Effects of Age, Memory, and Instruction on Second Language Learning in Middle Childhood and Early Adolescence: Evidence from Cross-situational Learning

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Abstract

A fundamental challenge in language acquisition is to associate words to their referents in the environment and identify syntactic structures in which these words occur. One proposed mechanism underpinning this process is known as cross-situational learning, during which learners track co-occurrence statistics across situations to build up word-referent mappings and grammar knowledge. While young children acquire their first language (L1) rapidly and seemingly effortlessly, usually without substantial explicit instruction, the process of additional language (L2) learning becomes more complex as they enter middle childhood. This transition, marked by increasing cognitive maturity and the onset of formal education, introduces variation in both internal factors (e.g., changes in chronological age, individual differences in memory capacity) and external factors (e.g., openness to formal instruction) to shape the language acquisition process and outcome. Despite the critical cognitive and metalinguistic developments occurring from middle childhood through adolescence, this population remains underrepresented in L2 acquisition research more broadly, and in cross-situational learning research specifically. Across three experiments involving 220 children, this thesis investigates the effects of age, individual differences in memory, and explicit instruction on L2 learning through cross-situational learning with a particular focus on eight- to thirteen-year-old learners.

Study 1 investigated whether 8- to 9-year-old children could simultaneously acquire novel vocabulary and grammar via a cross-situational learning paradigm adapted from Rebuschat et al. (2021). During the task, learners were exposed to ambiguous sentence-scene mappings without feedback or instruction, and they could only develop word-referent mappings as well as grammar knowledge (i.e., sentence word order knowledge) through tracking the input statistics. Results indicated that children at this age acquired grammar (i.e., word order) effectively, but no evidence of vocabulary learning. This suggested that the sentence word order information may become available earlier and serve as a scaffold for subsequent lexical learning. This study also suggested a child-adult difference in cross-situational learning: whereas previous adult studies showed effective learning of both vocabulary and grammar from similar input, children only presented successful grammar learning.

Study 2 expanded the age range and introduced an explicit instruction condition to examine when and to what extent instruction affects child L2 learning. This study observed a qualitative change at around the age of 12, at which point children became more responsive to explicit instruction. Results also indicated age and metalinguistic awareness as moderating factors on the effect of explicit instruction on L2 learning.

Study 3 examined whether individual differences in working memory, procedural memory and declarative memory explained additional variance in L2 learning under explicit instruction, beyond the effect of age. It was observed that age, memory abilities and their interactions accounted for the variance in early stages of L2 development.

Overall, these findings demonstrate that the early stages of L2 learning between the ages of 8 and 13 are shaped by the interplay of external (explicit instruction) and internal (age and memory capacities[1]) factors. Rather than assuming implicit learning works equally well for children, our results highlight significant room for metalinguistic knowledge and awareness to facilitate learning. In turn, explicit instruction is not uniformly effective but requires developmental readiness. These findings have practical implications for educators, curriculum developers, and AI-based language learning tools, supporting the design of age- and cognitively-appropriate instructional approaches.

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[1] In the current thesis, age serves as a proxy for maturational changes, while memory captures within-age variability.

Author’s declaration

This thesis is my own work and has not been submitted in substantially the same form for the award of a higher degree elsewhere. This thesis includes three published or publishable papers. The following pages contain the authorship statements signed by all co-authors of each paper.

Authorship statement

The article “Children’s simultaneous or successive acquisition of vocabulary and grammar: Evidence from cross-situational learning” has been published in Journal of Child Language with authors Wensi Zhang, Padraic Monaghan, Sophie Bennett and Patrick Rebuschat. Wensi Zhang was responsible for writing up the article, carrying out the research, conceptualization and design, and formal analysis. Sophie Bennett contributed to participant recruitment and data collection, including contacting school and testing children together with Wensi Zhang. Padraic Monaghan and Patrick Rebuschat were responsible for supervision, conceptualization and design, guidance on formal analysis, and providing comments on the text.

Signature:

Authorship statement

The article “The role of age and instruction in statistical learning of vocabulary and grammar” has been submitted and under review in Language Learning with authors Wensi Zhang, Patrick Rebuschat and Padraic Monaghan. Wensi Zhang was responsible for writing up the article, carrying out the research, conceptualization and design, and formal analysis. Patrick Rebuschat and Padraic Monaghan were responsible for supervision, conceptualization and design, guidance on formal analysis, and providing comments on the text.

