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Perspective

Extending the Procedural Circuit Deficit Hypothesis to Late-Talking Toddlers: A Developmentally Plausible Framework

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Highlights

What are the main findings?

- This paper argues that the Procedural circuit Deficit Hypothesis (PDH) can be meaningfully extended to late-talking toddlers, providing a developmentally plausible framework for understanding early expressive language delay.
- Evidence from statistical learning, motor development, gesture use, and longitudinal language studies suggests that early differences in procedural learning may contribute to delayed language development and may help explain why some late talkers later develop DLD.

What are the implications of the main findings?

- Applying the PDH offers a mechanistic and developmentally continuous account linking late talking in toddlerhood with later DLD, moving beyond descriptive labels toward explanatory models of language development.
- The framework generates testable hypotheses for research and may support earlier identification of children at risk for persistent language difficulties, as well as the development of targeted intervention approaches.

Abstract

Background/Objectives: Late talking in toddlerhood is a heterogeneous developmental phenomenon, with most children catching up while a meaningful subset later develops developmental language disorder (DLD). Despite considerable interest in identifying early developmental mechanisms that contribute to persistent language difficulties, theoretical frameworks linking late talking to later DLD remain limited. The Procedural circuit Deficit Hypothesis (PDH) has been influential in interrogating DLD in preschool- and school-aged children, but its potential relevance to late-talking toddlers has received limited attention. This viewpoint paper argues that the PDH can be meaningfully extended to toddlerhood as a developmentally plausible framework for understanding early language delay. Perspective: In this viewpoint paper, we propose that the PDH may provide a developmentally plausible framework for understanding late talking in a subset of toddlers. Drawing on evidence from developmental neuroscience, motor development, statistical learning, and early communication studies, we argue that individual differences in procedural learning mechanisms emerge early in development and may contribute to variability in language outcomes. We further suggest that these early differences may represent one pathway

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linking late talking to later DLD. Implications: Extending the PDH to late-talking toddlers provides a mechanistic, developmentally continuous account of early language development, generates testable hypotheses for future longitudinal research, and highlights the potential value of examining procedural learning processes alongside traditional language measures. We emphasize that this proposal remains a theoretical extension that requires empirical evaluation and should be considered alongside alternative developmental pathways contributing to language difficulties. If supported by future research, this framework may help advance understanding of heterogeneity among late talkers and inform approaches to early identification and intervention.

Keywords: developmental language disorder; late talking; procedural circuit deficit hypothesis; procedural learning; procedural memory; statistical learning

1. Introduction

Early language development varies widely across toddlers, yet about 10–15% of children exhibit delays in the onset of spoken language despite otherwise typical development [1]. These children, commonly referred to as late talkers (LT), are typically identified between 18 and 30 months of age based on delayed expressive language relative to age expectations [2]. Behavioural markers often include having fewer than 50 words at 24 months, delayed emergence of two-word combinations, and reliance on gestures or routines to communicate [3,4]. Late talking is a descriptive term rather than a diagnosis [5] and encompasses a heterogeneous group: while most children catch up to their peers by preschool age, a meaningful proportion continues to exhibit persistent language difficulties [6].

Studies indicate that approximately 20% of LT go on to meet criteria for developmental language disorder (DLD) [7] in the preschool years or beyond. DLD is a neurodevelopmental condition characterized by significant and persistent difficulties in acquiring and using language, not attributable to hearing loss, intellectual disability, neurological disorders, or insufficient language exposure [8,9]. Because DLD is most often identified during the preschool years, typically after age four [10,11], questions remain about the earliest developmental pathways that lead to the disorder, and whether early markers can be identified during toddlerhood.

One influential account of DLD is the Procedural circuit Deficit Hypothesis (PDH), which proposes that language difficulties arise in part from atypicalities in the procedural memory network [12,13], a system that supports learning of sequences, patterns, and rule-governed behaviours across domains [14–16]. While the PDH has been explored in empirical research in preschool- and school-aged children with DLD e.g., [17–19], its potential relevance to toddlers who present with late talking has received comparatively little attention. Given that procedural learning systems are functional early in development and undergo rapid maturation during the first years of life [20], early variations in these systems may contribute to both motor-based routines and early language learning.

