun based on the preceding adjective. Proportion of looking to target versus during the noun recognition window (200-1800 ms after noun onset) was used to assess novel word learning. First, we evaluated whether each group looked significantly above chance in each window, in each condition using t-tests. Next, growth curve linear mixed effects models were applied to evaluate the effect of condition (predictable versus unpredictable) and group (ASD versus NT) on looking behavior during each window. All analyses were conducted using R (version 4.0.2, R Core Team, 2021) and R Studio software (version 2022.02.3+492, R Studio Team, 2020).

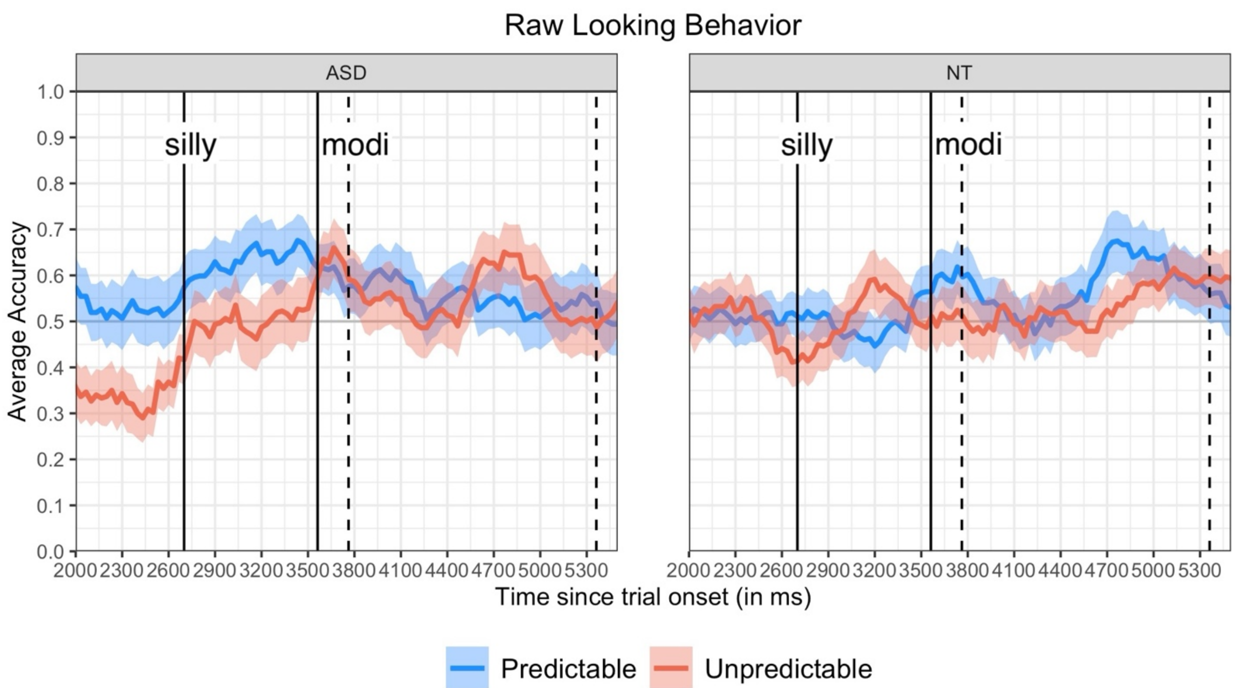
Anticipatory Window

To answer our first research question, whether groups differed in their ability to anticipate novel nouns based on preceding predictable versus unpredictable adjectives, we examined looks to target in the anticipatory window (200 ms after adjective onset until noun onset). See Figure 3.2 for a visualization of looking behavior during the full window. To evaluate whether children in both groups anticipated the target above chance, we conducted one sample t-tests for each condition, for each group, against the alternative hypothesis that the true mean is greater than 0.5 (chance performance). The ASD group demonstrated performance significantly above chance in the predictable condition ($t = 10.617$, $p < .001$) but not in the unpredictable condition ($t = -0.166$, $p = .566$). The NT group demonstrated performance that was not significantly above chance in either condition (predictable: $t = -0.373$, $p = .646$; unpredictable: $t = 0.415$, $p = .339$).

To evaluate the effect of diagnostic group and condition on changes in looking behavior over time, we fit a series of growth curve linear mixed effects models. In each growth curve mixed effects model, the dependent variable was the empirical log odds of looks to target versus nontarget during the anticipatory window. Models included fixed effects for diagnostic group (contrast coded: ASD=-0.5; NT = 0.5), condition (contrast coded: unpredictable= -0.5; predictable= 0.5), orthogonal polynomial time terms (linear, quadratic, and cubic), all possible interactions, and by-subject random intercepts and slopes for condition, linear and quadratic time, and their interactions. Linear time represents the average slope of the line, which indicates rate of change in fixation proportion. Quadratic time represents the rate of the symmetric rise and fall around the peak asymptote of fixation proportions. Cubic time represents the slope of the tails of the curve, therefore quantifying any delay in increased fixations to the target in response to the auditory cue.

Figure 3.2

Study 1 Raw Looking Behavior

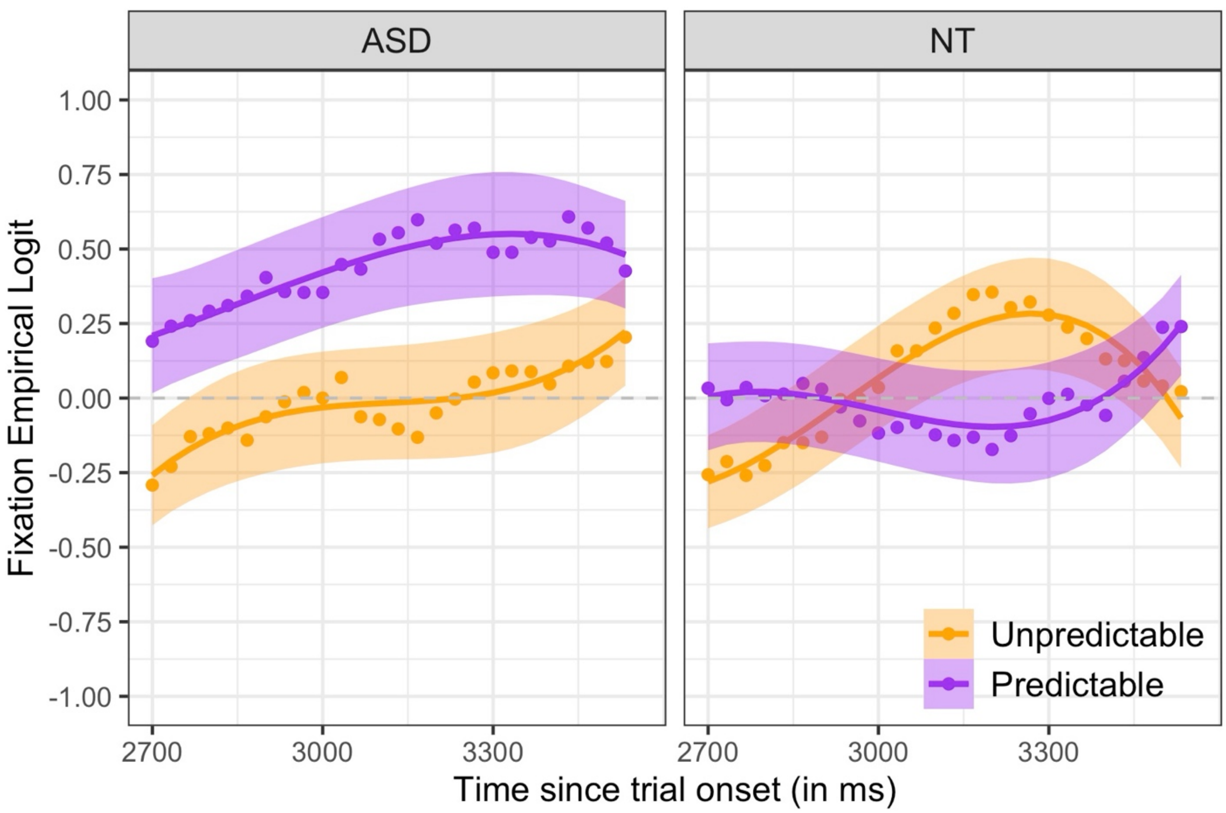


Note. Raw looking behavior for test trials plotted across trial (after baseline). Solid horizontal lines represent the anticipatory adjective window (200 ms after adjective onset to noun onset). Dashed horizontal lines represent the noun recognition window was 200-1800 ms after noun onset. Text ("silly modi") represents a visual approximation of auditory stimuli timing. ASD group is on the left (*N* = 27) NT group is on the right (*N* = 31). Predictable trials are represented in blue, unpredictable trials are plotted in red.

Results revealed that the main effect of intercept was not significant ($b = 0.122$, $p = .099$). This indicates that collapsing across groups and conditions, children's average fixation proportion was not significantly above chance. This is to be expected, as we would not expect children to have looked significantly above chance in the unpredictable condition. There was a significant main effect of linear time (*b* = 0.442, *p* = .04) indicating that children fixated the target more at the end of the window than the beginning. There were also significant interactions between group, condition, and quadratic time (*b* = 1.193, *p* = .023) and group, condition, and cubic time (*b* = 0.693, *p* = .029). This indicates that the two groups demonstrated different magnitudes of difference from the unpredictable to the predictable condition in the rate of change around children's peak asymptote of fixation proportions (quadratic effect), and between the slopes of the tails of the curves (cubic effect). See Figure 3.3 for the growth curve model plot. See Appendix B for full model results.

Figure 3.3

Growth Curve Model, Anticipatory Adjective Window



Note. Growth curves are plotted over time (in ms) in unpredictable condition (orange) and predictable condition (purple), during the anticipatory adjective window (200 ms after adjective onset until noun onset). Dashed horizontal line represents chance performance. ASD group is on the left (*N* = 27) NT group is on the right (*N* = 31).

To investigate this interaction further, we looked at each group separately. First, we fit a model including the autistic group, with fixed effects for condition (contrast coded: unpredictable= -0.5; predictable= 0.5), orthogonal polynomial time terms (linear, quadratic, and cubic), all possible interactions, and by-subject random intercepts and slopes for condition, all three time terms, and their interactions. This model revealed a significant main effect of linear time ($b = 0.506$, $p = .044$), indicating that autistic children fixated the target more at the end than the beginning of the window. There was a significant main effect of condition ($b = 0.456$, $p = .043$), indicating that in the autistic group, overall proportion of looks to target during the anticipatory window was greater in the predictable condition than the unpredictable condition. Next, we fit the same model including only the NT group. This model revealed non-significant condition effect ($b = -0.076$, $p = .738$). There was a significant interaction between quadratic time and condition ($b = 0.96$, $p = .017$), suggesting a difference in the rate of the symmetric rise and fall around the peak asymptote in the predictable versus unpredictable condition in the NT group. There was also a significant interaction between cubic time and condition ($b = 0.448$, $p = .01$), indicating a difference between the slopes of the tail ends of the curve between the predictable and unpredictable conditions.

Noun Recognition Window

To answer our second research question, whether autistic and non-autistic children learned words equally well when they were taught in predictable and unpredictable sentence contexts, we evaluated looking behavior during a noun recognition analytical window (200-1800 ms after noun onset). Analyses mirrored those described above for the anticipatory adjective window. First, we evaluated children’s ability to learn the words in each condition. To test whether children in both groups looked to the target noun above chance, we conducted one sample t-tests for each condition, for each group, against the alternative hypothesis that the true mean is greater than 0.5 (chance performance). The ASD group demonstrated performance significantly above chance in both conditions (predictable: $t = 5.665$, $p < .001$; unpredictable: $t = 5.263$, $p < .001$). The NT group also demonstrated performance significantly above chance in both conditions (predictable: $t = 8.55$, $p = p < .001$; unpredictable: $t = 3.714$, $p = p < .001$). Thus, both groups were able to learn the novel words in both conditions, as evidenced by looking to the target significantly above chance during the noun recognition window.

As with our anticipatory window analyses, we followed these t-tests with a series of growth curve linear mixed effects models to examine changes in looking behavior over time in each condition. See Appendix B for full model results. As above, the dependent variable in each model was the empirical log odds of looks to target versus nontarget during the noun recognition window. Models included fixed effects for diagnostic group (contrast coded: ASD= -0.5; NT = 0.5), condition (contrast coded: unpredictable= -0.5; predictable= 0.5), orthogonal polynomial time terms (linear, quadratic, cubic), all possible interactions, and by-subject random intercepts and slopes for condition, all three time terms, and their interactions. Model results revealed a significant main effect of cubic time ($b = -0.367$, $p = .029$) and a significant main effect of intercept ($b = 0.193$, $p = .004$), suggesting above chance accuracy collapsing across groups and conditions during the noun recognition window. This model also yielded a significant interaction between group, condition, and cubic time ($b = -1.636$, $p = .013$) indicating that the magnitude of the condition difference between the slopes of the tail ends of the curves was different between the two groups.

To further investigate this interaction, we evaluated groups separately. First, we fit a model including the autistic group, with fixed effects for condition (contrast coded: unpredictable = -0.5; predictable= 0.5), orthogonal polynomial time terms (linear, quadratic, and cubic), all possible interactions, and by-subject random intercepts and slopes for condition, all three of the time terms, and their interactions. This model revealed no significant main effects or interactions, though the main effect of intercept was marginal ($b = 0.154$, $p = .072$) and the interaction between condition and cubic time was marginal ($b = 1.026$, $p = .066$), indicating a difference in the slopes of the tail ends of the curves between the predictable and unpredictable conditions that approached significance. The model including the NT group revealed significant main effects of intercept ($b = 0.231$, $p = .023$), and cubic time ($b = -0.55$, $p = .021$), but no significant interactions between condition and any of the time terms.