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Table of contents

List of Tables

List of Figures

1 General introduction

1.1 Cross-situational learning across development

One of the fundamental challenges in language acquisition[2] is to identify the referents of words in ambiguous situations (e.g., Smith & Yu, 2008) and how words relate to one another within syntactic structures (e.g., Gleitman, 1990). This classic challenge is often illustrated by Quine's "*Gavagai*" problem (1960): upon hearing the utterance "*Gavagai*!" while observing a rabbit run by, the learner has to determine whether the word refers to the rabbit itself, its action, or some other property such as its color. How do learners reliably solve this referential ambiguity and acquire the correct mappings between linguistic forms and their meanings in the world? A growing body of evidence (e.g., Ge et al., 2025; Monaghan et al., 2021; Rebuschat et al., 2021; Saffran et al., 1996; Yu & Smith, 2007) suggests that such referential ambiguity can be reduced across situations where distributed statistics can support learning. Specifically, learners are shown to be able to track cross-situational statistics and unconsciously abstract grammatical patterns from the environment even in the absence of instruction (Batterink et al., 2015).

In a typical cross-situational learning (CSL) paradigm, learners are presented with multiple objects while listening to a set of pseudowords. It is not possible to build up correct word-object mappings within a single trial as each word appears with multiple potential referents. However, by tracking consistent pairings over successive trials, where correct pairings remain stable and foils vary, learners can form accurate word-object associations (Roembke et al., 2023). Cross-situational word learning has been found to be quickly and successfully by infants (e.g., Smith & Yu, 2008), children (4- to 7-year-olds, Benitez et al., 2020; 4- and 10-year-olds, Fitneva & Christiansen, 2017; 5- to 7-year-olds, Suanda et al., 2014; 2- to 7-year-olds, Venker, 2019; 2-to 5-year-olds,

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[2] For the purposes of this thesis, the terms language learning and language acquisition will be used interchangeably. Although some traditions reserve learning for formal, instructional contexts and acquisition for naturalistic or implicit development, this distinction is not strictly upheld here. Instead, both terms refer to the process of gaining knowledge of a L2, whether through exposure, instruction, or interaction.

Vlach & DeBrock, 2017), and adults (e.g., Roembke et al., 2023; Yu & Smith, 2007). In addition to learning nouns, CSL has also been found to be effective in learning other lexical classes (for verb learning, see Childers et al., 2023; Scott & Fisher, 2012; for adjective learning, see Akhtar & Montague, 1999).

However, the typical CSL paradigm tends to rely on perfectly uniform co-occurrence statistics, which does not mirror the variability regarding the linguistic statistical properties in natural language environments (Isbilen & Christiansen, 2022). One exception is Benitez and Li (2024), which investigated children and adults' CSL from varied mapping structures (contrasting one word attached to one object and two words attached to one object). It was found that children's learning performance was worse in the two-to-one condition (learning two words for one object) than in the one-to-one condition. Another simplification of the typical CSL paradigm, compared to naturalistic language acquisition, is its tendency to focus on words from a single grammatical category, for example, presenting isolated nouns with their referents (Yu & Ballard, 2007). In natural language learning, there is an interdependence in the meaning and grammatical roles of words within an utterance (Gleitman, 1990). This bootstrapping of word and syntax learning has been a topic of theoretical interest in language acquisition research (Abend et al., 2017; Höhle & Weissenborn, 2001), but how words and syntax are acquired simultaneously has been rarely explored. The exceptions, however, tend to pretrain learners on vocabulary, or using already known words, before exposing them to the target sentences (e.g., Amato & MacDonald, 2010; Friederici et al., 2002; Hu, 2017; Morgan-Short et al., 2014; Spit et al., 2022). Moreover, most CSL paradigms are stripped of the attentional, linguistic, and social cues that characterize naturalistic word learning (Yurovsky & Frank, 2015). These reductions in ambiguity simplify the learning task, but is less representative of the challenges faced during real-world language learning, and thus call for more ecological valid paradigms that better approximate the real-world simultaneous vocabulary and grammar learning.

More recent studies have begun to address this gap and indicated that adults can learn vocabulary and syntax simultaneously from cross-situational statistics in a more natural-like CSL paradigm (e.g., Monaghan et al., 2019, 2021; Rebuschat et al., 2021; Walker et al., 2020). This research exposed adult learners to a complex artificial language consisting of transitive sentences presented alongside contextually rich, dynamic visual scenes. These studies further introduced various types of interventions, such as auditory feedback (e.g., bell sounds) and rule-search instructions, to better reflect the types of cues available in real-world language learning environments (Monaghan et al., 2021; Ruiz et al., 2025). It was found that these external cues (e.g., auditory feedback and instruction) indeed enhanced adults' simultaneous learning of vocabulary and grammar. However, whether children are similarly able to integrate such external cues and track cross-situational statistics remains an open question.