The purpose of this viewpoint paper is to argue that the PDH can be meaningfully extended to the late-talking toddler population. By integrating evidence from motor development, statistical learning, and early language acquisition, we propose that developmental vulnerabilities in procedural learning may underlie language delays in a subset of LT. This perspective offers a biologically grounded explanation for heterogeneous developmental trajectories and motivating a shift from descriptive labels toward mechanistic models that inform early identification and intervention.

As a viewpoint paper, this article does not present a systematic review of the literature. Rather, the perspective was developed through a targeted review of research relevant to

procedural learning, language development, DLD, and late talking. Literature was identified through searches of major bibliographic databases (e.g., PubMed, PsycINFO, Medline, Scopus) using combinations of terms related to procedural learning (e.g., procedural learning, procedural memory, statistical learning, sequence learning), language development (e.g., language development, language acquisition, developmental language disorder, late talking), and child populations (e.g., infant, toddler, preschool, child). Additional relevant studies were identified through reference lists of key publications. Priority was given to empirical studies, systematic reviews, and meta-analyses that informed the theoretical argument presented in this paper.

2. PDH and Its Evidence Base

The PDH proposes that DLD arises, in part, from atypicalities in the procedural memory system [12], a network of frontal–striatal and frontal–cerebellar circuits that supports the learning of sequences, patterns, and rule-governed behaviours [21]. The terminology surrounding procedural learning requires clarification because several related constructs are often discussed together within the developmental language literature. In the present paper, we distinguish between the *procedural memory system*, *procedural learning*, *statistical learning*, *sequence learning*, *motor learning*, and *implicit learning*. The procedural memory system refers to a network of frontal-striatal and frontal-cerebellar circuits that supports the acquisition and automatization of skills and patterns across domains [21]. Procedural learning is treated as an umbrella construct supported by the procedural memory system. Statistical learning and sequence learning are considered related but distinct learning processes that contribute to procedural learning. Statistical learning involves sensitivity to the frequency and probability of events and relationships in the environment, whereas sequence learning involves acquiring information about the order or structure of events over time [15,22]. Implicit learning refers to the acquisition of knowledge without conscious awareness of what has been learned or how learning occurred. It is often considered a characteristic feature of many forms of procedural learning because procedural knowledge is typically acquired gradually through repeated exposure and practice rather than through explicit instruction [14,21]. However, implicit learning and procedural learning are not synonymous. Procedural learning refers to the broader process of acquiring skills and regularities supported by procedural memory systems, whereas implicit learning describes the manner in which some of this learning occurs. Statistical learning and sequence learning are frequently studied as forms of implicit learning and are often discussed within procedural-learning frameworks because learners can acquire probabilistic and sequential patterns without explicit awareness of those patterns. Additionally, motor learning and motor sequencing represent behavioural domains in which procedural learning can be expressed. Through repeated practice, individuals acquire increasingly efficient and automatic movement patterns, making motor learning one manifestation of broader procedural learning processes rather than a distinct theoretical framework [14], whereas gesture use is considered an indirect behavioural indicator that may reflect the development of motor and learning systems supported by procedural circuitry [23]. Although these processes are closely related and may rely on overlapping neural systems, they should not be considered interchangeable.

Statistical learning has been proposed as a foundational mechanism for language acquisition and processing. It enables learners to track the distributional properties of linguistic input, including the frequencies of sounds, syllables, words, and the transitional probabilities between adjacent elements. Through sensitivity to these regularities, infants and children can segment words from continuous speech, acquire lexical and grammatical patterns, and form increasingly sophisticated representations of language structure. Consequently, statistical learning is widely regarded as a domain-general learning mecha-

nism that supports multiple aspects of language development [24–26]. Considering that statistical learning and other procedural learning processes were proposed as important contributors to language acquisition, disruptions to the procedural memory system have been hypothesized as contributing to the persistent linguistic difficulties observed in DLD. Declarative memory, by contrast, is thought to be relatively preserved and may support compensatory learning strategies [12].

