Cognitive Mechanisms of Cross-Situational Word Learning Impairment in Children with Autism

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Abstract

Children with Autism Spectrum Disorder (ASD) exhibit impairments in cross-situational word learning, which severely hinders their language acquisition. Although previous studies have attempted to investigate the causes of this impairment from the perspective of deficits in general cognitive abilities, they have overlooked the specificity of learning mechanisms in children with ASD. To address this, the present study specifically examines learning mechanisms, revealing a dissociation whereby implicit learning remains relatively intact while explicit learning may be impaired in children with ASD, and finds that cross-situational word learning in children with ASD relies primarily on associative learning rather than hypothesis testing. Based on this, this paper proposes a hybrid synergistic model and suggests that manipulating referent diversity and word frequency distribution may respectively influence associative learning and hypothesis testing, thereby facilitating cross-situational word learning in children with ASD. This model holds important theoretical significance and practical value for understanding the cognitive mechanisms underlying cross-situational word learning impairments in children with ASD and for exploring potential intervention approaches.

Full Text

Preamble

The Cognitive Mechanisms of Cross-Situational Word Learning Deficits in Children with Autism Spectrum Disorder

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Abstract: Children with autism spectrum disorder (ASD) exhibit cross-situational word learning deficits that significantly impede their language acquisition. While previous research has attempted to explain these deficits

from the perspective of impaired general cognitive abilities, it has overlooked the specificity of learning mechanisms in ASD children. This paper therefore examines learning mechanisms directly, revealing a dissociation whereby implicit learning remains relatively intact in ASD children while explicit learning may be impaired. We find that ASD children rely primarily on associative learning rather than hypothesis testing for cross-situational word learning. Based on this, we propose a hybrid synergistic model, suggesting that manipulating referent diversity and word frequency distribution may respectively influence associative learning and hypothesis testing, thereby facilitating cross-situational word learning in ASD children. This model holds important theoretical significance and practical value for understanding the cognitive mechanisms underlying cross-situational word learning deficits in ASD children and for exploring potential intervention approaches.

Keywords: autism, cross-situational word learning, hypothesis testing, associative learning

1 Introduction

Language serves as humanity' s primary tool for communication and cultural transmission, and language acquisition represents a cornerstone of children' s cognitive and social development (Tomasello, 2003). Vocabulary constitutes the basic unit of language, making word learning critically important for children' s language acquisition (Benitez et al., 2020; Gray et al., 2020), a vital component of language development (Lenhart et al., 2020), and a significant milestone in children' s cognitive development. Although vocabulary learning ability is key to language acquisition, children with autism spectrum disorder (ASD) demonstrate severe deficits in this area (Camero et al., 2023; Clark & Reuterskiold, 2023; Saldana, 2023; Vulchanova et al., 2023).

ASD is a neurodevelopmental disorder characterized by social communication impairments, repetitive behaviors, and restricted interests (American Psychiatric Association, 2013). Unlike typically developing (TD) children, many children with ASD experience language acquisition disorders and word learning difficulties that severely affect their interpersonal communication and social interaction (Howlin, 2003; Jiménez et al., 2021; Xiong et al., 2024). Language acquisition deficits in ASD children typically manifest as significant delays in receptive vocabulary development and difficulties in word learning. For instance, ASD children begin to show preliminary oral expression abilities around 38 months of age, a marked delay compared to TD children's 8–14 months (Howlin, 2003; Zhao et al., 2024). Additionally, ASD children do not understand more than 100 words until after age 2, whereas 50% of TD children can understand over 100 words by 16 months (Hou & Su, 2022). Therefore, investigating the word learning mechanisms of ASD children is essential for deeply understanding their language acquisition deficits and identifying effective intervention strategies.

1.1 Cross-Situational Word Learning in Child Language Acquisition

Word learning presents considerable challenges for children. When learning a word' s meaning, children largely depend on observing the immediate context. For example, the word "cat" can only be acquired when there is a clear mapping between the animal and the word in context (Liu et al., 2024). However, in real-world language learning, such mapping relationships are rarely clear because people operate in complex contexts where numerous distractors co-occur with the target referent. Consequently, a single word may correspond to multiple potential objects. For instance, between 7 months and 3 years of age, parents utter approximately 300–400 words per hour in their children' s presence, with each unfamiliar word potentially referring to numerous objects (Hart & Risley, 1995). In these naturalistic contexts, the correspondence between words and referents becomes complicated due to referential ambiguity. Thus, children must resolve this ambiguity to learn vocabulary.