Following this line of work (e.g., Monaghan et al., 2021; Ruiz et al., 2025; Walker et al., 2020), the present thesis adopted a more ecologically valid CSL paradigm than traditional word-referent mapping tasks. Specifically, learners were exposed to a complex artificial language containing multiple linguistic features, including nouns, verbs, case markers, and word-order rules, presented alongside two juxtaposed dynamic visual scenes with high referential ambiguity. I also incorporated external cues such as explicit instruction to simulate real-world language-learning environment.

In line with the recent CSL research examining simultaneous vocabulary and syntax learning (e.g., Monaghan et al., 2021; Ruiz et al., 2025), the learning of syntax in the current thesis is conceptualized as learners' sensitivity to structured positional regularities governing sentence organization in the artificial language (i.e., the verb-final word order constraint). This operationalization does not presuppose the acquisition of abstract hierarchical syntactic representations or fully specified grammatical category knowledge. Rather, learning may occur at different representational levels, ranging from distributional sensitivity to recurring positional patterns (e.g., particular word forms consistently appearing in sentence-final position) to more abstract lexico-syntactic representations in which learners associate specific lexical items with structural roles.

We cannot infer children's CSL mechanisms from adult data, given potential qualitative differences in how the two populations process input information (Fitneva & Christiansen, 2017; Yurovsky & Frank, 2015). For example, Ramscar et al. (2013)

identified a marked difference in strategies that young children and adults adopted in word learning. It was found that children tended to rely on informativity (mapping objects to words based on object's informativity in the input), while adults tended to adopt logical, exclusion-based strategies when resolving ambiguity.

Age has been found to significantly shape CSL performance (Newport, 2020). Specifically, adults generally perform better than children, and among children, older individuals tend to outperform younger ones (e.g., Arciuli & Simpson, 2011; Benitez & Li, 2024; Fitneva & Christiansen, 2017; Raviv & Arnon, 2018; Vlach & DeBrock, 2017). Recent ERP (event related potentials) research also provided evidence suggesting that learners' sensitivity towards statistical patterns vary developmentally (e.g., Walk & Conway, 2015). While these findings suggested the role of age in learning from input statistics, empirical studies to date have largely focused on infants, young children (typically under 8 years), and adults, leaving children in middle childhood and adolescence underrepresented in CSL research (Fitneva & Christiansen, 2017; Isbilen & Christiansen, 2022).

Taken together, there is a need to investigate how CSL functions under more ecologically valid conditions and across a broader developmental range. In particular, including learners in middle childhood and early adolescence is essential for establishing a more complete understanding of the developmental trajectory of CSL.

1.2 The driving factors of language learning across development

The role of age in L2 acquisition has been a central topic in both theoretical and empirical research. Early hypotheses, such as the Critical Period Hypothesis (CPH; Lenneberg, 1967), suggests that learners past a certain age (typically around puberty) are worse at learning a language than younger learners. Empirical research supports that younger starters are more successful L2 learners particularly for pronunciation (e.g., Birdsong, 2005) and grammar features (e.g., Qureshi, 2016). In a meta-analysis study, for example, Qureshi found a medium to large effect size for age effects on ultimate L2 grammar acquisition. On the other hand, accumulating empirical evidence has reported a seemingly paradoxical trend: during the initial stages of L2 learning, older learners outperformed their younger peers (e.g., Menks, 2024; Jia & Fuse, 2007; Snow & Hoefnagel-Höhle, 1978; Snedeker et al., 2012). For example, Menks (2024) observed a steep developmental trajectory of novel grammar learning outcomes, measured with a grammaticality judgment task (GJT) which tests learners' capability to judge whether sentences were grammatical or not, on learners from the age of 8 to around 15, after which GJT scores became less affected by age. These findings present different pictures regarding the role of age in L2 acquisition, and thus raise an important question: what drives such age-related changes in early L2 learning?