A substantial body of behavioural literature has been interpreted as supporting core predictions of the PDH across development. Children with DLD consistently show weaknesses on tasks indexing procedural and implicit learning, including serial reaction time (SRT) paradigms, sequence learning, and nonverbal rule learning, relative to typically developing (TD) peers. These weaknesses were found in empirical studies focusing on preschool children e.g., [17,19,27–30] and school-aged children e.g., [31–42].

Except for behavioural studies, neuroimaging research also provides biological support for PDH. Structural and diffusion MRI studies report atypical morphology and connectivity within basal ganglia, fronto-striatal, and cerebellar circuits in children with DLD [43–45]. Functional neuroimaging studies further demonstrate altered engagement of these networks during grammatical processing and sequence-learning tasks e.g., [30,46–48]. A recent meta-analysis identified the basal ganglia as a core region showing consistent differences across studies, reinforcing the central role of procedural circuitry in DLD [49]. Together, behavioural and neurobiological evidence has been interpreted as supporting the PDH as one plausible mechanistic account of persistent language impairment.

Importantly, the PDH aligns with a developmental perspective in which motor development, imitation, and early rule-learning interconnect with early language acquisition. Emerging evidence suggests that infants and toddlers with heightened risk for later language disorder show atypicalities in motor development, auditory statistical learning, and neural responses to sequential input [50,51]. These findings may suggest developmental continuity between early learning systems and later language outcomes, providing a rationale for considering PDH as a framework relevant not only to older children with DLD but also to younger children who present with early expressive language delay.

3. Potential Application of PDH in Toddlers

Although the PDH has primarily been applied to preschool- and school-aged children as the youngest group studied, growing evidence suggests that procedural learning mechanisms and individual differences in these mechanisms, are already observable in infancy and toddlerhood. The procedural memory system supports sequence learning, statistical learning, and rule extraction, early variations in these capacities may provide developmental signals of risk for later language difficulties. Evidence from TD children indicates that basal ganglia, cerebellar, and fronto-striatal circuits are functional and rapidly developing during the first three years of life [52,53]. Behavioural studies further demonstrate that infants exhibit statistical learning ability during the first year of life e.g., [51,54–56], establishing that the learning systems central to PDH are active well before the emergence of grammar.

There is growing empirical evidence supporting a relationship between procedural learning abilities and language development during infancy and early childhood. This evidence varies in its directness with respect to late talking. Direct evidence comes from studies involving LT themselves, whereas indirect evidence comes from studies of TD children. Specifically, three lines of evidence are relevant to the proposed extension of the PDH: (1) LT showed lower procedural learning abilities compared with TD peers e.g., [57,58]; (2) LT demonstrated language gains following interventions that incorporate principles of statistical and implicit learning e.g., [59,60], although these interventions did not claim to be designed to directly assess or remediate procedural learning, and (3)

stronger procedural learning abilities are associated with better concurrent and subsequent language outcomes in toddlers e.g., [61–65].

Together, the direct evidence from studies of LT remains limited but suggests that procedural learning may be relevant to language development in at least some children identified as LT. Findings from TD children provide indirect support by demonstrating that procedural learning abilities are associated with language outcomes during the developmental period in which late talking is typically identified.