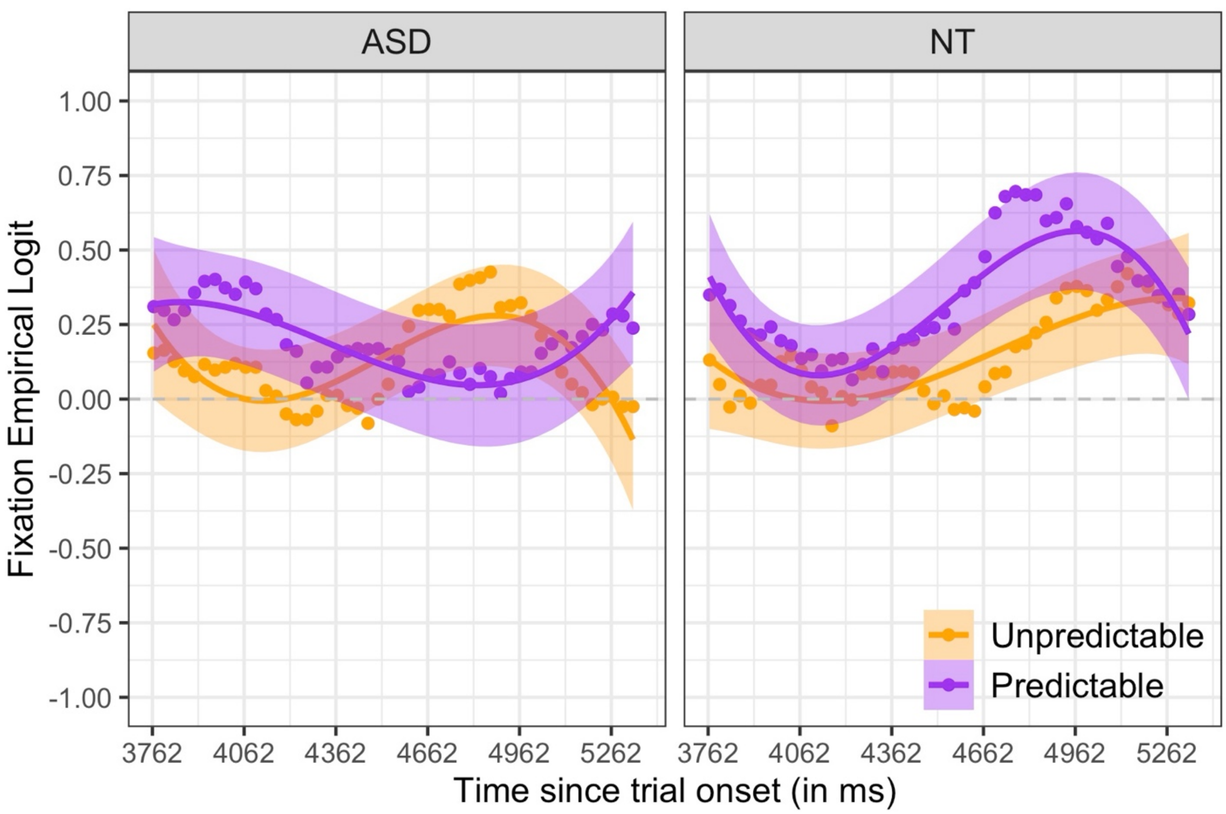
Discussion

In this study, we asked two research questions. First, we asked whether autistic and cognitive ability-matched NT peers were able to anticipate newly learned words based on predictable versus unpredictable adjectives. Findings from the anticipatory window analyses suggest that autistic children were able to use a preceding, predictable adjective to anticipate newly learned novel nouns that were taught in predictable sentence contexts, whereas cognitively-matched NT children did not demonstrate anticipation significantly above chance in either condition. This suggests a relative strength for autistic children. However, it should be noted that our NT group was significantly younger than our autistic group. As such, autistic children demonstrated a relative strength in anticipation when compared to cognitively-matched NT children, but we do not know whether the same strength would be evident when compared to an age-matched NT sample. It should also be noted that NT children did not demonstrate anticipation significantly above chance in either condition. It is possible that our NT sample was too young to learn both the antecedent-consequence relationship between adjectives and nouns and the novel label-object pairing. Prior literature has demonstrated that NT children as young as 6 months-old can demonstrate anticipatory eye movements to novel stimuli (McMurray & Aslin, 2004). Moreover, research on NT toddlers has found that two-year-old NT children can demonstrate anticipatory eye movements in a word learning context (Benitez & Saffran, 2018). Our NT sample was, on average, two years old. However, there was a broad range of age (19-39 months) within our NT sample. Thus, it is possible that some on the younger end of our age range were simply too young. The role of age in task performance will be explored further in Chapter 5: "Individual Differences in Prediction and Word Learning among Autistic Children."

Our second research question examined whether autistic children and cognitive ability-matched NT peers could demonstrate learning of novel nouns taught in predictable and unpredictable sentence contexts. Results from the noun recognition window analyses suggest that both groups were able to learn the novel words in both conditions, and that there was a difference in looking behavior such that there was a significant three-way interaction between group, cubic time, and condition. Further exploration of this interaction revealed a difference such that there was an interaction between condition and cubic time that approached significance in the autistic group ($b = 1.026$, $p = .066$), whereas there were no significant condition by time interactions in the NT group. This effect in the autistic group suggests a marginal difference in the tail ends of the curve between the two conditions, such that autistic children looked more to the target at the tail end of the curve in the predictable condition than in the unpredictable condition. This suggests a greater latency in response in the predictable condition for the autistic group, demonstrated by an upward slope of the end of the curve in the predictable condition that is not evident in the unpredictable condition. See Figure 3.4 for a visualization of this effect. One potential explanation for this effect is that this latency effect occurred as a result of autistic children's looking behavior during the anticipatory window. That is, in the anticipatory window, autistic children fixated the target in the predictable condition more than the non-target. After this, they appear to have shifted to the non-target object briefly before returning their gaze to the target. As such, while both groups were able to learn the words in both conditions, there was a group difference in the impact of condition on latency of noun recognition looking behavior, such that the autistic group demonstrated a greater impact of condition on looking behavior than the NT group. Taken together, these findings suggest that predictable sentence contexts may support autistic children's ability to anticipate and recognize newly learned novel words.

Figure 3.4

Growth Curve Model, Noun Recognition Window



Note. Growth curves are plotted over time (in ms) in unpredictable condition (orange) and predictable condition (purple), during the noun recognition window (200-1800 ms after noun onset). Dashed horizontal line represents chance performance. ASD group is on the left ($N = 27$) NT group is on the right ($N = 31$).

In this study, autistic children demonstrated commensurate word learning, based on performance in the noun recognition window, across both conditions as compared to younger NT peers who were matched on a measure of cognitive ability. This finding is consistent with findings from several other studies comparing word learning in autistic and non-autistic children in various word learning tasks. Luyster and Lord (Luyster & Lord, 2009) found that autistic and non-autistic toddlers similar in age to our sample (20-30 months) and matched on expressive vocabulary demonstrated similar word learning abilities, even when the word learning task involved social task demands. Both Venker (2019) and Hartley, Bird & Monaghan (2019) found commensurate cross-situational word learning in autistic and non-autistic, vocabulary-matched children. Our study differed from these in several important ways. First, rather than relying on cross-situational cues, children were explicitly taught the novel labels. Our sample was also younger than those of Venker (2019) and Hartley, Bird and Monaghan (2019). In our study, an additional manipulation of the input during word learning (predictable versus unpredictable sentence contexts) differentially impacted autistic children compared to non-autistic peers. While both autistic and non-autistic children were able to learn the novel words in the present study, differences emerged in both children's ability to predict the upcoming novel word based on a preceding adjective, and in the differences in children's looking behavior during the noun recognition window between the two conditions.

These findings have important theoretical implications when considered within the PIA theoretical framework. Indeed, Cannon and colleagues (Cannon et al., 2021) paint a relatively nuanced picture of the literature to date on predictive abilities in ASD, particularly as it relates to autistic individuals' ability to aggregate probabilities based on statistically-constrained input and make accurate predictions. They highlight mixed findings within this review with respect to differences in learning predictive associations between antecedents and consequences. Prior research has broadly elucidated a relative strength in this type of learning for autistic individuals within behavioral studies (Mayo & Eigsti, 2012; Obeid et al., 2016). But, brain imaging and EEG studies suggest some differences in autistic and non-autistic individuals during this type of learning (Scott-Van Zeeland et al., 2010). The present study was behavioral, and findings are consistent with other behavioral experiments, such that making predictions based on learned antecedent-consequence associations appeared to be a relative strength for our autistic group. That is, autistic children were able to learn the association between a predictable adjective and a novel word and anticipate the novel noun based on this adjective before it was named. Moreover, autistic children in our study demonstrated a significant effect of condition during the anticipatory adjective window, such that they fixated the target significantly more during the anticipatory window in the predictable condition than the unpredictable condition. This was an effect that was not observed in the NT group.

It is important to address some limitations and possible alternative explanations in our study. First, we must acknowledge the somewhat arbitrary nature of the anticipatory versus the noun recognition windows. While we based each window on prior literature, it is important to note that we cannot know what children were thinking when they looked at a given image at a given time. Indeed, we can only infer based on looking behavior. As such, we can infer that when children were taught the label "modi" alongside the predictable adjective "silly," and demonstrated looking above chance levels toward that object associated with "modi" when they heard the preceding adjective “silly” that they were anticipating that the “modi” would be named based on the adjective “silly.” However, we must acknowledge the possibility that instead children mapped the predictable adjective (i.e., “silly”) to the novel object associated with “modi,” and thus were looking to the novel object during the anticipatory window in response to that mapping. It could be that autistic children in our sample had less robust extant semantic knowledge of the adjectives used in the study. Indeed, prior work has suggested less mature lexical-semantic knowledge in autistic children (Haebig et al., 2015). Whether children mapped the adjective or the noun to the object, there were group differences observed in both windows. Autistic and non-autistic children demonstrated differential effects of the condition manipulation. Parsing through the exact underlying mechanisms of this observed difference will be an important next step for future research.

We can consider possible clinical implications of these findings. Autistic children demonstrated above chance learning, commensurate with cognitive-matched NT peers for the novel nouns in both the predictable and unpredictable conditions. Autistic children demonstrated a relative advantage with respect to their anticipation of the upcoming noun when words were taught in sentence contexts with predictable adjectives. To understand the clinical utility of predictable sentence contexts, it will be important to also examine the effect of this manipulation on children’s ability to both retain and generalize newly learned object-label pairings. Chapter 4: “*Retention and Generalization of Object-Label Pairings Learned from Predictable and Unpredictable Input in Autistic and Non-autistic Children,”* will begin to elucidate this issue. Additionally, clinical implications are difficult to attain from laboratory studies. Future research examining word learning from predictable versus unpredictable stimulus in more naturalistic environments (e.g., in-home and intervention contexts) would be needed to understand the impact of this type of stimuli on broader vocabulary development.

The present study represents the first experiment to date examining the role of predictable versus unpredictable sentence contexts on word learning in young autistic children. Findings demonstrate that there are group differences between autistic and non-autistic children in the impact of sentence predictability on both children's anticipation of upcoming nouns and their recognition of the novel noun.

Table 3.1 Study 1 participant characteristics.

	ASD Group (n = 30) Mean (SD) range	NT Group (n = 31) Mean (SD) range	Group Comparisons
Age (Months)	40.05 (7.32) 27.1-50.2	27.14 (6.39) 19.1-39.2	Cohen's d = 1.90 $p < .001$
Receptive Language			
Raw Scores	22.68 (8.13) 13-41	33.19 (9.66) 19-65	Cohen's d = -1.17 $p < .001$
Standard Scores	62.64 (15.69) 50-94	110.55 (13.04) 67-134	Cohen's d = -3.35 $p < .001$
Expressive Language			
Raw Scores	25.28 (7.14) 13-40	31.57 (6.64) 24-49	Cohen's d = -0.92 $p < .001$
Standard Scores	72.08 (15.03) 50-103	107.87 (10.90) 87-130	Cohen's d = -2.77 $p < .001$
Nonverbal Cognition			
Raw Scores	37.1 (8.28) 28-57	37.9 (5.74) 29-51	Cohen's d = -0.11 $p = .448$
Standard Scores	81.77 (13.45) 56-116	104.32 (5.96) 93-118	Cohen's d = -2.18 $p < .001$
Adaptive Behavior	69.93 (8.86) 53-97	98.04 (8.14) 85-116	Cohen's d = 3.30 $p < .001$

Autism Traits			
Severity Score	2.29 (0.59) 1-3	—	—
Total Score	35.09 (4.55) 26.5-47	—	—
Demographic Information			
Race	18 White 8 More than One Race 4 Black or African American	31 White	
Ethnicity	27 Not Hispanic or Latino 3 Hispanic or Latino	31 Not Hispanic or Latino	
Sex	7 Female 23 Male	17 Female 14 Male	

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Chapter 4: Retention and Generalization of Object-Label Pairings Learned from Predictable and Unpredictable Input in Autistic and Non-autistic Children

Introduction

Retention of Novel Words in Autism Spectrum Disorder

Study 1 examined the impact of predictable versus unpredictable input during word learning on autistic and non-autistic children's ability to map labels onto novel objects. Much of the existing literature on word learning in ASD stops at the level of initial mapping. This type of work is crucial for understanding the mechanisms which underlie differences in object-label mapping in autistic children. However, to understand the downstream impacts of word learning differences on broader vocabulary and structural language, we must examine children's ability to retain these newly learned words. Indeed, in their natural environments, children learn words across multiple exposures over time. To build their lexicons, they must integrate and consolidate these exposures of object-label pairings. Children must not only map object-label pairings, but they must also retain and flexibly integrate word meanings into their vocabularies. Thus, memory processes play an important role in word learning and lexical development. Both short- and long-term memory processes play important roles in children's vocabulary development. Storkel (2015) highlights the importance, and the interplay, of input and environment on these memory processes. Indeed, the input a child receives interacts with these processes and may impact their retention of newly learned words. These memory processes, their interactions with the environment, and their impact on word learning, are not particularly well understood in ASD. Thus, investigating the impact of manipulations of word learning input on retention of newly learned words may be important for understanding the unique progression of lexical development in ASD.

The interplay between memory processes and word learning has not yet been sufficiently explored in ASD. Hartley and colleagues (2019, 2020) have tested retention of newly-learned words in cross-situational and referent-selection tasks in school-age autistic children. Hartley (2019) found that autistic children demonstrated initial learning commensurate with receptive vocabulary-matched NT peers in a fast-mapping word learning task but displayed substantially decreased accuracy after a short retention interval (5 minutes). In a subsequent study, Hartley and colleagues (2020) evaluated school-aged autistic children's ability to retain words learned in a cross-situational word learning task. Autistic children demonstrated retention performance commensurate with their vocabulary-matched NT peers on retention trials. Thus, retention of words learned in cross-situational learning contexts appears to be a relative strength for autistic children. Importantly, the features of the input that best supports memory for words in autistic children is not well understood to date. A recent study by Carter and Hartley (2021) found that autistic toddlers retained label-object pairings better over a 5-minute delay when words were taught using stimuli that was more realistic (i.e., color photographs) than when stimuli consisted of black-and-white cartoons. These authors attribute this finding to the "greater iconicity" inherent to color photographs. However, it is not clear whether the inclusion of color itself facilitated learning, perhaps via increased attention. Thus, additional work is needed to further understand the type of input that best supports retention in this population. Specifically, there is limited research to date investigating the linguistic features of the input that best supports memory for newly learned words in autistic children.

Generalization of Novel Words in Autism Spectrum Disorder

In addition to retaining word meanings, in order to flexibly integrate words into their lexicons, children must be able to extend word meanings beyond initial exemplars and generalize meaning to other objects within the same category. The complex process of generalization of word meanings has been demonstrated as a particular area of difficulty in the language profiles of autistic children (Happe & Frith, 2006; Hartley & Allen, 2014). Thus, to understand the mechanisms underlying broader structural language deficits in this population, examining differences in generalization may be a fruitful area of inquiry. Prior research has examined the use of generalization mechanisms in autistic children, revealing some atypical patterns. For example, research has established that autistic children demonstrate atypical use of the shape bias (the tendency to categorize objects of the same shape together) to generalize labels to shape-matched objects in this population (Tek et al., 2008; Tovar et al., 2020). Hartley and colleagues (2019) examined generalization of newly learned words in school-age autistic children, finding impaired generalization of fast-mapped words in autistic, school-aged children compared to NT peers matched on receptive vocabulary. However, Hartley and colleagues (2020) found similar generalization performance for words learned via cross-situational word learning in receptive language-matched autistic and non-autistic children.