One proposal is maturational constraints (e.g., Newport, 1990), which argues that language learning abilities improve as a result of brain maturation. Under this view, chronological age itself would be expected to strongly predict language outcomes, while other cognitive factors, such as memory, play only a secondary role. However, empirical evidence has increasingly challenged this maturational account. Rather than viewing age itself as a biological constraint, recent research conceptualized age as a macro-variable that captures a range of co-developing factors, such as cognitive maturation, literacy, schooling, and learning experience (Birdsong, 2018; Flege, 2019; Unsworth, 2016). Older children, for instance, may gain an advantage through their ability to engage in explicit learning strategies and transfer their first language literacy skills (Hartshorne, 2022; Lightbown, 2003). From this perspective, age effects are developmentally interdependent with underlying cognitive systems, such as memory, rather than outcomes of age per se.

To date, there remains a paucity of research that included both age and memory variables in CSL studies. An important exception is Vlach and DeBrock (2017), who examined the relationship between age, memory, and cross-situational word learning in 2- to 5-year-old children. In this study, researchers tested the developmental system theory of CSL, which believes that what drives the changes in CSL is the combination of multiple cognitive systems. Their findings showed that the task-specific memory abilities (including visual recognition memory, auditory recognition memory and recognition memory for word-object pairings), together with children's language abilities, were stronger predictors of CSL than age itself, suggesting that cognitive systems may drive developmental changes more directly than age alone. It is important to note that the memory assessed in this study was task-specific recognition memory, measured via a paired-associates task. As suggested by the authors of this study, CSL places high cognitive demands on learners, particularly due to the need to retain and integrate a large amount of information over time. Therefore, the global memory abilities (i.e., the amount of information that learners can hold) are also likely to underpin CSL performance and warrant further investigation. They also called for future investigations that include long-term memory measurements. Responding to this call, the present thesis project examined both domain-general memory abilities, namely working memory (WM), and long-term memory systems, namely procedural and declarative memory, in the context of children's CSL.

1.3 Cognitive memory systems in L2 acquisition

WM, which refers to the cognitive capacity to store, maintain, and process information in ongoing tasks (Li, 2022), has been found to develop during childhood (e.g., Ahmed et al., 2022; Luna et al., 2004; Heled et al., 2022), improving linearly from about age of four to early adolescence (Gathercole et al., 2004). WM has been widely identified as a predictor of language learning outcomes (Linck et al., 2014; Tagarelli et al., 2011; Williams, 2015). Although various theoretical models have been proposed to explain the structure and function of WM (e.g., Baddeley & Hitch, 1974; Cowan, 2010; Engle, 2018), this thesis follows the Baddeley and Hitch's (1974) model, as it has been the most widely used in research exploring WM and L2 learning (Ruiz et al., 2021). According to Baddeley and colleagues (e.g., Baddeley, 2017), WM is a system that consists of storage subsystems responsible for temporarily storing and processing both verbal and visual-spatial information; a domain-general central executive component responsible for attentional control and cognitive regulation; and an episodic buffer that connects these subsystems to long-term memory.

For research on WM and L2 acquisition, a common distinction is drawn between 'phonological short-term memory' and 'complex working memory' according to whether the research focused on storage capacity (e.g., the phonological loop) or both storage and processing aspects of WM (the phonological loop plus the central executive) respectively (Li, 2017, p. 398). This thesis adopts this widely used distinction between phonological short-term memory (PSTM) and complex WM, depending on whether tasks tap only storage or both storage and processing (Li, 2017). PSTM is typically assessed using simple span tasks, such as digit span or nonword repetition, which involve the temporary storage of verbal items, while complex WM is measured through complex span tasks that require individuals to store and process information simultaneously (Verhagen & Leseman, 2016). Research on child L2 learning has shown that these two components may contribute differently. Specifically, PSTM has been found to significantly relate to both L2 vocabulary and grammar learning (e.g., French & O'Brien, 2008; Masoura & Gathercole, 2005; Verhagen, Messer, & Leseman, 2015), while complex WM tended to only predict L2 grammar learning (e.g., Engel de Abreu & Gathercole, 2012; Verhagen & Leseman, 2016).

Despite the important and widely acknowledged role of WM in L2 research more broadly, whether it accounts for learning variations in CSL has received comparatively limited attention, particularly in child populations. Cross-situational word learning is a demanding task, during which children must store verbal information, retrieve previously observed information, and update the stored word-object mappings according to the new scene, and this process is likely to engage working memory (Sia et al., 2023).