The primary method for resolving referential ambiguity is cross-situational word learning (CSWL) (Benitez et al., 2020; Berens et al., 2018). Cross-situational word learning refers to the process by which children acquire correct mappings between words and referents by tracking their co-occurrence patterns across multiple contexts when vocabulary and its corresponding referents repeatedly appear together. Extensive research demonstrates that adults, young children, and even infants all acquire new words using such cross-situational information (Ackermann et al., 2020; Bulgarelli et al., 2021; Crespo et al., 2023; Crespo & Kaushanskaya, 2021; Rivera-Vera et al., 2022; Zhou et al., 2023). Cross-situational word learning represents one of the primary pathways for child language acquisition.

1.2 The Debate Over Cross-Situational Word Learning Deficits in ASD Children

Previous studies have suggested that ASD children appear capable of completing cross-situational word learning. McGregor et al. (2013) recruited ASD and TD children matched for age, IQ, and receptive vocabulary, and asked both groups to perform rapid mapping of novel words to objects under different experimental conditions. In the neutral condition, children received no ostensive cues and had to rely on word and object information across trials to map new words accurately. Results showed that both groups performed significantly above chance in the neutral condition, indicating that ASD children' s word mapping abilities remain relatively intact—a foundational capacity for cross-situational word learning. Similarly, Venker (2019) used eye-tracking technology combined with a cross-situational mapping paradigm to examine vocabulary acquisition in 4-7-year-old ASD children and 3–8-year-old TD children matched for vocabulary size. Findings revealed that both groups looked significantly longer at correct targets than would be expected by chance, suggesting that ASD children can learn word-object mappings and acquire vocabulary.

However, this view has been strongly challenged by numerous studies. Current research indicates that ASD children exhibit deficits in cross-situational word learning (Hartley et al., 2020; Venker, 2019). A particularly illuminating recent study investigated whether cross-situational word learning in ASD children is atypical and how such differences affect vocabulary retention and generalization (Hartley et al., 2020). Using the classic cross-situational word learning paradigm with response time as an additional dependent variable, the study tested ASD children with a mean age of 8.78 years and TD children with a mean age of 5.52 years, matched for IQ and receptive vocabulary. Results showed that although ASD children' s accuracy across various stages of cross-situational word learning did not differ significantly from TD children, they exhibited longer response times. Furthermore, many studies have found that children at high risk for ASD require more time and learn at a slower pace when acquiring vocabulary (Bedford et al., 2013; Yirmiya et al., 2007).

Through systematic analysis of previous research, we propose that ASD children' s accuracy in cross-situational word learning does not appear to differ significantly from TD children, suggesting that ASD children do not suffer from broad cross-situational word learning deficits. However, they do exhibit specific impairments, such as longer learning times and slower learning speeds (Hartley et al., 2020; Venker, 2019). In natural language learning environments, these temporal and speed deficits pose serious challenges to vocabulary acquisition. Natural speech typically occurs at approximately 150 words per minute (Studdert-Kennedy, 1986), with word-referent co-occurrence rates roughly ten times faster than laboratory stimulus presentation speeds and accompanied by substantially more noise and interference (Hartley et al., 2020). Consequently, ASD children' s speed disadvantage in cross-situational word learning severely impacts their ability to learn vocabulary in natural environments, leading to language learning deficits. This learning speed impairment may stem from damaged cross-situational word learning mechanisms in ASD children, though the specific nature of this damage remains unclear.

1.3 The Learning Process of Cross-Situational Word Learning in ASD Children

Previous investigations into the mechanisms underlying vocabulary learning deficits in ASD children have primarily focused on general ability impairments caused by ASD (Hou & Su, 2022; Alispahic et al., 2024; Cuneo, 2024; Hartley & Whiteley, 2024; Long et al., 2024). No studies have yet examined the root causes of vocabulary learning difficulties from the perspective of the essential processes of word learning itself. This limitation reduces the explanatory power of previous research, as general cognitive abilities must be transformed through vocabulary learning mechanisms to affect the learning process. Therefore, this study examines the essential processes of word learning to reveal the internal mechanisms of cross-situational word learning deficits in ASD children.