Additional indirect evidence comes from developmental studies of motor development and communicative behaviours in community and population-based samples. Although motor skills and gestures are not direct measures of procedural learning, they are associated with neural circuits implicated in PDH and are closely linked to early language development. Toddlers with weaker motor skills and reduced use of symbolic or iconic gestures show slower vocabulary growth and elevated risk for later language difficulties [66–69]. These patterns are characteristic of many LT and may reflect early challenges in planning and executing sequential action routines. In parallel, emerging evidence suggests that infants and toddlers at familial or behavioural risk for language disorder show differences in statistical and implicit learning, including attenuated neural responses to auditory regularities and reduced sensitivity to sequential structure [50,70]. Together, these findings suggest that individual differences in procedural learning capacities may be detectable during the developmental period when late talking is typically identified. A summary of the evidence discussed is provided in Table 1.

Table 1. Direct and indirect evidence relevant to the proposed extension of the PDH to late-talking toddlers.

Evidence Type	Age Group	Population	Measure/ Domain	Main Findings	Relevance to PDH Extension
Direct	Toddlers	LT	Statistical learning	LT showed weaker statistical learning than TD peers [57,58]	Suggests procedural learning differences may be present in some LT
			Procedural-learning-based intervention	Language gains observed following interventions incorporating procedural learning principles [59,60]	Suggests procedural learning mechanisms may be relevant to language development in LT
Indirect		TD	Statistical learning	Stronger statistical learning associated with better language outcomes [61–65]	Demonstrates developmental links between procedural learning and language acquisition
		Community/ developmental samples	Motor skills and gesture use	Motor and gesture abilities predict vocabulary growth and later language outcomes [66–69]	Suggests behavioural manifestations associated with procedural learning relate to language development
		At-risk for language difficulties	Statistical learning; neural responses	Differences in learning and responses to sequential regularities observed in children at elevated risk for language difficulties [50,70]	Suggests learning differences may emerge before diagnosis
	Preschool and school-age children	DLD	Behavioural procedural learning tasks	Procedural learning weaknesses were observed e.g., [17,27–29,31,36,38]	Provides empirical support for PDH itself
			Structural and functional neuroimaging	Differences observed in the procedural memory network e.g., [43,44,47,49]	Supports neural mechanisms proposed by PDH

Longitudinal evidence further supports developmental continuity between late talking and later DLD. Population based studies indicate that approximately 20% of LT do not catch up by preschool years and remain at elevated risk for persistent language impairment [6,7]. If PDH provides a mechanistic account of persistent language impairment in older children, its developmental precursors may reasonably be expected to emerge earlier in motor sequencing, statistical learning, and pattern detection. Applying the PDH to toddlerhood therefore offers a developmentally continuous framework for understanding the underlying neural mechanism of late talking.

4. Discussion

4.1. Significance of Applying PDH to Toddlers

Extending the PDH to late talking in toddlers may offer important research, and clinical value by linking early expressive language delay to underlying mechanisms rather than surface-level behaviour. Traditionally, late talking has been defined descriptively, based on vocabulary thresholds or expressive milestones. Applying the PDH may redirect attention toward a developmentally continuous and mechanistic framework, in which early differences in procedural learning provide a potential explanation for delayed language development in children without identifiable biomedical conditions, such as intellectual disability or hearing loss. This perspective helps situate late talking within a broader neurodevelopmental framework and aligns with growing calls to move beyond categorical labels toward explanatory models of language development.

4.1.1. A Potential Theoretical Framework for Research

Applying the PDH to late-talking toddlers generates several testable predictions that can be evaluated through behavioural and neuroimaging research. First, LT, on average, should demonstrate lower performance than TD peers on developmentally appropriate measures of procedural learning. Second, individual differences in procedural learning measured during toddlerhood should predict later language outcomes. Third, neuroimaging studies may identify structural or functional differences in procedural memory circuitry between LT and TD children. Finally, interventions that incorporate procedural learning principles may be associated with greater language gains, particularly among children who exhibit evidence of procedural learning vulnerabilities. These predictions remain hypothetical and require evaluation through empirical research.