The predictive impairment in autism (PIA) hypothesis (Cannon et al., 2021; Sinha et al., 2014) may have important implications for generalization of object-label meanings in autistic children. See "Chapter 1: *Introduction*" for a more thorough description of this theoretical framework. Hyperplasticity, or the tendency to treat all or most environmental stimuli as new learning, disproportionally weighing these experiences when integrating new exposures with existing knowledge, may be detrimental in the context of word learning. Treating stimuli disproportionally as novel may result in decreased ability to integrate current input with previous exposures, thus potentially impairing the ability to generalize object-label pairings across exposures. Given the established difficulty with generalization of newly learned words in ASD, this theoretical framework may be useful in understanding the mechanisms underlying generalization differences.

The Current Study

The current study is an extension of Study 1 (see Chapter 3: *"Word Learning from Predictable and Unpredictable Input in Autistic and Non-autistic Children"),* intended to examine autistic children's ability to retain and generalize words learned from predictable versus unpredictable input, compared to cognitively-matched NT peers. Following the completion of Study 1, children had a short retention interval (five minutes) before the present set of studies was administered. These experiments were designed to answer two research questions:

1. Are autistic toddlers and cognitively-matched NT peers able to retain object-label pairings after a five-minute retention period when the words were initially taught in predictable and unpredictable sentence contexts?
2. Are autistic toddlers and cognitively-matched NT peers able to generalize novel labels to shape-matched objects when the words were initially taught in predictable and unpredictable sentence contexts?

Methods

General Procedure

Studies 2a and 2b were administered following the administration of Study 1 (see Chapter 3: *"Word Learning from Predictable and Unpredictable Input in Autistic and Non-autistic Children"*). These studies were designed to test each of the object-label pairings taught in Study 1 for retention (Study 2a) and generalization (Study 2b). To examine this, immediately following the completion of Study 1, the experimenter set a visual timer for four minutes. During this interval, children played with their caregiver, just outside of the experimental booth with a set of toys that were chosen to require minimal verbalization for engagement (e.g., marble run or pinwheel toy). While the child was playing with their caregiver, the experimenter prepared the booth and experimental computer to be able to start the next experiment immediately upon the child's return to the booth. After this timer went off (4 minutes) the experimenter let the child know that it was time to return to the experimental booth to "watch another movie," and escorted the child and their caregiver back into the booth. The experimenter started the delayed test experiment upon the child's return to the booth. While every effort was made to transition efficiently, it should be acknowledged that it is possible that some children took longer to transition back into the booth, and thus may have experienced a delay slightly longer than five minutes. The same experimental setup described for Study 1 was used for Studies 2a and 2b (i.e., television screen, camera, speaker). See Chapter 2: *"General Methods,"* and Chapter 3: *"Word Learning from Predictable and Unpredictable Input in Autistic and Non-autistic Children"* for more information about the experimental procedure. Both experiments were administered via Eprime software. Study 2a and 2b were programmed such that there was no break between them. That is, Study 2b began immediately after Study 2a, with a short attention-getter video in between.

Participants

Participants were the same as those described in Chapter 3: *"Word Learning from Predictable and Unpredictable Input in Autistic and Non-autistic Children,"* with the exception of one NT participant who did not participate in Study 2a and 2b due to difficulty with task compliance. As such, there were 30 NT and 30 ASD participants. See Table 4.1 for participant characteristics. These groups were matched on a measure of nonverbal cognition, DAY-C raw scores (t = -0.375, p = 0.709), see Chapter 2: *"General Methods"* for more information on group matching procedures.

Eyegaze Tasks

Study 2a: Retention of Novel Words

Study 2a began with two trials that cued children to identify familiar objects (e.g., sock, apple). These trials were included to re-familiarize children to the experiment, as in Study 1, but were not analyzed. Following these trials, each of the four novel objects taught in Study 1 were tested twice, totaling eight retention trials. The structure of retention trials was the same as in Study 1, except that there were no adjectives in the cue sentence (e.g., *"Find the modi"*). We chose to exclude adjectives from the delayed test as we were interested in children's retention of the nouns rather than their retention of the adjective that predicted them. The order of presentation of the nouns was pseudorandomized across two orders of the experiment.

Study 2b: Generalization of Novel Words

Study 2b was designed to test children's generalization of labels to shape-matched objects. We chose to evaluate shape-match generalization given that autistic children have demonstrated atypical use of the shape bias mechanism for generalization (Tek et al., 2008, Tovar et al., 2020). As such, understanding the input that best supports autistic children's ability to engage in shape-based generalization is theoretically and clinically significant. Immediately following the retention trials, children saw eight trials which presented shape-matched objects. For each of the four objects initially taught, children saw two trials testing whether they would generalize the label to shape-matched objects. Shape-matched images were created using Adobe Photoshop, changing the color of the objects that were presented in Study 1 and Study 2a. See

Figure 4.1 for an example of shape-matched stimuli and see Figure 2.1 in Chapter 2: "*General Methods*," for the full set of novel object and shape-matched generalization stimuli.

Data Cleaning and Processing

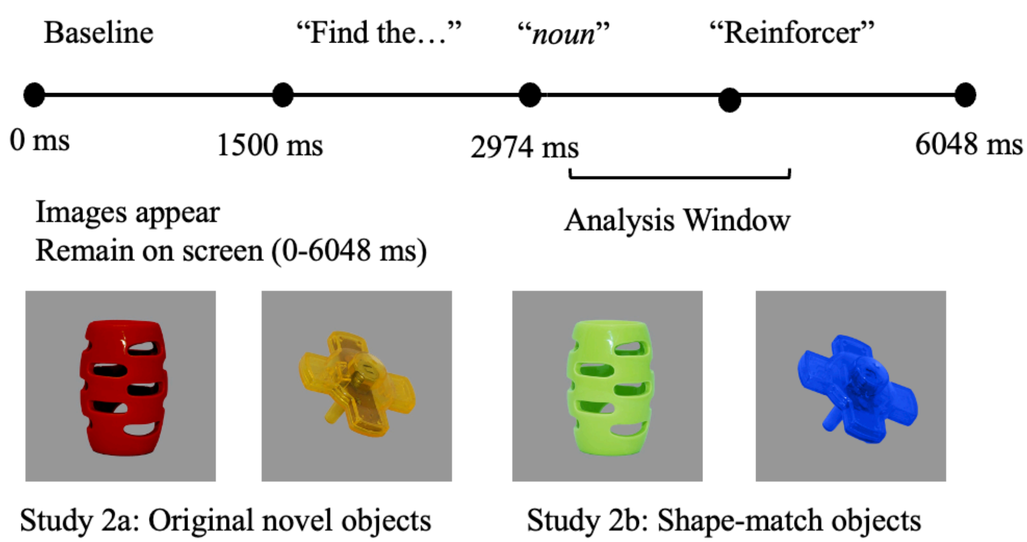
As in Study 1, in Studies 2a and 2b, proportion of looking to target during the experimental window was used to assess accuracy on retention (Study 2a) and generalization (Study 2b) trials. Children's looking behavior was coded offline using Peyecoder software (Olson et al., 2020) and the same procedures described in Chapter 3: *"Word Learning from Predictable and Unpredictable Input in Autistic and Non-autistic Children."* Each child's data from Study 2a and 2b was exported and coded within one video. To assess inter-coder reliability, 20% of videos were coded independently by a second coder. Frame agreement (the mean proportion of frames on which coders agreed) was 98% for the NT group and 98% for the ASD group. Shift agreement (the mean proportion of shift frames on which coders agreed) was 89% for the NT group and 90% for the ASD group.

We separately cleaned and analyzed retention and generalization trials to answer each research question. For both sets of analyses, we examined looking behavior during the analytical window, 200-1800 ms after noun onset. See Figure 4.1 for trial timing. As in Study 1, this window accounts for the time it takes children to execute a saccade (Canfield et al., 1997; Matin et al., 1993). Consistent with Study 1, and with prior literature (Mathée-Scott et al., 2021; Venker, Edwards, et al., 2019) we excluded test trials in which children attended to the screen for less than 50% of the analytical window. After this cleaning criteria was applied, children must have contributed at least two useable test trials for their data to be included (out of 8 possible). For Study 2a (retention trials), this resulted in four autistic participants being excluded. Resultant groups (N = 26 ASD; N = 30 NT) were still matched on our measure of cognitive ability (t = -

0.875, *p* =.386). For Study 2b (generalization trials) two autistic participants were excluded due to not contributing enough test data. Again, we confirmed that resultant groups (*N* = 28 ASD; *N* = 30 NT) were still matched on our measure of cognitive ability (*t* = -0.064, *p* =.949).

Figure 4.1

Study 2a and 2b Trial Schematic



Note. Timing was identical for Study 2a and Study 2b. Time is represented in milliseconds (ms) from trial onset. The analysis window for both studies was 200-1800 ms after noun onset.

Results

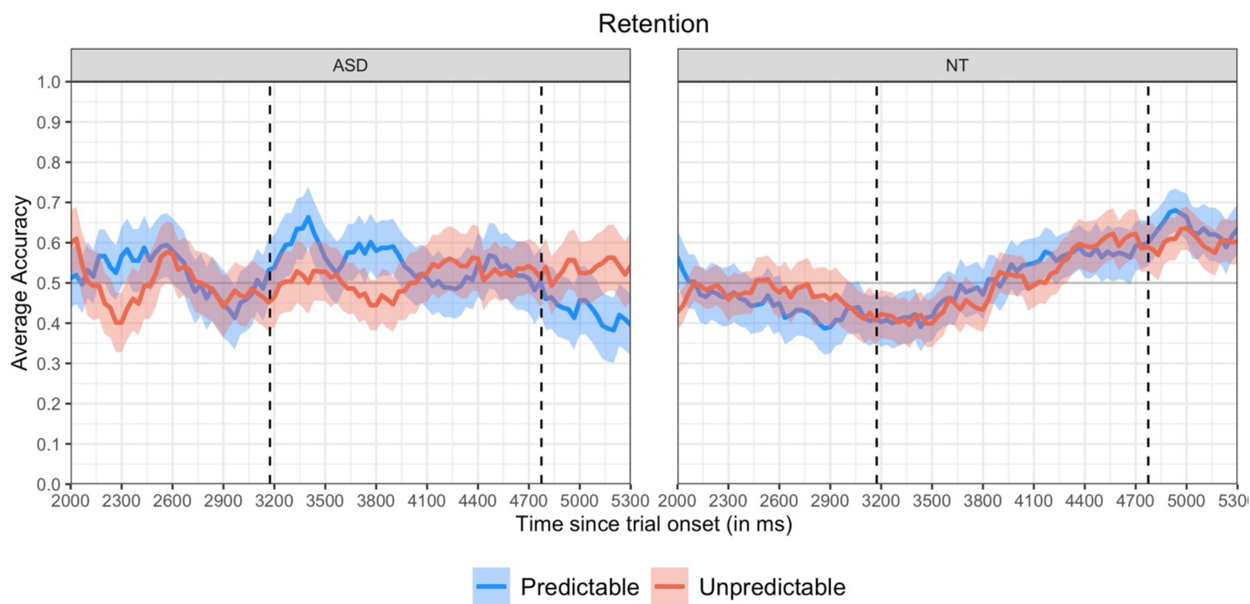
As in Study 1, we used both t-tests and growth curve models to evaluate accuracy at delayed test and for generalization, as well as the effect of condition and group on time-based looking behavior at delayed test (Study 2a), and to shape-matched objects (Study 2b).

Study 2a: Retention Trials

We first confirmed that children in both groups were able to retain object-label pairings after a five-minute delay. To evaluate this, we conducted one sample t-tests for each condition, for each group, against the alternative hypothesis that the true mean of average accuracy during the analytical window is greater than 0.5 (chance performance). The ASD group demonstrated performance significantly above chance in the predictable condition (t = 4.397, p < .001) but not in the unpredictable condition (t = 1.129, p = .129). The NT group demonstrated performance that was not significantly above chance in either condition (predictable: t = 1.216, p = .112; unpredictable: t = 0.589, p = .278). See Figure 4.2 for a visualization of raw looking behavior during retention trials.

Figure 4.2

Visualization of Raw Looking Behavior, Study 2a



Note. Raw looking behavior for Study 2a (retention) test trials plotted across trial (after baseline). Dashed horizontal lines represent the analytical window (200-1800 ms after noun onset). ASD group is on the left (N = 26) NT group is on the right (N = 30). Predictable trials are represented in blue, unpredictable trials are plotted in red.

To evaluate the effect of group and condition on looking behavior over time, we fit a series of growth curve mixed effects models. As in Study 1, the dependent variable in each model was the empirical log odds of looks to target versus nontarget during the analytical window (200-1800 ms after noun onset). Models included fixed effects for diagnostic group (contrast coded: ASD=-0.5; NT = 0.5), condition (contrast coded: unpredictable= -0.5;

predictable= 0.5), orthogonal polynomial time terms (linear, quadratic, cubic), all possible interactions, and by-subject random intercepts and slopes for condition, all three time terms, and their interactions. Model results revealed a significant main effect of linear time (b = 0.691, p = .019), indicating that across both groups and conditions, children fixated the target more at the end of the window than the beginning. This model also yielded a significant interaction between group and linear time (b = 1.494, p = .012), indicating a difference in linear time between two groups. See Appendix C for full model results. There were no significant main effects or interactions of condition.

To further examine the interaction between group and linear time, we evaluated each group independently. The model containing the autistic group revealed no significant effects. The model containing the NT group revealed a significant main effect of linear time (b = 1.4340, p < .001) suggesting that children in the NT group fixated the target significantly more at the end of the window than the beginning. These results suggest that while there was a linear effect in the NT group not evident in the ASD group, there was no significant impact of our condition manipulation on time-based performance in either group.