Only recently, researchers started to directly examine whether WM supports children's (cross-situational) statistical learning, and results are mixed. Specifically, some studies did not find a significant association between WM and CSL (e.g., McGregor et al., 2022; Mettler, 2023; Sia et al., 2023), while others found positive correlation between WM and statistical learning (for distributional statistical learning, see Zhou et al., 2024; for statistical learning of non-adjacent dependency, see Broekhuis, 2025). A possible reason for this discrepancy is that most of the null findings come from studies focused on children under the age of 8, before WM has fully matured. In contrast, Zhou et al. (2024) found that WM (measured by backward digit span) positively predicted visual statistical learning in 6- to 12-year-olds. Similar results have been reported in adults, where WM (measured via backward digit span and nonword repetition) significantly predicted word learning through CSL (e.g., Neveu & Kaushanskaya, 2023). These findings raise the possibility that WM's contribution to CSL may become more clearly in middle childhood, as cognitive systems mature, and that the interplay of WM and age may explain learning trajectories in CSL more accurately than age alone.

In addition to WM, recent research has emphasized the roles of declarative and procedural memory systems in explaining the variability in how we learn a language (see Hamrick et al., 2018; Morgan-Short et al., 2022; Morgan-Short & Ullman, 2023, for reviews). These two memory capacities follow distinct developmental trajectories (Pili-Moss, 2021). Procedural memory reaches functional maturity early in infancy and early childhood, while declarative memory develops slowly and continues to mature into early adulthood (Bauer, 2008; Hulstijn, 2015, Ullman, 2004). Empirical studies have shown that children between the ages of 5 and 10 years generally possess adult-like procedural memory ability, but their declarative memory remains underdeveloped in comparison to adults (e.g., Finn et al., 2016; Lum et al., 2010).

According to the declarative/procedural (D/P) model (Ullman, 2004; Morgan-Short & Ullman, 2023), these two memory systems underlie the learning and use of different aspects of language. Declarative memory is a domain-general neurocognitive system responsible for the conscious retrieval of factual knowledge (semantic memory) and experiences (episodic memory). It also plays a key role in the rapid learning and retention of arbitrary associations (Ullman, 2020). In contrast, procedural memory is a general-purpose system that underlies the implicit learning of skills, routines, and patterns of behavior. Procedural memory tends to result in the knowledge that is difficult to verbalize due to its nature of operating largely outside of conscious awareness (Ullman, 2020). Whereas declarative memory enables fast learning from limited exposure, procedural learning tends to unfold more slowly through repeated practice over time.

Ullman's D/P model (2001, 2004, 2005) associates the learning of certain language properties to declarative and procedural memory systems separately and dynamically across development. For L1 acquisition in early childhood, declarative memory is proposed to support the acquisition of the mental lexicon (e.g., sounds and meaning of words; irregular morphological forms), while procedural memory underpins the learning of mental grammar (e.g., rule-based morphology and syntax). For L2 learning in adulthood, declarative memory underpins both vocabulary and grammar learning, at least the initial learning stages (Hamrick, 2015; Morgan-short et al., 2014). Regarding CSL of vocabulary and grammar specifically, existing evidence (Ruiz et al., 2018; Walker et al., 2020) shows a positive association between declarative memory and grammar among adult populations.

Nevertheless, little is known regarding how procedural and declarative memory capacities moderate children's CSL of vocabulary and grammar. A notable exception is Pili-Moss (2021), who found that procedural memory significantly predicts word order learning in 8- to 9-year-old children while no effect of declarative memory was observed. This finding aligns with the D/P model and suggests a developmental continuity between L1 and L2 grammar learning in childhood. Specifically, children (at around age of 8) presented a similar pattern to child L1 learning, i.e., procedural memory, but not declarative memory, supporting rule-based learning. However, two important questions remain unanswered. First, Pili-Moss's study trained children the novel vocabulary before being exposed to the artificial language, making it unclear how these memory systems may interact when vocabulary and grammar are learned simultaneously, as there might be a particular role of declarative memory in learning word-referent associations as suggested in the D/P model (Ullman, 2020). Second, given the distinct developmental trajectories of procedural and declarative memory from childhood through adolescence, an important question is whether learners in this age range rely on these two memory systems in a manner consistent with child L1, like young child L2 learners in Pili-Moss (2021), or adult L2 acquisition.

Taken together, previous research has identified the critical role of individual differences in age as well as short- and long-term memory capacities in L2 learning. However, most of the theoretical accounts and empirical evidence focus on younger children and adults, leaving the developmental window of middle childhood to early adolescence underexplored. Given that this period is marked by substantial growth in memory abilities, it is of importance to have direct data from this particular population, so that the driving factors underlie language development can be fully understood.