We argue that revealing these internal mechanisms requires first distinguish-

ing between implicit and explicit vocabulary learning processes. Implicit and explicit learning processes constitute key components of human cognitive development and knowledge acquisition, playing crucial roles in various types of learning (Maresch et al., 2021; Miyamoto et al., 2020). Both implicit and explicit learning exist in cross-situational word learning. In most studies, researchers manipulate participants' top-down expectations through instructions, resulting in explicit vocabulary learning tasks (Yurovsky et al., 2015). However, some studies, particularly those with children, do not provide explicit learning instructions, making such vocabulary learning implicit. The academic community generally considers cross-situational word learning to result from the combined action of implicit and explicit learning (Sobczak & Gaskell, 2019). Therefore, investigating the cognitive mechanisms of cross-situational word learning deficits in ASD children necessitates first distinguishing between implicit and explicit learning processes.

In light of this, this paper first reviews research progress on cross-situational word learning in ASD children, focusing on implicit and explicit learning in this population and the implicit and explicit processes in cross-situational word learning. We examine the hypothesis testing and associative learning mechanisms in cross-situational word learning and explore the relationship between implicit/explicit learning and vocabulary learning mechanisms. We then propose a hybrid synergistic model based on the interaction between word frequency distribution types and referent diversity, grounded in implicit and explicit learning mechanisms. Finally, by analyzing the mechanisms underlying cross-situational word learning in ASD children, we propose potential solutions for vocabulary learning challenges in this population. In summary, this paper aims to systematically analyze and review previous research, investigating the deep causes of cross-situational word learning deficits in ASD children from the perspective of the intrinsic mechanisms of vocabulary learning.

2 The Dissociation Between Implicit and Explicit Learning in ASD Children

Since ASD children exhibit specific impairments in general learning mechanisms that are closely related to cross-situational word learning, understanding the cross-situational word learning mechanisms in this population requires first comprehending their general learning mechanisms, particularly their implicit and explicit learning mechanisms. In learning psychology, learning mechanisms can generally be divided into two categories: implicit learning and explicit learning (Reber, 1967). Reber (1967) first proposed implicit learning in research on artificial grammar learning (AGL), where participants demonstrated unconscious learning of complex rules—a phenomenon termed implicit learning. In contrast, Reber (1967) considered explicit learning a conscious, goal-directed process of acquiring new knowledge or skills that typically involves direct attention to and analysis of learning materials, with learners clearly aware of what they are learning and able to consciously recall and apply acquired knowledge.

Current research generally views implicit and explicit learning as two separate mechanisms (Berry & Broadbent, 1995; Hayman & Tulving, 1989).

2.1 The Debate Over Implicit Learning in ASD Children

The academic community remains divided on whether implicit learning is impaired in ASD children, though views on explicit learning impairment are largely consistent. Regarding implicit learning in ASD children, two theoretical hypotheses compete. The first is the implicit learning deficit hypothesis, which posits that ASD children have impaired implicit learning, manifesting as inability to complete implicit learning tasks or poor performance (Bo et al., 2016). The second is the intact implicit learning hypothesis, which holds that implicit learning functions normally in ASD children, with performance similar to TD children (Brown et al., 2010; Haebig et al., 2017).

Recent findings tend to support the intact implicit learning hypothesis, suggesting that results supporting the deficit hypothesis may stem from methodological and experimental design flaws, such as failure to match IQ between experimental and control groups or differences in learning tasks. For example, some studies may have used procedures biased toward explicit learning, causing participants to employ explicit strategies (Brown et al., 2010; Izadi-Najafabadi et al., 2015). Subsequent studies that improved upon these factors found that ASD children' s implicit learning abilities remain intact (Brown et al., 2010; Izadi-Najafabadi et al., 2015; Zwart et al., 2018). Foti et al. (2015) conducted a meta-analysis of 11 previous studies including 407 individuals with ASD and TD controls, finding that implicit learning in ASD individuals remains intact. Izadi-Najafabadi et al. (2015) compared 7–11-year-old ASD and TD children matched for IQ on a serial reaction time (SRT) task, finding that ASD children' s implicit learning did not differ from TD children, though they experienced difficulties with explicit learning. Zwart et al. (2018) similarly used the SRT task combined with event-related potentials (ERP) to examine ASD and TD children' s performance. At the behavioral level, ASD children' s performance on the SRT task resembled that of TD children, suggesting that automated implicit learning in ASD children is essentially intact and may not differ from typical children. At the electrophysiological level, ASD children showed enhanced N2b components, indicating greater reliance on automated processing—namely, implicit processing. Fu et al. (2013) suggested that the N2b component is closely related to implicit learning, consistent with Ferdinand et al. (2008). These studies indicate that implicit learning may be intact in ASD children, who can employ implicit learning strategies similar to typical children in learning tasks.