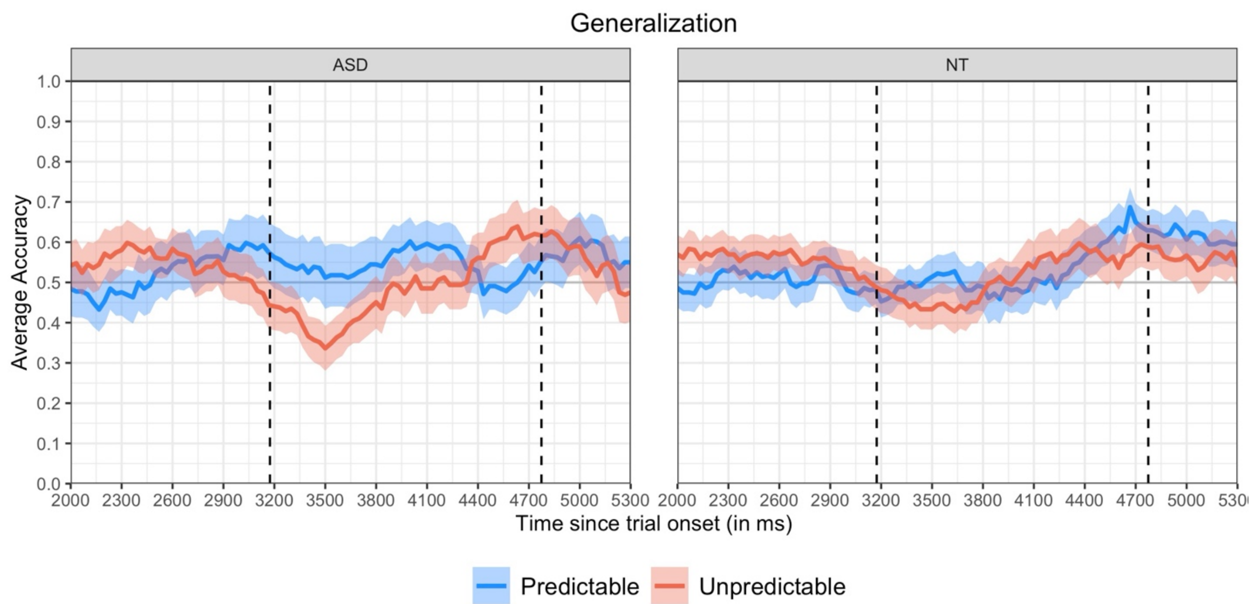
Study 2b: Generalization Trials

Next, we aimed to confirm that children in both groups were able to generalize object-label pairings to shape-matched objects. As in Study 2a, we conducted one sample t-tests for each condition, for each group, against the alternative hypothesis that the true mean of average accuracy during the analytical window is greater than 0.5 (chance performance). The ASD group demonstrated performance significantly above chance in the predictable condition (t = 4.212, p < .001) but not in the unpredictable condition (t = -1.913, p = .972). The NT group also demonstrated performance significantly above chance in the predictable condition (t = 3.221, p <

.001) but not the unpredictable condition (t = 1.509, p = .066). See Figure 4.3 for a visualization of raw looking behavior in generalization trials.

Figure 4.3

Visualization of Raw Looking Behavior, Study 2b



Note. Raw looking behavior for Study 2b (generalization) test trials plotted across trial (after baseline). Dashed horizontal lines represent the analytical window (200-1800 ms after noun onset). ASD group is on the left (N = 28) NT group is on the right (N = 30). Predictable trials are represented in blue, unpredictable trials are plotted in red.

As in Study 2a, we followed these t-tests with a growth curve mixed effects model to evaluate the effect of group and condition on looking behavior over time. The dependent variable was the empirical log odds of looks to target versus nontarget during the analytical window (200-1800 ms after noun onset). The model included fixed effects for diagnostic group (contrast coded: ASD=-0.5; NT = 0.5), condition (contrast coded: unpredictable= -0.5; predictable= 0.5), orthogonal polynomial time terms (linear, quadratic, cubic), all possible interactions, and by-subject random intercepts and slopes for condition, all three time terms, and their interactions. This model revealed a significant main effect of linear time (b = 0.966, p = .003), indicating that across both groups and conditions, children fixated the target more at the end of the window than the beginning. See Appendix C for full model results. There were no significant main effects of group, condition, nor their interactions. This suggests that overall, time-based performance on generalization trials was similar between the two groups and conditions.

Discussion

Findings from Study 2a revealed that autistic children were able to retain words learned from predictable sentence contexts but not those learned from unpredictable sentences. This difference was evident in our t-test analyses, revealing average accuracy significantly above chance in the predictable condition, but not in the unpredictable condition. However, this condition effect did not reach significance in our growth curve analyses. Study 2a also revealed that our NT sample did not retain words significantly above chance based on our t-test analyses. However, our growth curve analyses revealed a significant effect of linear time in the NT group. This suggests that the NT group fixated the target more at the end of the window than the beginning (see Figure 4.2). Thus, it is possible that the NT group took longer to fixate the target and did not achieve above chance fixations until the end of our analytical window. This delay may have resulted in an average accuracy that was not significantly above chance when averaged across the full window. Indeed, based on visualization (see Figure 4.2), the NT group's peak looks to target (i.e., the asymptote of the curve) appears to have occurred after the end of our analytical window. The analytical window ending at 1800ms after noun onset was based on prior similar studies (Mathée-Scott et al., 2021; Venker, Edwards, et al., 2019). However, it is possible that at delayed test, the younger NT group needed more time to fixate the target object. This may also explain the significant linear effect, indicating greater target fixations at the end of the window than the beginning, that was evident in the NT group, but not the ASD group.

Following Study 2a, we evaluated children's ability to generalize object-label pairings to shape-matched objects (Study 2b). Findings from Study 2b suggest that both the ASD and NT groups were able to generalize object-label pairings for words learned in predictable contexts, but not those learned in unpredictable contexts. This pattern was observed in our t-test analyses. Our growth curve analyses for Study 2b revealed a significant linear effect across both groups and conditions, suggesting a tendency to fixate the target more at the end of the window than the beginning. Growth curve models revealed no significant differences between groups in generalization trials, suggesting that autistic and NT children, matched on nonverbal cognitive ability, demonstrated commensurate generalization abilities in this task.

Autistic children's ability to retain words after a five-minute delay in the predictable condition in Study 2a is consistent with prior studies of autistic children, finding retention of novel words commensurate with receptive vocabulary-matched NT peers (Hartley et al., 2019, 2020). Similarly, our findings from Study 2b suggesting that autistic children were able to generalize words to shape-matched objects in the predictable condition are consistent with Hartley and colleagues' (2020) findings. In that study, autistic children and receptive vocabulary-matched peers demonstrated similar generalization performance for words learned via cross-situational. An important consideration in contextualizing these findings with prior literature is that our matching variable differed from these prior studies. Hartley and colleagues' 2019 and 2020 studies both matched groups on receptive vocabulary. Our samples were matched on a measure of nonverbal cognition, which was chosen based on the theoretical framework of the present study (see Chapter 2: "*General Methods*" for more information about group matching). Indeed, our groups are significantly different on our measure of receptive language ability (see Table 4.1) such that our autistic group demonstrated significantly lower scores on our receptive language measure (PLS-5 Auditory Comprehension). However, our autistic sample still showed retention and generalization abilities commensurate with NT peers, even when the NT group had significantly better extant language abilities. Future research including a receptive-language matched comparison group would help to better situate the present study's findings within the context of prior literature.

We must also acknowledge some limitations of the present study. First, as described in *General Procedure,* our delay procedure allowed for some margin of error in the length of retention interval. That is, some children may have taken longer than others to transition back to the experimental booth to begin Study 2a, and we did not have a way to control for this analytically. Next, we had some significant data loss in this study, particularly in the autistic group. This was likely the result of fatigue and task compliance difficulty, given that these tasks were administered after Study 1. This resulted in a reduced sample size, which necessarily impacted our experimental power. This may explain why, in the autistic group in particular, there were condition differences observed in our t-test analyses, but these differences did not reach significance in our growth curve analysis linear mixed effects models, which require greater experimental power. Additionally, we chose to examine generalization to shape-matched objects and did not include color-matched foils, as in Hartley et al. (2020). Our experimental paradigm (Looking-While-Listening; see Chapter 2: *"General Methods"*) is most commonly used with two areas of interest (AOI's), which differs from the touch screen paradigm used by Hartley and colleagues (2020) which allows for more AOI's and therefore the inclusion of two foil objects.

Additionally, conclusions about the NT group, and group comparisons to the autistic group, must be made cautiously, given that our NT sample did not demonstrate above chance retention of object-label pairings in either condition in Study 2a. As previously noted, it may be the case that the NT group would have achieved performance significantly above chance in a longer analytical window. Interestingly, the NT group did demonstrate generalization above chance in the predictable condition, even though they did not show retention above chance. It is possible that engaging in retrieval practice during Study 2a supported their memory for the objects such that they were able to engage in generalization in Study 2b. This is consistent with several prior studies of NT children, finding that forgetting supports both later retrieval accuracy as well as abstraction and generalization. Vlach and colleagues (2012) demonstrated that NT children who learned words with short intervals between presentations (i.e., spaced condition) showed forgetting initially. However, those children improved their accuracy on subsequent retrieval attempts. Similarly, Leonard and colleagues (2020) found that, for both children with developmental language disorder (DLD) and NT children, increased retrieval practice supported long term generalization. Thus, our finding that the NT group demonstrated forgetting in Study 2a, followed by above chance generalization in Study 2b are consistent with the hypothesis that forgetting and retrieval practice support subsequent generalization.

Despite these limitations, both groups' ability to generalize object-label pairings, and the autistic group's ability to both retain and generalize words that were learned in predictable sentence contexts above chance levels is notable. Prior literature has demonstrated a lack of shape bias generalization in similarly-aged autistic children (Tek et al., 2008). While our autistic group's performance in the unpredictable condition was consistent with this, our findings demonstrate that a shape bias generalization might be observed in autistic children when words are taught in predictable sentence contexts. Impressively, autistic children achieved accuracy of 60-70% in both retention and generalization trials in the predictable condition, which was significantly above chance levels, based on our t-test analyses.

Overall, our findings indicate that NT children did not retain object-label pairings above chance levels in either condition but did generalize above chance for objects in the predictable condition. Older, cognitively-matched autistic children were able to both retain and generalize words initially learned in predictable sentences, but not those learned in unpredictable sentences. Thus, findings from this study suggest that predictable sentence contexts may support retention and generalization of newly learned words in autistic children. However, conclusions must be made with caution, as group and condition differences in time-based looking behavior were not statistically significant in our growth curve model analyses. The impact of individual differences, such as age and extant language ability on the impact of stimulus predictability on retention and generalization will be explored in Chapter 5: "*Individual Differences in Prediction and Word Learning among Autistic and Non-autistic Children.*"

Table 4.1 Study 2a and 2b participant characteristics.

	ASD Group (n = 30)	NT Group (n = 30)	Group Comparisons
	Mean (SD) range	Mean (SD) range	
Age (Months)	40.05 (7.32) 27-50	23.03 (5.20) 16-31	Cohen's d = 2.65 $p < .001$
Receptive Language			
Raw Scores	22.68 (8.13) 13-41	33.17 (9.82) 19-65	Cohen's d = -1.15 $p < .001$
Standard Scores	62.64 (15.69) 50-94	110.97 (13.05) 67-134	Cohen's d = -3.38 $p < .001$
Expressive Language			
Raw Scores	25.28 (7.14) 13-40	31.52 (6.75) 24-49	Cohen's d = -0.90 $p < .001$
Standard Scores	72.08 (15.03) 50-103	108.24 (10.90) 87-130	Cohen's d = -2.79 $p < .001$
Nonverbal Cognition			
Raw Scores	37.1 (8.28) 28-57	37.8 (5.81) 29-51	Cohen's d = -0.10 $p = .512$
Standard Scores	81.77 (13.45) 56-116	104.47 (6.0) 93-118	Cohen's d = -2.18 $p < .001$
Adaptive Behavior	69.93 (8.86) 53-97	98.04 (8.14) 85-116	Cohen's d = -3.30 $p < .001$
Autism Traits			

Severity Score	2.29 (0.59) 1-3	—	—
Total Score	35.09 (4.55) 26.5-47	—	—
Demographic Information			
Race	18 White 8 More than One Race 4 Black or African American	30 White	
Ethnicity	27 Not Hispanic or Latino 3 Hispanic or Latino	30 Not Hispanic or Latino	
Sex	7 Female 23 Male	15 Female 14 Male	

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Chapter 5: Individual Differences in Prediction and Word Learning among Autistic and Non-autistic Children

Introduction

Heterogeneity in Autism Spectrum Disorder

ASD is a disorder characterized by broad heterogeneity. This heterogeneity is described by Wolfers and colleagues (2019) in three subcategories. These include variations in the biological markers of the disorder (biological heterogeneity), heterogeneity arising from environmental factors that differentially impact behavior and biology (environmental heterogeneity), and heterogeneity in the clinical presentation of ASD traits (clinical heterogeneity). As described in the previous chapters, there is broad clinical heterogeneity in the area of structural language in ASD (Koegel et al., 2020). These wide variations can create challenges for both theory and intervention, as it is difficult to universally explain and address all variations of the ASD presentation. As such, it has become broadly evident that investigating individual differences is imperative for creating both theories and interventions that appropriately capture the presentation of various ASD phenotypes. Indeed, in the context of structural language, individual differences approaches may serve to disentangle the underpinnings of the heterogeneity we observe in this population.

In the domain of word learning, several studies have begun to examine the impact of individual differences, such as extant vocabulary knowledge, cognition, and demographic factors. Abdelaziz and colleagues (2018) examined the impact of individual differences on the use of the shape bias in autistic children. They found no individual variable that sufficiently explained shape bias performance. For example, vocabulary differences did not significantly account for performance. However, for children with low verbal ability and ASD, there was a positive association between initiation of joint attention and the use of shape bias. In the context of cross-situational word learning, Hartley and colleagues (2020) investigated the role of individual differences in age, receptive vocabulary and nonverbal cognition. While individual differences in each of these variables appeared to have effects on accuracy and response time in both groups, the authors acknowledge that intercorrelations between these variables make conclusions about each of their individual contributions to word learning difficult to make.

The present dissertation is grounded in prediction-based theories of ASD. See Chapter 1: "*Introduction,*" for a more thorough review of this theoretical framework. Given that prediction-based theories of ASD have only emerged within the past decade, the explanatory power of individual differences in understanding variations in prediction abilities in ASD remains an open question. Indeed, more recently, Cannon and colleagues' highlight in their (2021) review that understanding the relationship between prediction differences and individual differences in other areas (e.g., ASD traits, genetic profiles, cognitive ability, language ability) will be an important step toward refining their original theory (i.e., the PIA hypothesis). They emphasize, however, that understanding the individual differences that contribute to prediction abilities will be crucial for allowing this theoretical framework to be appropriately applied to intervention contexts.

Individual Difference in Neurotypical Word Learning

Large-scale studies of NT children have attempted to chart the developmental course of vocabulary acquisition (Braginsky et al., 2016.; Frank et al., 2017). There is evidence that both intrinsic and extrinsic individual differences contribute to the process of vocabulary acquisition and word learning abilities. For example, complex cognitive processes appear to be involved in word learning, thus, individual differences in these processes have shown some explanatory power with respect to word learning abilities. Gray and colleagues (2022) found that working memory abilities, over and above nonverbal cognition and extant vocabulary, predicted novel word learning performance in second-grade NT children. Similarly, efficiency of lexical processing appears to be predictive of novel word learning in NT children (Lany, 2018). Individual differences that are extrinsic to the child, such as the home environment, may also play a role. Yu and colleagues (2019) demonstrated that both infant sustained attention and joint attention with parents predicted vocabulary size at 12 and 15 months. Weisleder and Fernald (2013) found that infants who were spoken to in child-directed speech were more efficient in processing familiar words and had larger expressive vocabularies. Moreover, the impact of child-directed speech on productive vocabulary was mediated by lexical processing efficiency, suggesting that exposure to a rich language environment strengthens children's ability to process and learn language.