1.4 The effect of instruction on L2 learning

Children have been primarily believed to be implicit language learners, meaning that their learning typically occurs without conscious awareness of "the statistical properties and the degree of regularity in the linguistic stimuli to which (s)he is exposed" (Hulstijn, 2015, p. 30). For example, the Fundamental Difference Hypothesis (Bley-Vroman, 1988) contends that children learn a language almost entirely through implicit and domain-specific mechanisms, while adults largely lost this competence and have to learn a language through alternative mechanisms, relying mostly on explicit strategies, such as problem-solving capacities. Similarly, other researchers have proposed that a biologically determined shift occurs over development, with cognitive and neurological changes driving a transition from implicit learning in childhood to explicit learning in adolescence (e.g., Paradis, 2004, 2009).

However, Lichtman (2013) argued that as there is a lack of direct empirical evidence comparing child L2 learners' implicit and explicit learning capacities, what has been interpreted as a maturational shift may in fact reflect differences in learning environments. Specifically, older learners tend to receive more instruction and less input, while young learners tend to be exposed to activities such as songs and stories which deliver the whole-language input. Lichtman thus proposed an instructional hypothesis, highlighting the importance of examining the external factors (i.e., learning environment) when examining the marked change from implicit learning in childhood to explicit learning in adulthood. Therefore, there is a need to integrate both the internal factors (e.g., age and memory capacities) and external factors (e.g., explicit instruction and feedback) in understanding child-adult differences in L2 acquisition.

In the current thesis, instruction is viewed as the deliberate and systematic intent that modifies learning mechanisms (e.g., attention) and/or the conditions under which learning takes place (de Graaff & Housen, 2009; Ruiz et al., 2025). Explicit instruction in particular, guides learners’ attention to language forms by directly providing learners with knowledge about grammatical rules, often using metalinguistic terminology or by directly asking them to search for rules of the target language (DeKeyser, 1995; Lichtman & VanPatten, 2021; Ruiz et al., 2025). Drawing on Schmidt’s (1990) noticing hypothesis, such instruction enhances the likelihood that learners detect and encode relevant patterns, particularly when those forms are otherwise subtle or non-salient in the input. In the present thesis, instruction is operationalized in a deliberately narrow way, namely as brief pre-exposure metalinguistic information that directs learners’ attention to a structural feature of the target language. This operationalization allows the current studies to isolate one potential mechanism of instruction (the guidance of learners’ attention), but it does not capture the broader range of instructional practices typically found in classroom settings, where explicit explanation is often accompanied by input-based activities, output practice, repetition, and feedback (e.g., Kasprowicz et al., 2019).

In second language acquisition (SLA) literature, there seems to be broad consensus that instruction on language structure and vocabulary contributes to adult L2 development (Goo et al., 2015; Norris & Ortega, 2000). However, for CSL studies specifically, the role of explicit instruction is less consistent. CSL is not necessarily an implicit process, and evidence that learners, even child learners, develop awareness during statistical learning has been observed (e.g., Spit et al., 2021). To test the interplay of explicit instruction on CSL, Monaghan et al. (2019) trained adult learners with intransitive sentences consisting of syntactic markers indicating nouns and verbs in the sentence. Results indicated that participants who received explicit instructions about the knowledge of marker words acquired the nouns and verbs better than the peers that were not given this information. However, when being exposed to the complex transitive sentences, adult learners who received explicit instruction about the role of the marker words indicating the agent or patient role of nouns were observed to perform no differently than those without any instructions about the language structure (Monaghan et al., 2021). These findings indicated that explicit instruction could assist in promoting cross-situational word learning under some situations. For example, instruction may be more powerful when it was pointing to grammatical category information (i.e., markers indicating grammatical categories of nouns and verbs) than when it points to thematic role information (Monaghan et al., 2019, 2021).

Regarding the role of explicit instruction on child population, it is less clear as existing data in instruction studies is mostly from high school adolescents and young adults, while leaving young learners (under the age of 12)' openness towards explicit instruction rarely explored (Roehr-Brackin, 2024). Several exceptions recently have challenged the assumption that children are resistant to explicit instruction. For example, Lichtman (2016) trained children aged 5 to 7 and adult participants on an artificial language consisted of nouns, verbs, and gender determiners. Both children and adults in the explicit condition received direct instruction on the language's word order rule (VSO). Results indicated that participants in both the implicit and explicit groups successfully acquired the word order rule. However, only children in the explicit group were able to articulate the rule, whereas adults demonstrated explicit knowledge of the word order rule regardless of instructional condition. Spit et al. (2022b) examined whether kindergartners benefit from explicit instruction in L2 learning. Children were first trained on vocabulary through picture-word pairings before being exposed to the artificial language sentences. While explicit instruction on grammatical markers did not improve accuracy in a picture-matching task, eye movement data revealed earlier predictive looks toward the target image. These findings suggest that children may be capable of integrating instruction when provided, and that explicit learning mechanisms may be more accessible than previously thought.