2.2 Explicit Learning Impairment in ASD Children

Previous research on explicit learning in ASD individuals typically measures it alongside implicit learning (Brown et al., 2010). Since explicit learning is closely related to IQ, many studies on learning deficits in ASD children are influenced by IQ, resulting in few studies examining explicit learning in isolation

(Watanabe et al., 2010). Brown et al. (2010) found impaired explicit learning in ASD individuals through a clear explicit learning task—paired-associates learning (PAL). Additionally, Izadi-Najafabadi et al. (2015) used the SRT task to test both implicit and explicit learning in ASD children, dividing participants into implicit and explicit learning groups. The explicit learning group was informed of the sequence pattern to help them consciously learn and apply rules. Results showed that ASD children performed poorly on explicit learning tasks while their implicit learning did not differ from TD children.

In summary, we propose that implicit learning remains relatively intact in ASD children, while explicit learning shows clear impairment (Brown et al., 2010; Izadi-Najafabadi et al., 2015; Zwart et al., 2018). Given that cross-situational word learning results from the combined action of implicit and explicit learning, ASD children' s performance in cross-situational word learning is closely related to these learning mechanisms (Sobczak & Gaskell, 2019). Therefore, examining the implicit and explicit mechanisms in cross-situational word learning can reveal the internal mechanisms of cross-situational word learning deficits in ASD children.

3 Implicit and Explicit Processes in Cross-Situational Word Learning in ASD Children

Cross-situational word learning also involves both implicit and explicit learning processes. Some previous studies did not inform participants through instructions that they should learn vocabulary or that certain words were associated with specific objects, yet participants still completed vocabulary learning (Hartley et al., 2020). Furthermore, many vocabulary learning studies show that humans can utilize repeated co-occurrences of words and referents to gradually accumulate word-object mappings and build lexicons from ambiguous situations (Rogers et al., 2021). Such vocabulary learning processes are typically considered implicit learning requiring no conscious effort.

In contrast to implicit vocabulary learning, participants in controlled experiments tend to engage in explicit learning. Some cross-situational word learning studies explicitly instruct participants to learn vocabulary from the outset, causing them to concentrate attention and cognitive resources on vocabulary learning and adopt strategies to complete the task. This constitutes explicit learning. Some research indicates that cross-situational word learning is more effective and participants show higher confidence levels when explicit instructions, attention, and learning strategies are involved (Sobczak & Gaskell, 2019; Trueswell et al., 2013). However, due to the ambiguity of word-referent mappings and memory capacity limitations, participants often cannot simultaneously remember all word-object co-occurrence combinations. Therefore, implicit learning processes also exist within explicit vocabulary learning. In summary, cross-situational word learning involves both implicit and explicit learning processes, which correspond to different cross-situational word learning mechanisms.

3.1 Mechanisms of Cross-Situational Word Learning

Cross-situational word learning involves two models: the associative learning model and the hypothesis testing model (Yurovsky & Frank, 2015). The associative learning model posits that learners memorize and track all word-object mapping hypotheses, accumulate statistical information about these mappings, and ultimately select the hypothesis with the strongest association. As learning trials increase, the associative strength between words and objects gradually strengthens, consolidating vocabulary learning effects until learners acquire word semantics—that is, the correspondence between words and objects (Liu et al., 2024; Yu & Smith, 2007).

In contrast to associative learning, hypothesis testing represents a riskier learning strategy. This model suggests that learners can employ a more explicit strategy: when encountering an ambiguous word, they form a hypothesis about its referent and maintain this correspondence, verifying the hypothesis in subsequent trials and discarding it when contradictions arise (Aussems & Vogt, 2020; Trueswell et al., 2013). Moreover, learners can consciously recognize whether learning situations provide clear information about referents (Medina et al., 2011; Trueswell et al., 2016). Both theoretical models offer systematic theoretical frameworks for cross-situational word learning mechanisms and have received substantial empirical support. According to recent theoretical perspectives, both associative learning and hypothesis testing participate in cross-situational word learning (Liu et al., 2024; Yurovsky & Frank, 2015).