The Current Study

Individual differences approaches are a necessary step to further refining and applying prediction-based theories, as well as word learning theory in ASD. Thus, in the present study, we aimed to examine whether individual differences, such as age, language ability, cognitive abilities, daily living skills, and autistic traits were related to children's ability to learn, retain, and generalize words learned from predictable and unpredictable sentence contexts. To evaluate this, we employed statistical modeling approaches using data from Study 1, Study 2a, and Study 2b along with standardized assessment and demographic data. We answered the following three research questions:

> Research Question 1 (Study 3a): Are individual differences in age, language ability, cognitive abilities, daily living skills, and autistic traits related to autistic and non-autistic children's initial word learning from predictable and unpredictable sentence contexts?

Research Question 2 (Study 3b): Are individual differences in age, language ability, cognitive abilities, daily living skills, and autistic traits related to autistic and non-autistic children's retention of words learned from predictable and unpredictable sentence contexts?

Research Question 3 (Study 3c): Are individual differences in age, language ability, cognitive abilities, daily living skills, and autistic traits related to autistic and non-autistic children's generalization of words, learned from predictable and unpredictable sentence contexts, to shape-matched objects?

Methods

Participants

Participants were the same as those in Study 1, Study 2a, and 2b. For Study 3a, there were 30 autistic children (7 female) and 31 NT children (13 female). See Table 3.1 for participant characteristics. For Study 3b and 3c, there were 30 NT (7 female) and 30 ASD (15 female) participants. See Table 4.1 for participant characteristics. Participants in the ASD group had diagnoses of ASD consistent with DSM-5 criteria confirmed by diagnostic assessments administered by clinical staff in the research group (see Chapter 2: *"General Methods"*). Participants were recruited from the local area via a research registry at the Waisman Center, local parent groups and early intervention providers. Participants resided in monolingual, English-speaking households and were reported to have no known hearing or vision impairments.

Procedure

Participants' eyegaze data from Study 1, Study 2a, and Study 2b were entered into linear models including demographic data and data from standardized assessments. See Chapter

Chapter 3: *"Word Learning from Predictable and Unpredictable Input in Autistic and Non-autistic Children"* for a detailed explanation of Study 1. See Chapter 4: *"Retention and Generalization of Object-Label Pairings Learned from Predictable and Unpredictable Input in Autistic and Non-autistic Children"* for detailed explanations of Study 2a and Study 2b.

Individual differences in language ability, cognitive ability, daily living skills, and autism traits were derived from standardized assessments. Participants in both groups engaged in a battery of assessments administered by laboratory clinicians (speech language pathologists and clinical psychologists). Language ability was evaluated using the Preschool Language Scales, 5e (PLS-5; Zimmerman, Steiner, & Pond, 2011) which assessed children's receptive and expressive language. Nonverbal cognitive ability was measured using the cognitive subtest of the Developmental Assessment of Young Children, 2e (DAYC-2; Voress & Maddox, 2012). This measure was chosen as most of the items were designed to minimize the influence of language on the assessment of cognitive skills. Daily living skills was measured by the Vineland Adaptive Behavior Scales, 3e (Vineland-3; Sparrow, Cicchetti, & Saulnier, 2016), Comprehensive Parent/Caregiver Form. Additionally, we used demographic information (e.g., age) obtained by a background form, which was completed by participants' parents via Qualtrics survey software. For the autistic group, the Childhood Autism Rating Scale, 2e (CARS-2; Schopler et al., 2010), provided a measure of autistic traits. We have chosen to use the term autistic traits, which is sometimes referred to as autism symptom severity, as it has been expressed as the preferred term of autistic self-advocates (Bottema-Beutel et al., 2021).

Results

To examine the impact of individual differences, for each experiment described in the preceding chapters, (Study 1, Study 2a, and Study 2b) eyegaze data for each condition and each group were separately entered into linear regression models along with data from standardized and demographic measures. In each model, the dependent variable was average accuracy (proportion of looks to target versus non-target object) during the experimental window. Included as independent variables in each model were the following individual differences variables: cognitive ability (as measured by DAY-C cognitive domain raw scores), age (in months), receptive language ability (as measured by PLS-5 auditory comprehension subtest raw scores), expressive language ability (as measured by PLS-5 expressive communication subtest raw scores), daily living skills (as measured by Vineland Adaptive Behavior Scales, personal daily living skills raw scores), and autistic traits (autistic group only, as measured by CARS-2 total raw scores). Raw scores were used to reflect absolute ability and minimize collinearity with age. Each independent variable was scaled and mean-centered for modeling. All analyses were conducted using R (version 4.0.2, R Core Team, 2021) and R Studio software (version 2022.02.3+492, R Studio Team, 2020).

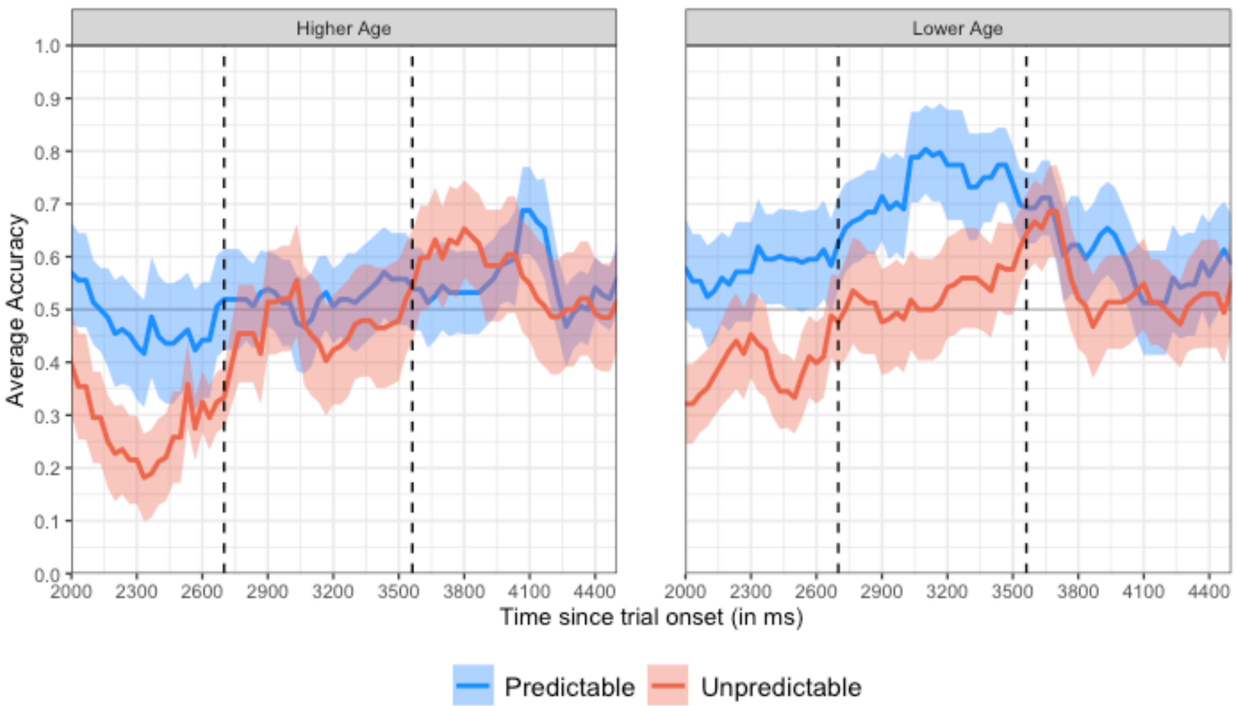
Study 3a: Individual Differences in Initial Word Learning

Autistic Group

First, we evaluated the role of individual differences in age, language ability, cognitive ability, daily living skills, and autistic traits within the autistic group on initial word learning and anticipation in Study 1. We separately examined this for each condition (predictable and unpredictable) and each experimental window (anticipatory window and noun recognition window) in Study 1. We fit a series of linear regression models in which the dependent variable was average accuracy, including each of the above individual differences variables as independent variables. For full model results, see Appendix D. These models revealed a significant effect of age on performance in the anticipatory window in the predictable condition (*b* = -0.14, *p* < .05). This is a surprising finding, suggesting that younger autistic children demonstrated better anticipation in the predictable condition than older autistic children. See Figure 5.1 for a visualization of this effect. There were no significant effects of any of the individual differences tested on performance in the unpredictable condition in the autistic group.

Figure 5.1

Study 1, Anticipation Window, Autistic Group, Median Split by Age



Note. Raw looking behavior for the autistic group for Study 1 test trials plotted across trial (after baseline). Dashed horizontal lines represent the anticipatory adjective window (200 ms after adjective onset to noun onset). After groups were split at the median of age, older ASD group is on the left (*N* = 16) younger ASD group is on the right (*N* = 14). Predictable trials are represented in blue, unpredictable trials are plotted in red.

Neurotypical Group

For the NT group, we evaluated the role of individual differences in age, language ability, cognitive ability, and daily living skills on initial word learning and anticipation in Study 1. As for the autistic group, we separately fit models for each condition and experimental window. The models were identical to those described for the autistic group, but did not include a measure of autistic traits, as this measure was not administered to NT children. See Appendix D for full model results. These models revealed a significant effect of expressive language ability (b = 0.17, $p < .05$) on noun recognition in the predictable condition. These results suggest that NT children with stronger expressive language abilities showed greater accuracy of initial word learning in the predictable condition. There was a significant effect of daily living skills on noun recognition in the unpredictable condition (b = -0.13, $p < .05$) suggesting that children who demonstrate greater independence in daily living skills demonstrated lower accuracy in noun recognition, see Discussion below for further exploration of this effect.

Study 3b: Individual Differences in Word Retention

Autistic Group

As in Study 3a, we separately evaluated each group and condition for the impact of individual differences. In the autistic group, we examined the role of individual differences in age, language ability, cognitive ability, daily living skills, and autistic traits on retention of words, using eyegaze data from Study 2a. As in Study 3a, in each linear model, the dependent variable was average accuracy (proportion of looks to target versus nontarget), including each of the above individual differences variables as independent variables. For full model results, see Appendix D. These models revealed no significant effects in either condition.

Neurotypical Group

In the NT group, we examined the role of individual differences in age, language ability, cognitive ability, and daily living skills on retention of words, using eyegaze data from Study 2a. As above, the dependent variable in each linear model was average accuracy (proportion of looks to target versus nontarget), and each of the above individual differences variables were independent variables. For full model results, see Appendix D. There were no significant effects of any of the individual differences examined on retention in either condition in the NT group.

Study 3c: Individual Differences in Generalization

Autistic Group

We repeated the same analytical process as described above for generalization trials, examining the impact of individual differences in age, language ability, cognitive ability, daily living skills, and autistic traits within the autistic group on generalization of words, using eyegaze data from Study 2b. See Appendix D for full model results. There were no significant effects of any of the individual differences analyzed on generalization in either condition.

Neurotypical Group

Finally, we examined the role of individual differences in age, language ability, cognitive ability, and daily living skills on NT children's generalization of words, using eyegaze data from Study 2b. As above, the dependent variable in each linear model was average accuracy (proportion of looks to target versus nontarget), and each of the above individual differences variables were independent variables. For full model results, see Appendix D. There were no significant effects of any of the individual differences examined on generalization in either condition in the NT group.

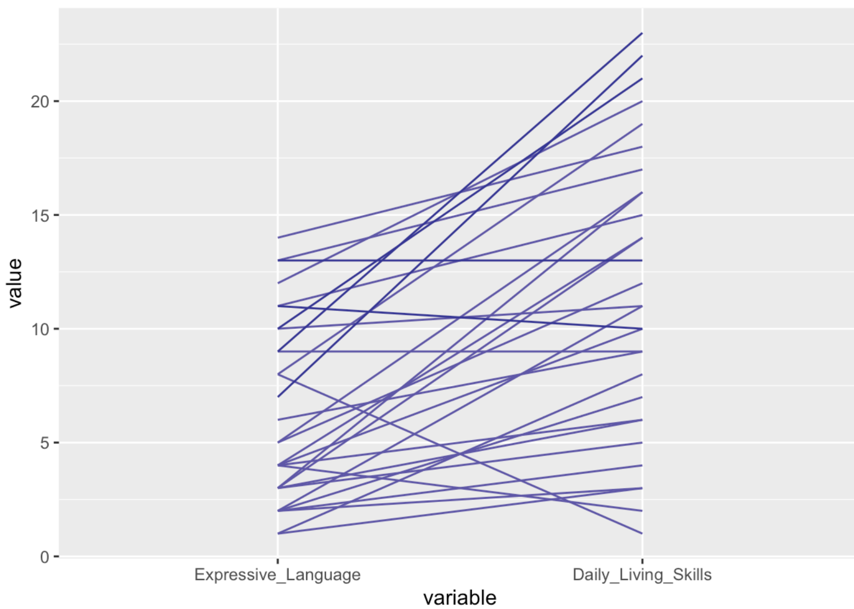
Discussion

Overall, our individual differences analyses revealed very few significant effects among the variables we examined; however, there were some interesting patterns. In the NT group, children with stronger expressive language abilities showed better initial word learning in the predictable condition. Surprisingly, there was a significant effect of daily living skills on noun recognition in the unpredictable condition, suggesting that NT children who demonstrated greater independence in daily living skills demonstrated lower accuracy in this condition. It is possible that the experimental task was not engaging enough for the NT children who were more independent, and thus they became bored and lost interest in the task. However, an effect in the opposite direction was evident for children with stronger expressive language abilities in the predictable condition. Thus, there may have been some NT children with higher independence in daily living skills, but weaker expressive language abilities, who struggled with attention to the task. Conversely, there may have been some children with lower independence in daily living skills and stronger expressive language abilities who performed better in the task. To examine this, we plotted these scores for each child in the NT group (see Figure 5.2). Based on visualization, it appears that there are indeed some NT children with disparate scores on these two measures. There were no significant individual differences effects in the NT group on performance on retention or generalization trials.

In the autistic group, there was a surprising effect of age. We found a significant effect of age on performance in the anticipatory window in the predictable condition in Study 1. The direction of this effect suggests that younger autistic children demonstrated better anticipation in the predictable condition than older autistic children. Similarly, there was a marginal effect of age in generalization trials (b = -0.11, p = .064) such that younger autistic children demonstrated marginally better generalization accuracy in the predictable condition. However, this effect did not reach statistical significance. This surprising pattern of results, and possible explanations for it, will be discussed further below. Additionally, autistic children with stronger expressive language abilities demonstrated marginally better noun recognition accuracy in the predictable condition (b = 0.15, p = .088). On retention trials, children with lower autistic traits demonstrated marginally better retention of words learned in predictable contexts (b = -0.18, p = .085). However, neither of these effects reached statistical significance.

Figure 5.2

Relationships Between Expressive Language and Personal Daily Living Skills



Note. Linear relationships between scores for each NT participant who had complete scores for both Expressive Language, as measured by PLS Expressive Communication raw scores, and Daily Living Skills, as measured by Vineland Personal Daily Living Skills raw scores (n = 30). Each line connects an individual participant's Expressive Language raw score to their Daily Living Skills raw score.