Given that learners of different ages may engage different learning mechanisms and respond differently to different learning environments, DeKeyser (2012) highlighted the importance of examining age-treatment interactions. However, empirical studies directly addressing this issue remain scarce as this is a relatively new area of research (DeKeyser, 2012). To address this gap, DeKeyser (2013) emphasized the need for experimental designs that tightly control over the input quality and quantity, such as those using artificial yet linguistically rich languages. The present thesis responses to this call by adopting a rich, but highly controlled artificial language to explore how age-treatment interactions shape children's acquisition of vocabulary and grammar in a CSL paradigm.

1.5 Interactions of individual differences and instruction in L2 acquisition

DeKeyser (2020) put forward a more holistic theoretical synthesis of the critical period hypothesis by attributing the seemingly contradictory findings regarding age-related effects (i.e., the younger-is-better trend in immersion settings versus older-is-better trend in foreign language settings, for more discussion, see Muñoz, 2008; Pfenninger & Singleton, 2017) to the complex interactions among age, aptitude and quality and quantity of the input. This interpretation is grounded in evidence from studies of both immigrants and foreign language learners (Huang et al., 2020; Kuo et al., 2020; Muñoz, 2008), as well as studies showing age-aptitude interactions (e.g., Abrahamsson & Hyltenstam, 2008). It was thus further argued that young children can exploit different learning mechanisms than older learners. Specifically, when L2 learning begins at an early age together with good quality and quantity of input, implicit learning process is dominant and driving successful acquisition, while aptitude for explicit learning play less of a role. In contrast, when input is limited (either in quality and quantity), or/and when learning starts at an older age, individual differences in aptitude for explicit learning becomes dominant on determining L2 learning outcomes. This account acknowledges both implicit and explicit learning mechanism in L2 acquisition on a child population and calls for further research exploring the complex interaction between input, age and aptitude.

Empirical evidence from aptitude-treatment interaction studies (mostly on adults) suggested that individual differences constrained the relative effectiveness of particular instructional treatments (Kachinske & DeKeyser, 2021; Linck et al., 2014; Ruiz et al., 2025; Suzuki & DeKeyser, 2017; Tagarelli et al., 2011). First, regarding individual differences in WM, studies have shown that learners with higher WM capacity tend to benefit more from explicit learning conditions that imposed greater attentional and cognitive demands (Doughty, 2001; Erlam, 2005; Fu & Li, 2021; Goo, 2012; Li, 2017; Ruiz et al., 2021; Tagarelli et al., 2011; Yilmaz & Granena, 2019). This is because such conditions often require simultaneous processing of meaning, form, and use. In contrast, learners with lower WM capacity may struggle under explicit instruction (Biedroń & Pawlak, 2016).

Declarative and procedural memory systems also appear to modulate the effectiveness of instructional conditions in L2 learning. Declarative memory is more likely to associate with learning in explicit and intentional contexts, such as classroom instruction or tasks requiring the conscious recall of language rules. A growing body of research has shown that stronger declarative memory is linked to greater success in both L2 learning of vocabulary and grammar in instructed (e.g., Robinson, 1997; Ruiz et al., 2021) and explicit feedback conditions (e.g., Yilmaz & Granena, 2021). In a recent laboratory-based study with adults, Ruiz et al. (2025) examined how declarative (measured by CVMT and paired-associates tasks) and procedural (measured by ASRT and LLAMA D tests) memory interact with learning conditions (implicit, rule-search, and rule-presentation) in a CSL paradigm. It was found that declarative memory predicted learners' overall learning trajectory under explicit learning condition. In contrast, procedural memory tends to support learning in implicit learning conditions, where learners receive little or no instruction and must extract regularities from input without conscious awareness (Brill-Schuetz & Morgan-Short, 2014; Morgan-Short et al., 2014; Ullman, 2016; Yilmaz & Granena, 2019). Empirical evidence has shown that individuals with stronger procedural memory benefit more from implicit feedback conditions, such as recast which reformulates learners' non-targetlike utterance into a targetlike form (Fu & Li, 2021; Granena & Yilmaz, 2019). However, how individual differences in short- and long-term memory systems modulate children's simultaneous vocabulary and grammar learning under different learning conditions remains unclear.