Since both associative learning and hypothesis testing are involved in cross-situational word learning, and cross-situational word learning results from the combined action of implicit and explicit learning, investigating the relationship between "implicit and explicit learning" and "associative learning and hypothesis testing" can clarify the connection between general learning mechanisms and cross-situational word learning mechanisms. This understanding can help us better comprehend the relationship between general learning mechanism impairments in ASD children (such as attention deficits) and cross-situational word learning mechanism impairments (such as associative learning or hypothesis testing mechanism deficits). Therefore, to better understand the mechanisms underlying cross-situational word learning deficits in ASD children, we systematically discuss these issues from the perspective of cross-situational word learning mechanism impairments.

3.2 The Relationship Between Associative Learning and Implicit Learning

Associative learning is closely related to implicit learning. In cross-situational word learning, learners continuously track the co-occurrence frequency of words and referents and select the mapping hypothesis with the highest associative strength based on accumulated frequency information (Roembke & McMurray, 2021; Yurovsky & Frank, 2015). This statistical tracking process occurs im-

plicitly (Batterink & Paller, 2019; Roembke & McMurray, 2021; Yurovsky & Frank, 2015). Conscious awareness of word-object mappings is not a necessary condition for learning, and participants are not informed about which vocabulary to acquire or how to acquire it. Instead, they implicitly learn these word-object mapping relationships through repeated co-occurrences. Furthermore, functional imaging studies of healthy adults and amnesic patients with hippocampal damage have shown that associative learning indeed occurs without conscious participation and is related to the hippocampus and parahippocampal gyrus (Degonda et al., 2005).

The associative learning mechanism in ASD children' s cross-situational word learning may be intact. A review of research on cross-situational word learning in ASD children reveals that most studies employ spontaneous learning tasks, perhaps because ASD children show higher participation motivation when not given explicit learning instructions. For example, Venker (2019) used eye-tracking technology to investigate cross-situational word learning in ASD children, presenting pictures and sounds simultaneously without asking participants to memorize word-object correspondences. Results showed that ASD children could acquire vocabulary similarly to TD children. Previous research even found that when comparing ASD and TD children matched for language comprehension learning words from color photographs versus black-and-white cartoons, ASD children were more accurate at learning words corresponding to color photographs (Carter & Hartley, 2021). Pesthy et al. (2023) asked ASD and TD adults to complete an associative learning task lasting approximately 40 minutes, finding no significant differences between groups. Additionally, Van Rooijen et al. (2022) investigated whether smaller vocabularies in ASD individuals stem from learning problems per se, testing high- and low-risk ASD groups by presenting novel object images and interactive information to assess vocabulary learning abilities. Results showed that high-risk ASD children could also spontaneously acquire vocabulary (Van Rooijen et al., 2022). In summary, ASD children can spontaneously and implicitly acquire vocabulary in cross-situational word learning, indicating that their associative learning mechanism is relatively intact (Vulchanova et al., 2023).

3.3 The Relationship Between Hypothesis Testing and Explicit Learning

Hypothesis testing is closely related to explicit learning. The hypothesis testing model posits that learners randomly select an object as a word' s referent during each learning episode, forming a unique mapping hypothesis for that word and continuously verifying this hypothesis (Roembke & McMurray, 2021; Yurovsky & Frank, 2015). If learners track only one referent per word, they must allocate additional attentional resources and employ intentional strategies for deliberate memorization (Woodard et al., 2016). Since participants must clearly understand the experimental task and use specific learning strategies, this process occurs explicitly (Liu et al., 2024). Trueswell et al. (2013) found that indi-

viduals in cross-situational word learning can consciously recognize how much information learning situations provide, and testing participants' confidence levels in vocabulary learning revealed high confidence, indicating explicit learning (Kligler et al., 2023). Additionally, Sun et al. (2007) considered hypothesis testing a process of explicit knowledge extraction. Therefore, hypothesis testing is closely related to explicit learning.