Given the unexpected effect of age on anticipation in the autistic group, we explored possible alternative explanations. One such explanation for our younger autistic children performing better is that the older autistic children simply found the task boring. Our autistic sample was broad in age range, from 27 to 50 months, with a mean age around 40 months. Thus, some of our autistic children were older than four years of age. It is possible that sitting with their parent and watching the experiment was monotonous and did not sufficiently hold their attention. Indeed, when divided via median split into older and younger groups, the 16 older autistic children had a larger mean percentage of missing data in Study 1 (M = 42.29%) than the

14 younger autistic participants (*M* = 34.39%). This suggests that older autistic children were more likely to lose interest in looking at the screen, possibly due to boredom. Another potential explanation is that this age difference arose from children being tested at different timepoints of the larger parent project. That is, all of the 16 older autistic children (based on a median split) were administered the present tasks at Time 2 of the parent project. Of the younger autistic group, 10 were administered these tasks at Time 1, and four participated in these tasks at Time 2. The other experimental and developmental tasks that were included in the visit protocol and the order of administration of these tasks differed slightly between the two timepoints. For example, there were three other word learning tasks administered during the Time 2 visit. Thus, it is possible that children became bored or overwhelmed with the tasks demands, particularly word learning demands, placed on them during these visits. Other than the timepoint at which the tasks were administered, the younger and older autistic subgroups did not differ significantly on the other individual differences measures (e.g., autistic traits, nonverbal cognition, language ability, daily living skills). However, it is also important to acknowledge the potential for intercorrelations among each of these individual differences. As in Hartley and colleagues (2020) many of the individual differences we examined here (e.g., age and expressive language ability) are likely to be intercorrelated. This means that we must take some degree of caution in interpreting the unique role of any individual variable.

These findings provide potentially important insights into the individual differences that may impact the interplay between prediction and word learning in young autistic and non-autistic children. Similar to prior studies (Weisleder & Fernald, 2013), individual differences in extant language ability appeared to be associated with initial word learning in both groups. For NT children, stronger extant expressive language abilities were associated with better initial word learning in the predictable condition. A similar, though marginal, effect emerged in the autistic group, such that children with higher expressive language abilities demonstrated marginally better initial word learning in the predictable condition. The effect of age paints a more nuanced picture. Older NT children performed marginally better on initial word learning in the predictable condition. In the autistic group, however, younger age was associated with better anticipation in Study 1. As such, more research will be required to discern the precise mechanisms underlying these individual differences and their relationships to prediction and word learning in this population.

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Chapter 6: General Discussion

Study 1: Anticipation and Word Learning Findings

Anticipation

In Study 1, we examined whether autistic children and cognitively-matched, younger NT peers were able to anticipate upcoming novel nouns based on a predictable adjective. Findings indicated that the ASD group demonstrated performance significantly above chance in the predictable condition but not in the unpredictable condition. The NT group demonstrated performance that was not significantly above chance in either condition. We followed these analyses with a series of growth curve models to evaluate the impact of group and condition on time-based looking behavior. These models revealed significant interactions among group, condition, and quadratic time and group, condition, and cubic time. This suggests that the two groups demonstrated different magnitudes of difference from the unpredictable to the predictable condition in the rate of change around children's peak asymptote of fixation proportions (quadratic effect), and between the slopes of the tails of the curves (cubic effect).

Noun Recognition

Next, we asked whether autistic children and cognitive ability-matched NT peers would demonstrate learning of novel nouns taught in predictable and unpredictable sentence contexts. We evaluated looking behavior during a noun recognition window of 200-1800ms after noun onset, based on prior similar studies (Mathée-Scott et al., 2021; Venker, Edwards, et al., 2019). Analyses mirrored those performed for the anticipatory window. Results from the noun recognition window t-test analyses suggested that both groups were able to learn the novel words significantly above chance levels in both conditions. Growth curve analyses revealed a difference in looking behavior such that there was a significant three-way interaction between group, cubic time, and condition. We explored this interaction further by evaluating each group individually. These models revealed an interaction between condition and cubic time that approached significance in the autistic group, whereas there were no significant condition by time interactions in the NT group. This suggests that in the autistic group, there was a marginal difference in the tail ends of the curve between the two conditions, such that autistic children looked more to the target at the tail end of the curve in the predictable condition than in the unpredictable condition. This difference was not evident in the NT group.

While both groups were able to learn the words in both conditions, there was a group difference in the impact of condition on latency of looking behavior in the noun recognition window. The autistic group demonstrated a greater impact of condition on looking behavior than the NT group. Taken together, these findings suggest that autistic children may possess a strength in predictive processing of sentences including novel words, and that predictable sentence contexts may support autistic children's ability to anticipate and recognize newly learned novel words.

Study 2a: Retention Findings

Following Study 1, we examined the impact of sentence context predictability during training on children's retention of novel words. This was an important next step in evaluating the clinical and theoretical impact of the findings from Study 1, as initial word learning provides an incomplete picture of children's integration of a new word into their broader lexicon. Thus, after participating in Study 1, children engaged in a short retention interval (five minutes) before Study 2a was administered. Study 2a was designed to ask whether autistic children and cognitively-matched NT peers were able to retain object-label pairings after a five-minute delay, when the words were initially taught in predictable and unpredictable sentence contexts.

First, we evaluated children's overall accuracy in retention trials using one sample t-tests for each condition, for each group, against chance performance. The ASD group demonstrated performance significantly above chance in the predictable condition but not in the unpredictable condition. The NT group demonstrated performance that was not significantly above chance in either condition. Thus, findings suggested that predictable sentence contexts supported memory for newly learned words for autistic children, but not for NT peers.

As in Study 1, we followed these t-test analyses with a series of growth curve models. These model results suggested that there was a linear effect in the NT group that was not evident in the ASD group, suggesting that the NT group fixated the target more at the end of the window than the beginning, when collapsing across conditions. There were no significant group by time by condition interactions, suggesting no significant impact of our condition manipulation on time-based performance in either group.

Study 2b: Generalization Findings

Immediately following Study 2a, we tested children's ability to generalize each novel word to shape-matched objects. Study 2a was designed to answer the research question: are autistic toddlers and cognitively-matched NT peers able to generalize novel labels to shape-matched objects when the words were initially taught in predictable and unpredictable sentence contexts? As in Study 2a, we first evaluated children's overall average accuracy in generalization trials. We conducted one sample t-tests for each condition, for each group, against chance performance. Similar to retention trials, the ASD group demonstrated performance significantly above chance in the predictable condition but not in the unpredictable condition. The NT group also demonstrated performance significantly above chance in the predictable condition but not the unpredictable condition. Again, we followed these t-tests with a series of growth curve models. These models revealed no significant main effects of group, condition, nor their interactions. This suggests that overall, time-based performance on generalization trials was similar between the two groups and conditions. Overall, these findings suggest that predictable sentences during training supported generalization for both autistic and non-autistic children.

Study 3: Individual Differences Findings

To better understand the mechanisms underlying differences in prediction and word learning, we examined the role of individual differences in explaining performance in the previously described studies. To this end, we entered participants' eyegaze data for each condition of each experiment into linear regression models along with data from standardized and demographic measures. We separately examined individual differences in each group. In each model, the dependent variable was average accuracy (proportion of looks to target versus non-target object) during the relevant experimental window. We included the following individual differences variables as mean-centered independent variables in each model: cognitive ability (as measured by DAY-C cognitive domain raw scores), age (in months), receptive language ability (as measured by PLS-5 auditory comprehension subtest raw scores), expressive language ability (as measured by PLS-5 expressive communication subtest raw scores), daily living skills (as measured by Vineland Adaptive Behavior Scales, personal daily living skills raw scores), and autistic traits (autistic group only, as measured by CARS-2 total raw scores).

For the autistic group, results revealed a significant effect of age on performance in the anticipatory window in the predictable condition of Study 1. Somewhat surprisingly, the direction of this effect suggests that younger autistic children demonstrated better anticipation in the predictable condition than older autistic children. In the NT group, children with stronger expressive language abilities showed higher noun recognition accuracy in Study 1 in the predictable condition. There was also a significant effect of daily living skills on noun recognition in the unpredictable condition of Study 1, such that NT children who demonstrated greater independence in daily living skills demonstrated lower accuracy in this condition.

Overall Summary of Findings

In sum, for words taught in predictable sentence contexts, autistic children demonstrated average looks to target above chance levels during anticipation, initial noun recognition, retention, and generalization trials. These initial word learning findings are consistent with prior literature, finding commensurate word learning between vocabulary-matched NT and autistic samples (Hartley et al., 2019; Luyster & Lord, 2009; Venker, 2019). Autistic children were also able to demonstrate initial learning of novel words taught in unpredictable sentence contexts, but those words were neither retained nor generalized above chance levels by the autistic group, on average. Cognitively-matched, younger NT children demonstrated above-chance average looks to target when words were taught in predictable sentences in initial noun recognition and generalization trials, but not during anticipation or in retention trials. As such, findings from these studies suggest that predictable sentence contexts may support predictive sentence processing, word learning, retention, and generalization in autistic children. These findings also suggest a relative strength for autistic children in this domain when compared to younger, cognitive ability-matched NT children.

Individual differences analyses revealed that age was related to anticipation in autistic children, although the direction of the effect suggested that younger autistic children anticipated more accurately than older autistic children. For NT children, those with higher expressive language abilities demonstrated greater accuracy in noun recognition in the predictable condition. This finding is consistent with prior studies finding associations between extant language abilities and word learning (Weisleder & Fernald, 2013). Similarly, there was a marginal effect of expressive language in the autistic group, such that children with higher expressive language abilities demonstrated marginally better initial word learning in the predictable condition. Conversely, NT children with higher daily living skills scores demonstrated poorer noun recognition accuracy in the unpredictable condition.

Alternative Explanations for Unexpected Findings

In Study 1, autistic children were able to anticipate newly learned novel nouns based on a preceding adjective when those words were taught in predictable sentence contexts, whereas NT children were not. Therefore, autistic children demonstrated a relative strength in anticipation when compared to cognitively-matched NT children. However, it is important to note that our autistic sample was significantly older than our NT sample. As such, it is not clear from this study whether the same strength would be evident if autistic children were compared to an age-matched NT sample. It is possible that our NT sample were too young to engage in this type of anticipation in the context of word learning for this particular task. Prior literature has found that NT two-and three-year olds are able to anticipate familiar nouns using facilitative verbs, and that predictable events during training support their word learning (Benitez & Saffran, 2018; Lukyanenko & Fisher, 2016). However, to our knowledge the ability to anticipate a newly learned word using preceding semantic information has not been tested in NT children this young. Additionally, some of our NT sample were younger than two-years old, with a mean age of 27 months. Our individual differences analyses did not reveal significant effects of age, but it may be that our sample overall was too young, meaning that individual differences would only have been revealed if older children were also included in the sample. Future studies including age-matched samples of autistic and NT children will be important to understand the impact of age in both groups.

Similarly, in Study 2a, NT children did not demonstrate retention of novel words above chance levels in either condition. The significant effect of linear time, collapsing across conditions, in this group suggests that NT children looked more to target at the end of the window than the beginning. This suggests a potential delay in initiating a saccade in response to hearing the noun in the NT group. It may be, therefore, that the younger NT group needed more time to engage in retention and shift their gaze to the target object in these trials. Conversely, NT children demonstrated above-chance looks to target in the predictable condition for generalization trials (Study 2b) within the analytical window. Thus, it may be that NT children benefitted from retrieval practice during retention trials, resulting in above chance performance in generalization trials, when they had not achieved accuracy above chance in retention trials. This is consistent with prior work demonstrating initial forgetting, followed by improvement in performance following retrieval practice in NT children (Leonard et al., 2020; Vlach, 2014).

In our individual differences analyses, there were some surprising findings. For example, NT children who demonstrated greater independence in daily living skills demonstrated lower accuracy in initial word learning the unpredictable condition. It is possible that the experimental task was not engaging enough for the NT children who were more independent, and thus they became bored and lost interest in the task. However, an effect in the opposite direction was evident for NT children with stronger expressive language abilities in the predictable condition. Thus, there may have been some NT children with higher independence in daily living skills, but weaker expressive language abilities, who struggled with attention to the task. We used data visualization to examine the relationships between expressive language and daily living skills in the NT group (see Figure 5.2) and observed that there were indeed some NT children with disparate scores on these two measures, particularly those with lower expressive language and higher daily living skills scores.

Finally, there was a marginal effect of age in generalization trials such that younger autistic children demonstrated marginally better generalization accuracy in the predictable condition. However, this effect did not reach statistical significance. We hypothesize that older autistic children may have lost attention to the task, resulting in poorer performance. We did confirm that older autistic children (when divided via median split) had a larger mean percentage of missing data in Study 1 (M = 42.29%) than younger autistic participants (M = 34.39%), suggesting that the task may not have held the attention of the older autistic children. We also posit that this may be related to the timepoint at which children saw the task. Most of the older autistic children were administered this task at the second timepoint of the parent project, (see Chapter 2: "*General Methods*") which may have resulted in less engagement in the present experiments due to increased task demands in the broader visit structure.

Comparison to Prior Literature

With respect to anticipation, our findings are consistent with prior literature indicating that autistic children are able to incrementally process language, for example, using a facilitative verb to anticipate an upcoming familiar noun (Prescott et al., 2022; Venker et al., 2019; Zhou et al., 2019). In relation to prior literature on initial word learning, our findings are consistent with studies that have demonstrated a strength for autistic children in certain types of word learning, particularly those where input is predictable and stable, such as linguistic statistical learning (Haebig, 2015; Obeid et al., 2016; but see Hu et al., 2023; Scott-Van Zeeland et al., 2010) and cross-situational word learning (Venker, 2019). These findings are also consistent with prior literature suggesting commensurate use of syntactic bootstrapping, or the use of syntactic information to facilitate processing and learning, in autistic and non-autistic children (Shulman & Guberman, 2007).

Our retention and generalization findings are interesting in comparison to prior literature. When examining the unpredictable trials, for which our autistic sample did not demonstrate looking significantly above chance in either retention or generalization trials, our findings are consistent with prior studies. For example, Hartley and colleagues (2019) found that autistic children demonstrated substantially decreased accuracy after a five-minute retention interval compared to receptive vocabulary-matched NT peers. These authors also found impaired generalization of fast-mapped words in autistic school-aged children compared to NT peers matched on receptive vocabulary. However, Hartley and colleagues (2020) found similar retention and generalization of words learned via cross-situational word learning in receptive language-matched autistic and non-autistic children. This finding is consistent with the findings of Study 2a and Study 2b, that autistic children demonstrated above-chance retention and generalization of words learned in predictable contexts.