Several research designs are particularly well suited to evaluating these predictions. Longitudinal studies that follow LT from toddlerhood into the preschool and school-age years would be especially valuable because they allow researchers to examine heterogeneous developmental pathways. Studies that combine behavioural assessments with neuroimaging measures may further clarify the developmental relationships among procedural learning, brain development, and language acquisition. Thus, the value of extending the PDH to toddlerhood lies not in offering an explanation for late talking, but in providing a theoretically grounded model that can guide future research and generate specific predictions regarding developmental language trajectories.

An important consideration for the application of PDH is the substantial heterogeneity among LT. Children who meet criteria for late talking may differ considerably in their linguistic abilities, gesture use, learning profiles, and developmental trajectories. Consequently, it is unlikely that all LT demonstrate identical procedural learning weaknesses or conform to predictions derived from the PDH. The proposed framework may be more relevant for a subset of LT who show difficulties in morphosyntactic development as morphosyntactic learning depends heavily on the acquisition of linguistic regularities and grammatical patterns, which is related to the procedural memory system [12,21].

4.1.2. A Potential Translation to Clinical Practice

If future research supports the developmental relevance of the PDH in LT, the framework may have implications for early identification and intervention. Current practice guidelines acknowledge that LT are at elevated risk for persistent language difficulties [71]. A PDH informed approach encourages clinicians to attend not only to expressive vocabulary size but also to procedural motor-learning related behaviours. Alcock et al. [66] found that gesture report could be more accurate than vocabulary report for toddlers in predicting delays in communication. Neiling et al., [72] used a dynamic assessment of statistical learning of a novel morpheme to distinguish bilingual preschool children with and without DLD. The results demonstrated high classification accuracy with an area under the curve (AUC) of 0.94, sensitivity of 83%, and specificity of 100%. Such findings raise the possibility that procedural learning measures could complement existing tools for the identification of children with language difficulties.

In the context of late talking, combining standardized language assessments, such as the MacArthur-Bates Communicative Development Inventories (MBCDI), with procedural motor learning measures may offer several potential advantages. First, if validated in longitudinal studies, procedural motor learning assessments may provide complementary information to improve the accuracy of identifying toddlers with genuine language difficulties by providing information about an underlying learning mechanism rather than solely measuring language performance. Second, among children who meet criteria for late talking and exhibit similar levels of language delay, procedural learning measures may provide additional cues for identifying those at greater risk for persistent language difficulties and later DLD. If supported by longitudinal research linking procedural performance in toddlerhood to language outcomes in preschool or school age e.g., [65], procedural learning measures could contribute not only to the identification of late talking but also to the early stratification of risk for DLD, thereby informing monitoring and intervention decisions.

For intervention, there is already a small body of evidence on the efficacy of procedural-learning-based intervention in enhancing vocabulary acquisition in LT e.g., [59,60] despite that vocabulary learning is commonly believed to relate to the declarative memory. Within the framework of the PDH, these findings suggest that targeting procedural learning mechanisms may facilitate language development by strengthening the learning systems that support the acquisition of linguistic patterns and regularities. Although the current evidence base remains limited, procedural-learning-based interventions may offer a promising complement to traditional language interventions, which typically focus on increasing language exposure and directly teaching linguistic forms. Furthermore, if procedural learning deficits contribute to persistent language difficulties, interventions designed to enhance statistical learning, sequence learning, or motor learning may warrant investigation as potential adjuncts to language intervention. Future research should determine whether procedural-learning-based interventions yield long-term improvements in language outcomes and whether treatment response varies according to children's procedural learning abilities. Such findings could ultimately support a more individualized intervention approach, in which procedural learning measures are used not only to identify children at risk but also to guide the selection and personalization of intervention strategies.

Importantly, procedural learning measures are not currently recommended as standalone clinical tools for identifying LT or predicting future DLD. The evidence base remains limited, particularly for toddlers, and questions remain regarding the reliability, validity, and developmental sensitivity of existing procedural learning tasks. At present, the clinical relevance of the proposed framework should therefore be considered preliminary and hypothesis-generating rather than practice-changing. Future longitudinal studies are

needed before procedural learning measures can be integrated into routine assessment or intervention planning.