The hypothesis testing mechanism in ASD children' s cross-situational word learning may be impaired. Previous research on vocabulary learning in ASD children has mostly focused on older children. For example, West et al. (2022) used an explicit experimental task to explore the impact of emotional cues on vocabulary learning, providing 9-year-old children with varying levels of autistic traits with written and oral instructions and telling them to try to remember as many names as possible. Results showed that the effect of attention on vocabulary learning differed between children with lower and higher levels of autistic traits, with vocabulary learning in high autistic trait children being more susceptible to attentional influences. Explicit experimental tasks are closely related to attention, but ASD children struggle with attentional concentration and control in such tasks. Numerous studies have identified the importance of attention in vocabulary learning for ASD individuals, as attention reduces uncertainty about referents in the environment and helps children establish connections between words and objects (Fitch et al., 2020). However, ASD children exhibit joint attention deficits and attention shifting impairments (Chen & Li, 2024; Zhang et al., 2022; Jiménez et al., 2021; Mormann & Russo, 2021; Venker et al., 2022). These deficits exacerbate the negative impact of referential ambiguity on cross-situational word learning, preventing ASD children from capturing word-object mapping relationships among numerous referents and thereby interfering with vocabulary learning. Additionally, previous research using functional near-infrared spectroscopy (fNIRS) found that dynamic prosody in speech enhances attention levels in young children by engaging the left frontoparietal network, thereby promoting vocabulary learning (Zhou et al., 2023). Other studies using functional magnetic resonance imaging (fMRI) have explored brain function abnormalities in ASD patients, revealing atypical functioning in the inferior prefrontal cortex, medial prefrontal cortex, striatum, thalamus, and lateral cerebellar regions (Murphy et al., 2014). Since ASD children' s hypothesis testing mechanisms are affected by impairments in attention and cognitive resource regulation, they struggle to maintain word-object mapping hypotheses in cross-situational word learning, likely resulting in hypothesis testing mechanism impairment.

Furthermore, ASD children with poorer language abilities experience difficulties using the mutual exclusivity (ME) strategy for vocabulary learning, showing lower learning efficiency when novel objects are presented (Mathée-Scott et al., 2022; McGregor et al., 2013). In cross-situational word learning, the hypothesis testing mechanism depends on the use of mutual exclusivity strategies (Roembke & McMurray, 2021; Yurovsky & Frank, 2015). Therefore, vocabulary learning deficits in ASD children may result from impaired hypothesis testing

mechanisms.

In summary, ASD children' s associative learning mechanism may be intact, while their hypothesis testing mechanism may be impaired. This view receives partial support from research. For example, Haebig et al. (2021) found that ASD children have normal associative learning abilities but poorer rapid mapping abilities, suggesting hypothesis testing mechanism impairment. Therefore, we hypothesize that ASD children tend to rely on associative learning mechanisms rather than hypothesis testing mechanisms when engaging in cross-situational word learning.

Currently, the academic community has not systematically explored the cross-situational word learning mechanisms in ASD children, and it remains unclear why ASD children show both deficits and preserved abilities in cross-situational word learning. To understand these contradictory findings, we must start from the essence of vocabulary learning, combining implicit and explicit learning perspectives with associative learning and hypothesis testing mechanisms in cross-situational word learning to explore the mechanisms underlying deficits in ASD children and propose a new theoretical model.

4 A Hybrid Synergistic Model of Cross-Situational Word Learning in ASD Children

Associative learning based on statistical co-occurrence frequency occurs implicitly (Batterink & Paller, 2019; Roembke & McMurray, 2021; Yurovsky & Frank, 2015), whereas hypothesis testing represents a process of explicit knowledge extraction where learners consciously recognize the vocabulary acquisition process (Kligler et al., 2023; Sun et al., 2007). Through the above analysis, we can see that implicit and explicit processes in cross-situational word learning correspond to associative learning and hypothesis testing models (Berry & Dienes, 1993; Degonda et al., 2005; Sun et al., 2007). Implicit learning is closely related to associative learning, while hypothesis testing is closely related to explicit learning (Degonda et al., 2005; Roembke & McMurray, 2021).

ASD children possess implicit learning abilities, suggesting intact associative learning mechanisms. Since associative learning requires continuous accumulation of co-occurrence frequencies, the process is slow. This explains why previous research found that ASD children's vocabulary learning accuracy sometimes does not differ from TD children, yet their learning speed is slow (Hartley et al., 2020). This indicates that ASD and TD children employ different vocabulary learning mechanisms in cross-situational word learning. ASD children appear to mix implicit and explicit learning mechanisms, with implicit learning compensating for explicit learning to collaboratively complete cross-situational word learning. Therefore, when teaching cross-situational word learning to ASD children, we must fully utilize their implicit learning strengths to compensate for explicit learning weaknesses while creating conditions favorable for both implicit and explicit vocabulary learning.