Limitations

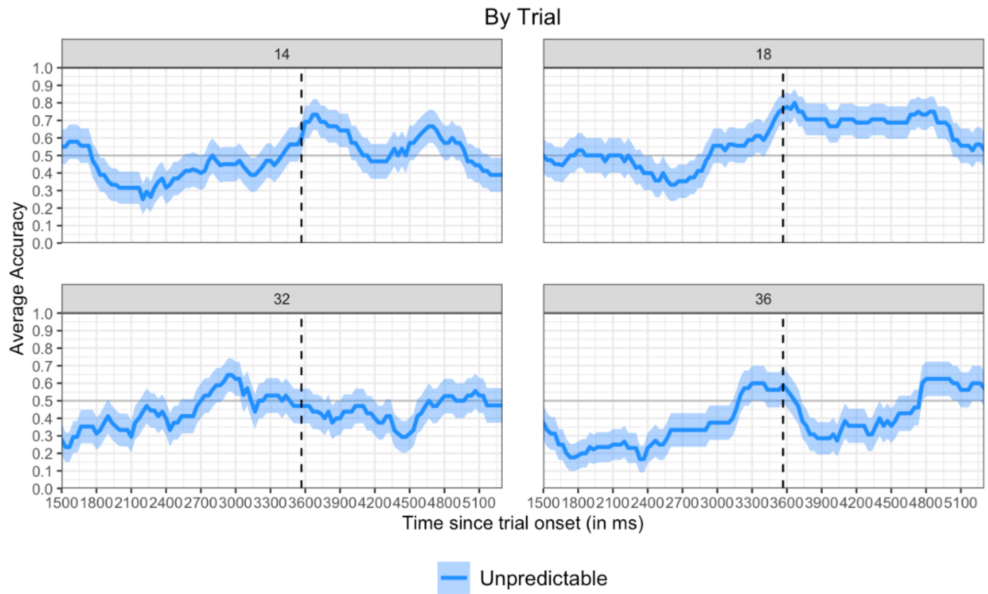
There are several limitations that we must acknowledge for these studies. First, as previously noted, we did not have an age-matched sample, and must acknowledge that our NT sample was significantly younger than our autistic sample. Our NT sample was comprised of one- and two-year olds, whereas our autistic sample was two-, three-, and four-year-olds. We chose to match on a measure of cognitive ability, because the theoretical framework that this work was based on, the PIA hypothesis (Sinha et al., 2014), posits that prediction-based differences in autistic individuals are domain-general. Thus, we wanted to include autistic children with a wide range of language abilities to have sufficient range to evaluate individual differences in extant language ability and their impact on performance in these tasks. But, we acknowledge that similar prior word learning studies have primarily matched groups on receptive vocabulary (Hartley et al., 2019; Luyster & Lord, 2009; Venker, 2019). Additionally, we must acknowledge that our sample is not representative of the population at large. Our NT sample included only white, non-Hispanic children. A sample with more racial and ethnic diversity would have strengthened the generalizability of these findings.

With respect to anticipation, we must acknowledge two limitations and cautions as we interpret findings. First, the analysis windows chosen for anticipation and noun recognition were determined based on similar prior studies (Prescott et al., 2022; Venker et al., 2019); however, it is difficult to determine exactly what children's eye movements during these windows indicate about anticipation versus word recognition. It is possible that children mapped the adjective to the novel object and thus were fixating the target during the anticipation window as a result of that mapping, as opposed to anticipation of the upcoming noun. Indeed, there is some prior evidence of less mature lexical-semantic knowledge in autistic children (Haebig et al., 2015). Thus, autistic children may have had less robust existing representations of the adjectives and therefore were vulnerable to mapping these to the novel objects. This seems less likely considering the findings from Study 2a and Study 2b, indicating that autistic children were able to identify the nouns absent of the adjective context in those trials. However, it is a limitation that should be accounted for when interpreting these findings. We also must acknowledge the possibility that coarticulation could have contributed to children's anticipation. Adjective tokens ending in vowels (silly, funny, happy, pretty) did include coarticulation. We used a perceptual stimuli test (see Appendix A) to evaluate whether adult listeners could anticipate the upcoming phoneme based on the adjective stimuli. Adult listeners were not able to do so for any of the four tokens tested. However, prior work has demonstrated that autistic children are able to use coarticulatory cues to facilitate processing of language in different phonetic contexts (Pomper et al., 2021). Importantly, however, coarticulatory cues would have been available to children in both the predictable and unpredictable conditions.

We would also like to acknowledge a surprising baseline effect in the autistic group that we discovered via data visualization in Study 1. In Figure 3.2, which plots raw looking behavior across the full trial, we observed that autistic children were looking below chance levels in the unpredictable condition at baseline. We plotted these trials individually in order to further explore this behavior (see Figure 6.1). The item that was the target in each of these trials varied between the two orders of the experiment. Thus, we also plotted looking behavior separately for each order, and it appears that this effect is evident in both orders (see Figure 6.2). Thus, it is possible that children found one of the objects more salient or interesting to look at, but this is less plausible given that the target objects differed in the two orders. It appears that the effect is most pronounced in the final trial (Trial 36). It is possible that the autistic children developed a preference for the predictable object over the course of the experiment. It is also possible that this effect simply reflects random noise. In other words, it may not be evident in a larger sample.

Figure 6.1

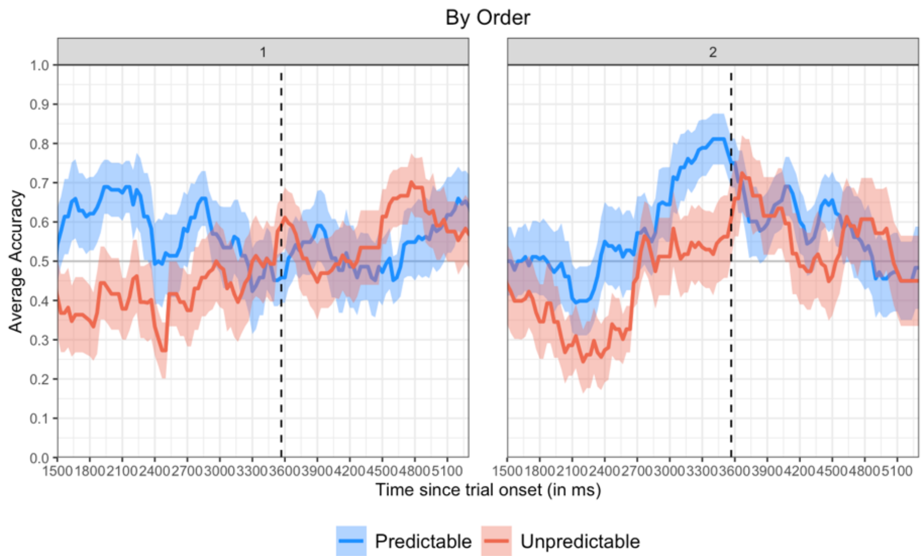
Study 1 Trial-by-Trial Looking Behavior for Unpredictable Trials, Autistic Group



Note. Study 1 raw looking behavior plotted from the onset of auditory stimuli to the end of the trial for only autistic children, unpredictable trials. Dashed vertical line represents noun onset. Gray horizontal line represents chance performance.

Figure 6.2

Study 1 Looking Behavior for Unpredictable Trials, Autistic Group, Faceted by Order



Note. Study 1 raw looking behavior plotted from the onset of auditory stimuli to the end of the trial for only autistic children, unpredictable trials, faceted by task order. Dashed vertical line represents noun onset. Gray horizontal line represents chance performance.

Implications and Future Directions

The present set of studies lend some, though not complete, support to prediction-based theories of ASD and their potential links to language. Autistic children in our sample demonstrated strengths in predictive sentence processing, consistent with prior research (Prescott et al., 2022; Venker et al., 2019; Zhou et al., 2019). Unpredictable sentence contexts appeared to present a relative challenge for autistic children, but they were not entirely detrimental to word learning. That is, autistic children were able to demonstrate learning for words taught in unpredictable sentence contexts above chance levels immediately following training. However, autistic children did not retain and generalize those words above chance levels, whereas they did retain and generalize those words taught in predictable sentences. This finding may lend support to the hyperplasticity hypothesis (Sinha et al., 2014). It may be that an unpredictable stimulus during word learning was more difficult for autistic children to integrate with prior learning, thus impacting their ability to retain, retrieve, and generalize those words.

It is likely premature to surmise significant clinical implications of this work. These findings suggest that perhaps consistent, predictable linguistic input might support vocabulary learning in autistic children. In particular, this work suggests that predictable input might support autistic children's retention and generalization of newly learned words. However, laboratory-based studies are only generalizable to children's natural language environments to a limited extent. Additionally, we only tested retention and generalization after a short (five-minute) delay. Thus, future studies examining predictable linguistic input in more naturalistic environments, and over longer timescales, will be necessary to determine the clinical utility of this work.

These studies lay the groundwork for future research examining the predictability of linguistic input and its impact on word learning in autistic children. Future studies examining whether autistic children would demonstrate the same strength in predictive processing as demonstrated in Study 1 when compared to an age-matched NT sample will be important. Future directions may also include testing other types of linguistic predictability besides predictable adjectives (e.g., predictable versus unpredictable environmental contexts, visual qualities, attributes of the speaker). As previously noted, it will also be important to test the impact of predictable learning contexts on retention and generalization over longer timescales. Finally, more clinically-relevant contexts should be tested. For example, do autistic children learn vocabulary words better from predictably-structured storybooks? Similarly, in intervention contexts, do autistic children learn new vocabulary words better when they are reinforced in the same play schemas versus with variable toys and schemas? These future studies will help to extend the findings of the present set of studies to autistic children's natural word learning environments.

Overall Conclusion

The present set of studies revealed some interesting links between prediction and word learning in autistic and non-autistic children. Findings from these studies suggest that predictable sentence contexts may support predictive sentence processing, word learning, retention, and generalization for autistic children. Indeed, autistic children demonstrated above-chance looking to target during anticipation, initial noun recognition, retention, and generalization trials when novel words were taught in predictable sentence contexts. Consistent with prior literature, (Hartley et al., 2019; Luyster & Lord, 2009; Venker, 2019) our autistic and cognitively-matched NT samples demonstrated commensurate initial word learning. Cognitively-matched, younger NT children demonstrated initial word learning and generalization above-chance levels for words taught in predictable sentences but did not achieve above-chance anticipation or retention. As such, these studies also reveal a potential relative strength in predictive sentence processing and word retention for autistic children as compared to younger, cognitive ability-matched NT children. These findings lend some theoretical support to prediction-based theories of ASD. Though preliminary, these findings suggest there may be some utility for predictable linguistic contexts for autistic children's vocabulary learning. However, future studies will be needed to determine the clinical implications of this work.

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Appendix A: Perceptual Stimuli Test

There were three participants in this perceptual stimulus test (laboratory staff and research assistants who were unaware of the answers). The goal of this test was to determine how much coarticulation was perceptible in the adjective stimuli. Participants opened a powerpoint file in which the sound files (adjectives) were saved as .wav files. They were asked to listen to the words in the auditory stimuli (adjectives) and guess which phoneme (sound) is coming next, from a set of four choices. They were also given the option to select "can't make a guess," if they were not able to. The correct answer is in bold. The number of times each answer was given (out of 3 possible) is recorded in parentheses next each answer.

1. Funny, next phoneme guess:

    a. /m/ (0)

    b. /p/ (0)

    c. /t/ (0)

    d. /b/ (0)

    e. Can't make a guess (3)

2. Pretty, next phoneme guess:

    a. /m/ (0)

    b. /p/ (0)

    c. /t/ (0)

    d. /b/ (2)

    e. Can't make a guess (1)

3. Silly, next phoneme guess:

    a. /m/ (0)

    b. /p/ (0)

    c. /t/ (0)

d. /b/ (0)

e. Can’t make a guess (3)

4. Happy, next phoneme guess:

a. /m/ (0)

b. /p/ (0)

c. /t/ (0)

d. /b/ (1)

e. Can’t make a guess (2)

Results: None of the three participants were able to correctly guess the upcoming phoneme of any of the four auditory stimuli tokens tested.

Appendix B: Study 1 Growth Curve Model Results

Table B.1. Study 1, model collapsing across conditions, collapsing across NT and ASD groups, for the anticipatory adjective window.

	Estimate	SE	*t* value	*p* value
Intercept	0.12	0.074	1.613	0.112
Linear time	0.442	0.21	2.106	0.04*
Quadratic time	-0.13	0.122	-1.063	0.292
Cubic time	0.015	0.082	0.185	0.854
Group	-0.182	0.149	-1.219	0.228
Condition	0.19	0.157	1.211	0.231
Linear time: Group	-0.131	0.42	-0.312	0.756
Quadratic time: Group	-0.017	0.244	-0.07	0.945
Cubic time: Group	-0.078	0.163	-0.477	0.635
Linear time: Condition	-0.274	0.432	-0.635	0.528
Quadratic time: Condition	0.361	0.256	1.41	0.164
Cubic time: Condition	0.108	0.155	0.695	0.49
Group: Condition	-0.531	0.313	-1.694	0.096
Linear time: Group: Condition	-0.51	0.864	-0.59	0.557
Quadratic time: Group: Condition	1.193	0.513	2.328	0.023*

Cubic time: Group: Condition	0.693	0.31	2.237	0.029*

Note. The independent variable was time, and the dependent variable was the empirical log-odds of looks to the target object during the experimental window.

Table B.2. Study 1, model containing the ASD group (n = 27), for the anticipatory adjective window.

	Estimate	SE	*t* value	*p* value
Intercept	0.21	0.111	1.896	0.069
Linear time	0.506	0.24	2.111	0.044*
Quadratic time	-0.124	0.191	-0.65	0.521
Cubic time	0.052	0.12	0.433	0.668
Condition	0.456	0.215	2.122	0.043*
Linear time: Condition	-0.018	0.694	-0.026	0.98
Quadratic time: Condition	-0.232	0.333	-0.696	0.493
Cubic time: Condition	-0.246	0.274	-0.896	0.378

Note. The independent variable was time, and the dependent variable was the empirical log-odds of looks to the target object during the experimental window.

Table B.3. Study 1, model containing the NT group (n = 31), for the anticipatory adjective window.

	Estimate	SE	*t* value	*p* value
Intercept	0.03	0.1	0.296	0.769
Linear time	0.376	0.332	1.132	0.266
Quadratic time	-0.139	0.155	-0.898	0.376
Cubic time	-0.021	0.109	-0.192	0.849
Condition	-0.076	0.225	-0.337	0.739
Linear time: Condition	-0.529	0.535	-0.989	0.33
Quadratic time: Condition	0.96	0.378	2.537	0.017*
Cubic time: Condition	0.448	0.163	2.739	0.01*

Note. The independent variable was time, and the dependent variable was the empirical log-odds of looks to the target object during the experimental window.

Table B.4. Study 1, model collapsing across conditions, collapsing across NT and ASD groups, for the noun recognition window.

	Estimate	SE	*t* value	*p* value
Intercept	0.193	0.065	2.986	0.004**
Linear time	0.337	0.31	1.087	0.281
Quadratic time	0.143	0.253	0.563	0.576
Cubic time	-0.369	0.164	-2.246	0.029*
Group	0.077	0.129	0.598	0.552
Condition	0.119	0.131	0.907	0.368
Linear time: Group	0.869	0.62	1.401	0.166
Quadratic time: Group	0.001	0.507	0.001	0.999
Cubic time: Group	-0.365	0.329	-1.111	0.271
Linear time: Condition	-0.26	0.711	-0.366	0.716
Quadratic time: Condition	0.201	0.43	0.468	0.642
Cubic time: Condition	0.212	0.319	0.666	0.508
Group: Condition	0.12	0.262	0.46	0.647
Linear time: Group: Condition	0.576	1.422	0.405	0.687
Quadratic time: Group: Condition	-1.06	0.861	-1.232	0.223

Cubic time: Group: Condition	-1.636	0.637	-2.566	0.013*

Note. The independent variable was time, and the dependent variable was the empirical log-odds of looks to the target object during the experimental window.