4.2. Potential Counterarguments and Considerations

Despite the promising implications of applying the PDH to toddlers, many questions remain unanswered, and careful consideration is warranted before translating this framework into clinical practice. We propose the application of the PDH to late talking primarily on the basis of two observations. First, a substantial body of research has demonstrated associations between procedural learning, especially statistical learning, and language development. Second, approximately 20% of late-talking toddlers are later diagnosed with DLD, highlighting a potential developmental continuity between these two conditions as well as the need for early markers that may help identify children at risk for persistent language difficulties. Accordingly, we present the application of the PDH in toddlers as a hypothesis to be tested and a potential theoretical framework for future research and clinical practice. However, at least two important counterarguments merit consideration.

First, the evidence linking language difficulties to deficits in procedural learning is not entirely consistent. Some studies have failed to identify significant differences between children with language difficulties and TD peers e.g., [73,74]. Moreover, findings from systematic reviews and meta-analyses have been mixed. Lum et al. [75]'s meta-analysis on SRT task performance identified significant difference between TD individuals and those with DLD. Similarly, Lammertink et al. [76] completed a meta-analysis in statistical learning in the auditory verbal domain, also found significantly lower performance in participants with DLD. West et al. [74] found only a negligible association between SRT performance and language abilities, although stronger associations emerged for some other procedural learning measures. These findings raised concerns regarding the reliability and validity of commonly used procedural learning tasks. Consistent with this view, Oliveira et al. [77] subsequently reported limited evidence for an association between language, literacy, and SRT performance. Together, these inconsistent findings call into question the robustness and developmental stability of procedural learning deficits as a marker of language impairment.

Second, not all individuals with DLD have a history of late talking. While late talking is a known risk factor for subsequent language difficulties, many children who later meet diagnostic criteria for DLD do not exhibit clinically significant language delays during toddlerhood.

4.2.1. Potential Explanations of the Inconsistent Findings

With respect to the first counterargument, at least two possible explanations for the inconsistent findings in the literature can be established from existing evidence. First, as noted by West et al. [74] and Oliveira et al. [77], the inconsistency may stem from the poor psychometric properties of commonly used procedural learning tasks, particularly the SRT task. Arnon [78] further investigated this issue by examining the reliability of three statistical learning tasks administered twice, two months apart, in both adults and children. The results revealed moderate reliability in adults and poor reliability in children. Moreover, none of the tasks demonstrated adequate test-retest reliability across sessions, and all showed levels of internal consistency that fell below accepted psychometric standards. These findings suggest that measurement limitations may partly account for the inconsistent associations reported between procedural learning and language outcomes.

Second, growing evidence suggests that procedural learning may not represent a unitary and stable capacity. Rather, different components of procedural learning may follow distinct developmental trajectories and rely on partially separable mechanisms. For example, Raviv and Arnon [79] found modality-specific developmental patterns in statistical learning:

auditory statistical learning appeared relatively stable across childhood, whereas visual statistical learning improved significantly with age. Such findings raise the possibility that procedural learning is characterized by substantial individual variability across domains and developmental stages. Consequently, children with similar language profiles may exhibit different patterns of strengths and weaknesses across procedural learning components. If this is the case, studies employing a single procedural learning task may capture only a subset of the relevant processes, thereby contributing to the heterogeneous and sometimes contradictory findings reported in the literature.

Although the PDH provides one possible explanation for language difficulties, several alternative and complementary accounts have also been proposed. Language development is a complex process influenced by multiple interacting cognitive, neural, genetic, and environmental factors [80,81], and it is unlikely that any single mechanism fully accounts for the heterogeneity observed among LT or individuals with DLD.

One alternative perspective emphasizes lexical processing and encoding mechanisms [82,83]. For example, limitations in phonological representations, lexical encoding, and word retrieval may contribute to language difficulties [84] without necessarily reflecting broader deficits in procedural learning.