Implicit vocabulary learning occurs primarily through associative learning, which depends on efficient matching between words and referents and achieves correct word-referent associations through gradual accumulation of co-occurrence probabilities. To increase the accumulation rate of co-occurrence probabilities for ASD children, referent diversity must be ensured. Suanda et al.' s (2014) Contextual Diversity Theory posits that variation in learning contexts (such as referent diversity) promotes vocabulary learning. Diverse referents can reduce learners' habituation responses, helping them maintain novelty toward referents during prolonged probability accumulation (Hartley & Whiteley, 2024). Current research indicates that ASD children struggle to utilize effective information provided by social attention, and their attention is easily distracted by irrelevant stimuli, potentially leading to unstable word-object associations that interfere with integrating these associations into mental lexicons and memory (Hartley et al., 2020). Conversely, ASD children prefer geometric patterns and novel, brightly colored objects (Bacon et al., 2020). Enhancing referent diversity (such as variations in color and shape) can help ASD children strengthen the formation and memory of word-object associations, thereby fully utilizing their intact associative learning mechanism to improve cross-situational word learning outcomes (Tovar et al., 2020). Additionally, since ASD children can categorize based on simple rules or typical features, using novel objects and implementing simple variations on referents can help them extract key features of referents, reducing memory load, promoting statistical accumulation in associative learning, and facilitating cross-situational word learning and generalization (Tek et al., 2008).

Explicit vocabulary learning occurs primarily through hypothesis testing, which depends on rapid hypothesis formation and verification, using mutual exclusivity strategies to acquire referent semantics. Therefore, while hypothesis testing is influenced by general cognitive mechanisms (such as attention and cognitive resources), it mainly manifests in the use of mutual exclusivity strategies in vocabulary learning. According to Lexical Constraints Theory, the mutual exclusivity strategy refers to children' s assumption that an object has only one corresponding name. Children can establish mappings between novel objects and new words because they believe objects with known names generally do not have other names (Markman & Wachtel, 1988). Hypothesis testing is closely related to the mutual exclusivity strategy in vocabulary learning, as learners randomly select an object as a word' s referent, forming a unique mapping hypothesis and continuously verifying it. Previous research also found that ASD children with severe language impairments experience significant difficulties using the mutual exclusivity strategy for vocabulary learning (Mathée-Scott et al., 2022; McGregor et al., 2013).

The Zipfian distribution is a long-tailed skewed distribution. When word frequencies follow a Zipfian distribution, high-frequency words learned quickly become anchors that strengthen the use of mutual exclusivity strategies. Therefore, the Zipfian distribution may represent a viable pathway for improving the hypothesis testing learning mechanism in ASD children, providing scaffolding for

their impaired hypothesis testing mechanism (Shi et al., 2024). The Zipfian distribution follows the power law P(r) = C/r^α, where r is word frequency rank, α is approximately 1, C is a constant, and P(r) is the word' s occurrence frequency (Hendrickson & Perfors, 2019; Lavi-Rotbain & Arnon, 2021). Additionally, human memory patterns conform to power laws, making words following Zipfian distributions easier to remember (Baronchelli et al., 2013). In uniform distributions, where each word occurs with equal frequency, there is virtually no word facilitation effect similar to that in Zipfian distributions, increasing learners' memory load to some extent (Shi et al., 2024). Since high-frequency words appear more frequently in Zipfian distributions, they help learners apply mutual exclusivity strategies for vocabulary learning, making it easier to establish mapping hypotheses between words and referents. Therefore, ASD children learning vocabulary based on Zipfian distributions may also strengthen hypothesis testing strategies, thereby compensating for their explicit learning deficits.

Through the above analysis, we have clarified how ASD children complete cross-situational word learning using relatively intact associative mechanisms and impaired hypothesis testing mechanisms, and how manipulating word frequency distribution and referent forms can fully utilize intact associative learning mechanisms while compensating for impaired hypothesis testing mechanisms. To better integrate previous research and provide more important reference value for future studies, this study, based on the above analysis and starting from the essential processes of vocabulary learning, has distilled a hybrid synergistic model of cross-situational word learning to macroscopically organize and integrate existing findings (see Figure 1 [Figure 1: see original paper]).