Table B.5. Study 1, model containing the ASD group (*n* = 27), for the noun recognition window.

	Estimate	SE	*t* value	*p* value
Intercept	0.154	0.082	1.873	0.072
Linear time	-0.098	0.474	-0.206	0.838
Quadratic time	0.145	0.299	0.485	0.632
Cubic time	-0.186	0.239	-0.777	0.444
Condition	0.059	0.165	0.357	0.724
Linear time: Condition	-0.549	1.229	-0.447	0.659
Quadratic time: Condition	0.728	0.577	1.262	0.218
Cubic time: Condition	1.026	0.534	1.92	0.066

Note. The independent variable was time, and the dependent variable was the empirical log-odds of looks to the target object during the experimental window.

Table B.6. Study 1, model containing the NT group (*n* = 31), for the noun recognition window.

	Estimate	SE	*t* value	*p* value
Intercept	0.154	0.082	1.873	0.072
Linear time	-0.098	0.474	-0.206	0.838
Quadratic time	0.145	0.299	0.485	0.632
Cubic time	-0.186	0.239	-0.777	0.444
Condition	0.059	0.165	0.357	0.724
Linear time: Condition	-0.549	1.229	-0.447	0.659
Quadratic time: Condition	0.728	0.577	1.262	0.218
Cubic time: Condition	1.026	0.534	1.92	0.066

Note. The independent variable was time, and the dependent variable was the empirical log-odds of looks to the target object during the experimental window.

Appendix C: Study 2a and Study 2b Growth Curve Model Results

Table C.1. Study 2a, model collapsing across conditions, collapsing across NT and ASD groups for retention trials.

	Estimate	SE	*t* value	*p* value
Intercept	0.063	0.065	0.962	0.34
Linear time	0.691	0.286	2.418	0.019*
Quadratic time	0.063	0.166	0.38	0.705
Cubic time	-0.05	0.159	-0.314	0.755
Group	-0.023	0.13	-0.18	0.858
Condition	0.069	0.124	0.56	0.578
Linear time: Group	1.494	0.572	2.614	0.012*
Quadratic time: Group	0.056	0.332	0.17	0.866
Cubic time: Group	-0.236	0.318	-0.743	0.46
Linear time: Condition	-0.523	0.666	-0.786	0.435
Quadratic time: Condition	-0.113	0.429	-0.262	0.794
Cubic time: Condition	0.112	0.282	0.396	0.694
Group: Condition	-0.032	0.248	-0.127	0.899
Linear time: Group: Condition	1.139	1.332	0.856	0.396
Quadratic time: Group: Condition	-0.385	0.858	-0.449	0.655

Cubic time: Group: Condition	0.063	0.065	0.962	0.34

Note. The independent variable was time, and the dependent variable was the empirical log-odds of looks to the target object during the experimental window.

Table C.2. Study 2a, model containing the ASD group (n = 26), for retention trials.

	Estimate	SE	*t* value	*p* value
Intercept	0.075	0.089	0.842	0.407
Linear time	-0.056	0.457	-0.122	0.904
Quadratic time	0.036	0.252	0.141	0.889
Cubic time	0.068	0.254	0.267	0.792
Condition	0.085	0.2	0.426	0.674
Linear time: Condition	-1.095	1.116	-0.981	0.336
Quadratic time: Condition	0.078	0.765	0.102	0.92
Cubic time: Condition	0.373	0.43	0.867	0.394

Note. The independent variable was time, and the dependent variable was the empirical log-odds of looks to the target object during the experimental window.

Table C.3. Study 2a, model containing the NT group (*n* = 30), for retention trials.

	Estimate	SE	*t* value	*p* value
Intercept	0.051	0.094	0.545	0.59
Linear time	1.434	0.355	4.04	<.001***
Quadratic time	0.093	0.216	0.431	0.67
Cubic time	-0.169	0.196	-0.858	0.398
Condition	0.054	0.153	0.352	0.727
Linear time: Condition	0.049	0.774	0.063	0.95
Quadratic time: Condition	-0.302	0.446	-0.677	0.503
Cubic time: Condition	-0.158	0.37	-0.426	0.673

Note. The independent variable was time, and the dependent variable was the empirical log-odds of looks to the target object during the experimental window.

Table C.4. Study 2b, model collapsing across conditions, collapsing across NT and ASD groups, for generalization trials.

	Estimate	SE	*t* value	*p* value
Intercept	0.075	0.068	1.089	0.280
Linear time	0.966	0.308	3.135	0.003**
Quadratic time	0.108	0.229	0.472	0.639
Cubic time	-0.119	0.137	-0.869	0.389
Group	0.011	0.137	0.079	0.938
Condition	0.134	0.126	1.065	0.291
Linear time: Group	0.317	0.616	0.515	0.609
Quadratic time: Group	0.247	0.458	0.540	0.591
Cubic time: Group	0.190	0.274	0.695	0.490
Linear time: Condition	-0.861	0.744	-1.156	0.252
Quadratic time: Condition	0.115	0.414	0.278	0.782
Cubic time: Condition	0.502	0.303	1.658	0.103
Group: Condition	-0.107	0.251	-0.427	0.671
Linear time: Group: Condition	1.640	1.489	1.101	0.275
Quadratic time: Group: Condition	1.027	0.829	1.239	0.220

Cubic time: Group: Condition	0.464	0.605	0.766	0.447

Note. The independent variable was time, and the dependent variable was the empirical log-odds of looks to the target object during the experimental window.

Appendix D: Individual Differences Model Results

Table D.1. Individual differences models, Study 1, ASD Group, anticipatory adjective window.

	Estimate	SE	*t* value	*p* value
Unpredictable Condition				
Intercept	0.522	0.070	7.468	<.001***
DAY-C Cognitive Domain Raw Score	-0.030	0.152	-0.199	0.845
Age	-0.030	0.085	-0.350	0.731
CARS Total	-0.021	0.096	-0.220	0.829
PLS Expressive Communication Raw Score	0.011	0.155	0.071	0.944
PLS Auditory Comprehension Raw Score	-0.035	0.156	-0.222	0.827
Vineland Personal Daily Living Skills Raw Score	0.033	0.106	0.316	0.756
Predictable Condition				
Intercept	0.609	0.05	12.114	<.001***
DAY-C Cognitive Domain Raw Score	-0.101	0.112	-0.909	0.377
Age	-0.136	0.061	-2.227	0.041*
CARS Total	-0.003	0.071	-0.047	0.963
PLS Expressive Communication Raw Score	0.087	0.113	0.772	0.452
PLS Auditory Comprehension Raw Score	0.033	0.114	0.29	0.776
Vineland Personal Daily Living Skills Raw Score	0.001	0.075	0.016	0.987

Note. The dependent variable was average looks to target during the experimental window.

Table D.2. Individual differences models, Study 1, NT Group, anticipatory adjective window.

	Estimate	SE	*t* value	*p* value
Unpredictable Condition				
Intercept	0.500	0.046	10.989	<.001***
DAY-C Cognitive Domain Raw Score	-0.069	0.089	-0.779	0.444
Age	-0.015	0.060	-0.256	0.800
PLS Expressive Communication Raw Score	-0.030	0.101	-0.300	0.767
PLS Auditory Comprehension Raw Score	0.153	0.084	1.817	0.082
Vineland Personal Daily Living Skills Raw Score	-0.057	0.063	-0.917	0.368
Predictable Condition				
Intercept	0.511	0.047	10.971	<.001***
DAY-C Cognitive Domain Raw Score	0.137	0.091	1.511	0.144
Age	0.027	0.061	0.437	0.666
PLS Expressive Communication Raw Score	-0.053	0.103	-0.510	0.615
PLS Auditory Comprehension Raw Score	0.076	0.086	0.886	0.385
Vineland Personal Daily Living Skills Raw Score	-0.117	0.064	-1.824	0.081

Note. The dependent variable was average looks to target during the experimental window.

Table D.3. Individual differences models, Study 1, ASD Group, noun recognition window.

	Estimate	SE	*t* value	*p* value
Unpredictable Condition				
Intercept	0.553	0.048	11.511	<.001***
DAY-C Cognitive Domain Raw Score	0.077	0.107	0.719	0.482
Age	0.018	0.058	0.318	0.755
CARS Total	0.020	0.067	0.295	0.772
PLS Expressive Communication Raw Score	-0.020	0.108	-0.182	0.858
PLS Auditory Comprehension Raw Score	-0.060	0.109	-0.552	0.588
Vineland Personal Daily Living Skills Raw Score	-0.049	0.071	-0.684	0.504
Predictable Condition				
Intercept	0.541	0.037	14.501	<.001***
DAY-C Cognitive Domain Raw Score	-0.096	0.083	-1.161	0.263
Age	-0.030	0.045	-0.659	0.520
CARS Total	-0.055	0.052	-1.052	0.309
PLS Expressive Communication Raw Score	0.152	0.083	1.817	0.088
PLS Auditory Comprehension Raw Score	-0.015	0.085	-0.177	0.862
Vineland Personal Daily Living Skills Raw Score	-0.071	0.055	-1.288	0.216

Note. The dependent variable was average looks to target during the experimental window.

Table D.4. Individual differences models, Study 1, NT Group, noun recognition window.

	Estimate	SE	*t* value	*p* value
Unpredictable Condition				
Intercept	0.540	0.039	13.682	<.001***
DAY-C Cognitive Domain Raw Score	-0.004	0.077	-0.053	0.959
Age	0.043	0.052	0.837	0.411
PLS Expressive Communication Raw Score	0.012	0.087	0.134	0.895
PLS Auditory Comprehension Raw Score	0.112	0.073	1.536	0.138
Vineland Personal Daily Living Skills Raw Score	-0.134	0.054	-2.467	0.021*
Predictable Condition				
Intercept	0.572	0.035	16.133	<.001***
DAY-C Cognitive Domain Raw Score	-0.123	0.069	-1.790	0.086
Age	0.083	0.046	1.792	0.086
PLS Expressive Communication Raw Score	0.166	0.078	2.120	0.045*
PLS Auditory Comprehension Raw Score	-0.026	0.066	-0.402	0.691
Vineland Personal Daily Living Skills Raw Score	0.063	0.049	1.297	0.207

Note. The dependent variable was average looks to target during the experimental window.

Table D.5. Individual differences models, Study 2a (retention trials), ASD Group.

	Estimate	SE	*t* value	*p* value
Unpredictable Condition				
Intercept	0.548	0.039	14.064	<.001***
DAY-C Cognitive Domain Raw Score	0.067	0.080	0.831	0.419
Age	0.042	0.047	0.883	0.391
CARS Total	0.046	0.055	0.828	0.421
PLS Expressive Communication Raw Score	-0.047	0.088	-0.538	0.599
PLS Auditory Comprehension Raw Score	-0.011	0.079	-0.133	0.896
Vineland Personal Daily Living Skills Raw Score	-0.011	0.060	-0.188	0.854
Predictable Condition				
Intercept	0.502	0.069	7.258	<.001***
DAY-C Cognitive Domain Raw Score	-0.068	0.142	-0.478	0.6394
Age	0.109	0.084	1.292	0.216
CARS Total	-0.181	0.098	-1.847	0.0846
PLS Expressive Communication Raw Score	0.059	0.155	0.383	0.707
PLS Auditory Comprehension Raw Score	0.027	0.139	0.191	0.8509
Vineland Personal Daily Living Skills Raw Score	-0.154	0.107	-1.446	0.1687

Note. The dependent variable was average looks to target during the experimental window.

Table D.6. Individual differences models, Study 2b (generalization trials), ASD Group.

	Estimate	SE	*t* value	*p* value
Unpredictable Condition				
Intercept	0.520	0.049	10.601	<.001***
DAY-C Cognitive Domain Raw Score	0.147	0.107	1.380	0.186
Age	0.016	0.058	0.269	0.792
CARS Total	0.094	0.071	1.319	0.206
PLS Expressive Communication Raw Score	-0.149	0.124	-1.200	0.248
PLS Auditory Comprehension Raw Score	0.109	0.114	0.951	0.356
Vineland Personal Daily Living Skills Raw Score	0.058	0.078	0.748	0.466
Predictable Condition				
Intercept	0.530	0.048	11.080	<.001***
DAY-C Cognitive Domain Raw Score	-0.038	0.104	-0.366	0.719
Age	-0.112	0.056	-1.994	0.064
CARS Total	-0.005	0.070	-0.070	0.945
PLS Expressive Communication Raw Score	0.028	0.121	0.230	0.821
PLS Auditory Comprehension Raw Score	0.117	0.111	1.053	0.308
Vineland Personal Daily Living Skills Raw Score	-0.084	0.076	-1.107	0.285

Note. The dependent variable was average looks to target during the experimental window.

Table D.7. Individual differences models, Study 2a (retention trials), NT Group.

	Estimate	SE	*t* value	*p* value
Unpredictable Condition				
Intercept	0.526	0.041	12.986	<.001***
DAY-C Cognitive Domain Raw Score	0.076	0.078	0.971	0.342
Age	0.052	0.052	1.004	0.326
PLS Expressive Communication Raw Score	-0.004	0.090	-0.041	0.968
PLS Auditory Comprehension Raw Score	-0.018	0.077	-0.234	0.817
Vineland Personal Daily Living Skills Raw Score	0.012	0.056	0.224	0.825
Predictable Condition				
Intercept	0.534	0.045	11.917	<.001***
DAY-C Cognitive Domain Raw Score	-0.113	0.087	-1.309	0.204
Age	0.055	0.057	0.960	0.347
PLS Expressive Communication Raw Score	0.087	0.099	0.878	0.389
PLS Auditory Comprehension Raw Score	0.043	0.085	0.511	0.614
Vineland Personal Daily Living Skills Raw Score	0.062	0.061	1.017	0.32

Note. The dependent variable was average looks to target during the experimental window.

Table D.8. Individual differences models, Study 2b (generalization trials), NT Group.

	Estimate	SE	*t* value	*p* value
Unpredictable Condition				
Intercept	0.514	0.043	11.901	<.001***
DAY-C Cognitive Domain Raw Score	-0.006	0.084	-0.068	0.946
Age	0.007	0.055	0.119	0.906
PLS Expressive Communication Raw Score	0.054	0.095	0.569	0.575
PLS Auditory Comprehension Raw Score	0.002	0.082	0.019	0.985
Vineland Personal Daily Living Skills Raw Score	0.006	0.059	0.103	0.919
Predictable Condition				
Intercept	0.526	0.041	12.986	<.001***
DAY-C Cognitive Domain Raw Score	0.076	0.078	0.971	0.342
Age	0.052	0.052	1.004	0.326
PLS Expressive Communication Raw Score	-0.004	0.09	-0.041	0.968
PLS Auditory Comprehension Raw Score	-0.018	0.077	-0.234	0.817
Vineland Personal Daily Living Skills Raw Score	0.012	0.056	0.224	0.825

Note. The dependent variable was average looks to target during the experimental window.