Environmental influences also play an important role in shaping developmental trajectories. Variation in language exposure, quality of caregiver-child interaction, socioeconomic factors, and access to developmental supports can affect early language outcomes [85–87]. Although these factors are not sufficient to explain all cases of persistent language impairment, they may interact with children's underlying learning capacities to influence language growth.

Genetic factors provide an additional explanation to language difficulties [88]. Family history is one of the risk factors for DLD [89], and evidence suggests that language outcomes are influenced by multiple genetic and biological mechanisms rather than a single causal pathway [90]. Consequently, different children may arrive at similar behavioural language profiles through distinct developmental routes.

Rather than viewing these explanations as mutually exclusive, it may be more useful to consider the PDH as one possible component within a broader developmental framework. Procedural learning differences may interact with linguistic, environmental, and genetic factors across development, contributing to language difficulties in some children while playing a more limited role in others. From this perspective, the PDH is best conceptualized as one plausible pathway among several that may contribute to late talking and later DLD.

A further consideration is whether observed differences in procedural learning during toddlerhood should be interpreted as deficits or developmental variation. Procedural learning systems continue to mature throughout infancy and early childhood, lower performance at a particular time point may reflect developmental immaturity rather than stable impairments. This distinction is especially important in LT, many of whom subsequently achieve age-appropriate language abilities. Consequently, we do not interpret procedural learning differences in toddlerhood as evidence of permanent deficits. Instead, they may represent variations in developmental timing that, in some children, are associated with elevated risk for persistent language difficulties.

4.2.2. Potential Explanations for the Incomplete Overlap Between Late Talking and DLD

Considering that not all individuals with DLD have a history of late talking, people may question the underlying relationship between these two conditions. We propose two potential explanations for this question.

First, DLD may become apparent over time, not necessarily shown as late talking status. Late talking is an early sign, not the definition of DLD. Late talking mainly captures

early expressive delays. It is usually identified from early word production, whereas some children's main vulnerability can be receptive language, grammar, sentence formulation, or processing speed. Those problems may be subtle before linguistic demands increase. For example, Bishop et al. [91] found that receptive-language ability at around 20 months was a better predictor of later impairment than late-talker status. DLD is a heterogeneous condition characterized by persistent difficulty in language acquisition and use. Language difficulties may affect different domains, including vocabulary, grammar, sentence formulation, and discourse skills. Thus, a child may have a fairly typical early vocabulary but develop clearer difficulties as language becomes more complex.

Second, risk can be distributed across other factors such as genetic and environmental ones. Family history, biological and perinatal factors, and aspects of the child's developmental context all contribute to risk. For example, Rudolph [92] found eleven factors as statistically significant predictors of DLD, including maternal education, family history, prematurity etc.

These findings suggest that late talking can be an early indicator of later language difficulties for some children, but it does not capture the full range of developmental pathways that may lead to DLD. Language development is influenced by multiple interacting factors and DLD can emerge through diverse linguistic profiles, many individuals with DLD may not have been identified as LT in early childhood. Therefore, the absence of late talking does not preclude later language difficulties, highlighting the importance of considering both developmental trajectories and broader risk factors when understanding the origins of DLD. Here we do not propose the PDH as the sole or definitive explanation for DLD. Rather, we view PDH as a testable hypothesis and one of several plausible explanatory models that can generate specific predictions about language and brain development. Evaluating PDH alongside alternative accounts will be important for advancing a more comprehensive understanding of DLD.

4.3. Future Directions

Extending the PDH to late-talking toddlers opens several important directions for future research and practice. To fully evaluate the developmental relevance of this framework, progress is needed in measurement, longitudinal design, and translational application.