Figure 1. Hybrid Synergistic Model of Cross-Situational Word Learning in ASD Children

The hybrid synergistic model posits that cross-situational word learning in ASD children still includes spontaneous implicit learning processes and controlled explicit learning processes. However, implicit learning processes remain relatively intact in ASD children, while explicit learning processes are somewhat impaired. From a mechanistic perspective, implicit learning processes primarily depend on associative learning mechanisms, while explicit learning processes primarily depend on hypothesis testing mechanisms. Therefore, to promote cross-situational word learning in ASD children, we must present diverse referents and create a to-be-learned vocabulary following a Zipfian distribution. Referent diversity can enhance learning outcomes through relatively intact associative learning mechanisms, compensating for impaired hypothesis testing mechanisms and achieving synergistic integration of learning mechanisms. The Zipfian distribution can strengthen the hypothesis testing learning mechanism, compensating for impaired explicit learning and promoting synergy among learning mechanisms. The theoretical framework of the hybrid synergistic model can fully utilize relatively intact associative learning mechanisms while compensating for impaired hypothesis testing mechanisms. Moreover, in cross-situational word learning, implicit and explicit learning, as well as associative learning and hypothesis

testing, are not completely separate; they interact and synergistically promote the vocabulary learning process. Establishing the hybrid synergistic model has important theoretical and practical value for understanding the mechanisms underlying vocabulary learning difficulties and other language disorders in ASD children and for exploring targeted language intervention programs.

5 Summary and Future Directions

Currently, the academic community has not reached a consensus on the internal mechanisms of cross-situational word learning in ASD children. Through a review of previous research, this study proposes that cross-situational word learning deficits in ASD children essentially result from impaired learning mechanisms, particularly hypothesis testing mechanism impairment, while their associative learning mechanism remains relatively intact. Therefore, promoting cross-situational word learning in ASD children requires first fully utilizing their intact associative learning mechanism and compensating for their impaired hypothesis testing mechanism. Specifically, increasing referent diversity in learning contexts can enhance ASD children' s associative learning mechanism, while presenting a Zipfian-distributed vocabulary can help ASD children quickly form and verify efficient hypotheses, thereby achieving a mixture of associative learning and hypothesis testing that synergistically promotes cross-situational word learning. To integrate these theoretical perspectives, this study proposes the hybrid synergistic model to provide reference for future research.

The hybrid synergistic model also opens up many novel research directions for future studies on cross-situational word learning in ASD children. Based on the atypical nature of cross-situational word learning in ASD children and the multidimensional factors affecting it, future research could examine deeper learning mechanisms by exploring cross-situational word learning mechanisms and the connections between implicit and explicit learning. Additionally, future studies could attempt to apply the hybrid synergistic model to develop real language intervention programs for ASD children, exploring how innovative learning methods can promote language rehabilitation. We briefly summarize three future research directions for reference.

First, future research should explore additional factors that enhance associative learning mechanisms in ASD children. For example, studies could attempt to strengthen associative learning mechanisms through regular, structured learning materials. EEG research on neural entrainment has found that perceptual binding of visual triplet structures promotes statistical learning (Batterink et al., 2015). Perceptual binding refers to learners perceiving repeatedly co-occurring adjacent pictures as a larger unit (such as a triplet structure). Since ASD children prefer structured and predictable stimuli (Tola et al., 2021), future research could examine whether providing ASD children with ordered, structured learning materials (such as triplet-structured learning sequences) can enhance their relatively intact implicit learning, thereby promoting cross-situational word learning.

Second, future research should explore changes in cross-situational word learning mechanisms across different developmental stages in the ASD population. Over time, language development and environmental adaptation in ASD individuals evolve. Language function in ASD adults varies dramatically, ranging from remaining nonverbal to living and working independently (Roux et al., 2013). Some studies show that statistical learning in ASD adults does not differ from healthy populations (Pesthy et al., 2023), while other research finds that ASD adults still cannot orient attention to invisible gaze cues (Yang et al., 2024). This suggests that ASD adults have developed some language learning abilities (such as statistical learning) to cope with communication challenges. Future research could examine whether cross-situational word learning mechanisms differ across age groups in ASD individuals, helping design better language learning programs for ASD individuals of different ages.

Third, future research should explore how to use the hybrid synergistic model to promote vocabulary learning in ASD children in language intervention practice. Future studies need to examine the actual effects of referent diversity and word frequency distribution on improving cross-situational word learning in ASD children in language intervention contexts, as well as what degree of diversity and what level of Zipfian distribution optimally promote vocabulary learning in ASD children.

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Note: English references were already in proper format and are omitted here for brevity, but would be included in the full paper.

Note: Figure translations are in progress. See original paper for figures.