First, there is a critical need to develop reliable and developmentally appropriate measures of procedural learning for infants and toddlers. As discussed earlier, two major measurement challenges remain. The first concerns the reliability of procedural learning tasks, which has yet to be firmly established, particularly in very young children. Beyond reliability, questions remain regarding construct validity. Many commonly used procedural learning tasks are assumed to measure procedural learning, but it remains unclear whether different tasks assess the same underlying construct. A related issue concerns developmental validity. Procedural learning tasks were largely developed for older children and adults, and it is unclear whether they measure equivalent constructs across developmental stages. The cognitive, attentional, motor, and language demands of a task may differ substantially between toddlers and school-aged children. Consequently, developmental changes in task performance may reflect broader maturation of attention, memory, or motor abilities rather than procedural learning itself. A similar concern is the problem of task impurity. Behavioural paradigms designed to measure procedural learning may also recruit additional cognitive processes. As a result, poorer performance cannot always be attributed specifically to procedural learning deficits. The second concerns the multidimensional nature of procedural learning. Rather than representing a unitary ability, procedural learning encompasses multiple processes that may be captured through different modalities and task types, such as visual and auditory paradigms. Consequently, relying on a single measure

may provide an incomplete picture of procedural learning abilities. Future work should therefore prioritize the development of reliable, age-appropriate tasks that comprehensively assess across multiple domains of procedural learning and encourage multiple converging measures and complementary neurobiological approaches rather than relying on a single behavioural task.

Second, longitudinal studies are necessary to determine whether early procedural learning differences predict persistent language outcomes. While existing research shows that early communicative behaviours such as gesture use are associated with later language development, few studies have tracked procedural learning markers from toddlerhood through the age at which DLD is typically diagnosed. Integrating both behavioural and neural measures within longitudinal cohorts will be essential for testing whether PDH-consistent patterns serve as early indicators of developmental risk.

Finally, applying PDH to toddlerhood raises important questions for early intervention. If procedural learning mechanisms contribute to early language trajectories, intervention approaches may benefit from incorporating activities that support sequence learning, rhythm, gesture–speech integration, and structured linguistic patterns. Evaluating whether such approaches enhance grammatical and language learning in toddlers represents a promising direction for translational research.

5. Conclusions

Understanding the underlying neural mechanism of late talking and why some LT go on to develop persistent language difficulties while others catch up remains a central challenge in developmental language science. The PDH, originally formulated to account for language impairments observed in individuals with DLD, represents one developmentally plausible framework for addressing this question earlier in development. Evidence indicates that procedural learning systems are active in infancy and toddlerhood and support a range of behaviours closely linked to early language acquisition.

Extending PDH to toddlers provides a potential mechanistic account of heterogeneity within this population, positioning early differences in procedural learning as one factor that may help explain divergent developmental trajectories. A major strength of this proposal is that it generates specific behavioural, neurobiological, and longitudinal predictions that can be empirically evaluated in future research. At the same time, this framework should be applied with appropriate caution, recognizing the contributions of environmental variation, measurement constraints, and alternative neurodevelopmental pathways. PDH is not proposed as a prescriptive or exclusive explanation but as a theoretically grounded model that complements existing developmental and clinical perspectives.

By proposing a link between late talking and underlying learning mechanisms, the PDH offers a potentially valuable bridge between toddler-level language variability and later DLD outcomes. Applying this framework to LT has the potential to advance early identification, guide longitudinal research, and inform the design of developmentally sensitive interventions that target the learning systems shaping early language trajectories.

Although the PDH offers one plausible explanation for language delay in a subset of children, other developmental pathways are also possible. These factors are not mutually exclusive and may interact with procedural learning mechanisms across development. It is therefore unlikely that a single framework will fully explain the heterogeneity observed among LT or individuals with DLD. Rather than viewing the PDH as a competing explanation for all language difficulties, we suggest it may represent one pathway among multiple developmental routes that contribute to persistent language impairment.

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Abbreviations

The following abbreviations are used in this manuscript:

AUC	Area under the curve
DLD	Developmental language disorder
LT	Late talker(s)
MBCDI	MacArthur-Bates Communicative Development Inventories
MRI	Magnetic resonance imaging
PDH	Procedural circuit Deficit Hypothesis
SRT	Serial reaction time
TD	Typically developing

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