In summary, middle childhood through adolescence is characterized by significant developmental changes shaped by not only the maturation of cognitive capacities but also the increased exposure to different learning environments (e.g., formal instruction). Nevertheless, this particular population remains underrepresented in SLA studies more broadly, and CSL studies, largely due to practical and logistical constraints (e.g., young children are less accessible for research participation than university students) (Roehr-

Brackin, 2024). Therefore, studies focusing on this certain population can advance our understanding of the underpinning mechanisms through which language learning in early childhood (e.g., L1 and L2 acquisition) transitions to adulthood. Moreover, such research provides empirical evidence to the theories regarding age-related effects (e.g., Critical Period Hypothesis; Lenneberg, 1967; Fundamental Difference Hypothesis; Bley-Vroman, 1988) in SLA.

1.6 Research questions

This thesis investigates the role of age, individual differences in memory capacities and explicit instruction, as well as their interactions in the acquisition of vocabulary and syntax in a complex artificial language. I adopted a more ecological valid CSL paradigm compared to the previous typical ones which did not mirror natural language learning variability. In addition, I focused on the learner population across a critical developmental period (ages 8 to 13) to capture both cognitive maturation and improvements in the ability to engage in explicit learning strategies. In a series of three studies, this thesis project addresses the following research questions:

RQ1: How does cross-situational learning of vocabulary and grammar change across middle childhood to early adolescence?

RQ2: To what extent does the external factor (i.e., explicit instruction) affect children’s learning of vocabulary and grammar through cross-situational learning, and how does this factor interact with age?

RQ3: To what extent do internal factors, including age, working memory, procedural memory and declarative memory, affect children’s learning of vocabulary and grammar through cross-situational learning under explicit instruction, and how do these factors interact?

Research question 1 is answered by data from the three studies. Study 1 tested 20 8- to 9-year-old children’s learning performance in the adopted CSL paradigm. It addresses the first research question by underscoring the extent to which 8- to 9-year-old children can acquire vocabulary and grammar simultaneously through cross-situational statistical learning. As most previous studies adopting this similar CSL task focused on adult populations, this study also establishes a baseline for how much children can learn from cross-situational statistics in the complex and immersive CSL task. Study 2 and 3 further expanded the sample to include children from a broader age range, from 8 to 13 years old and tested this population through the same CSL tasks. These three studies together answer research question 1 through presenting the CSL performance from a total of 220 learners across middle childhood to early adolescence.

Research question 2 is answered by Study 2. To answer how explicit instruction about the syntactic structure affects CSL and whether the effect interacts with age, this study introduced an explicit instruction condition where learners were taught the grammar knowledge of the target artificial language pre-exposure.

Research question 3 is answered by Study 3. Study 3 focused on the same age range and adopted the same CSL paradigm as study 2. To investigate the age-memory interactional effect in L2 learning under the explicit learning condition as asked in research question 3, in addition to training children in the CSL paradigm, this study included four individual differences measurements, including digit span forward, digit span backward, Alternating Serial Reaction Time Task (ASRT) and Continuous Visual Memory Test (CVMT), each for the measurement of phonological short-term memory, complex working memory, procedural memory, and declarative memory respectively.

2 Published paper 1: Children's simultaneous or successive acquisition of vocabulary and grammar: Evidence from cross-situational learning

Page number: 36-63

Abstract

Recent evidence from cross-situational learning (CSL) studies have shown that adult learners can acquire words and grammar simultaneously when sentences of the novel language co-occur with dynamic scenes to which they refer. Syntactic bootstrapping accounts suggest that grammatical knowledge may help scaffold vocabulary acquisition by constraining possible meanings, thus, for children, words and grammar may be acquired at different rates. Twenty children (ages 8 to 9) were exposed in a CSL study to an artificial language comprising nouns, verbs, and case markers occurring within a verb-final grammatical structure. Children acquired syntax (i.e., word order) effectively, but we found no evidence of vocabulary learning, whereas previous adult studies showed learning of both from similar input. Grammatical information may thus be available early for children, to help constrain and support later vocabulary learning. We propose that gradual maturation of declarative memory systems may result in more effective vocabulary learning in adults.

Keywords: child language acquisition; cross-situational word learning; statistical learning

Introduction

In early language acquisition, a key challenge is to determine the exact referent from the infinite number of possible ones when a word is heard in speech. This is often referred to as the "Gavagai" problem, following Quine (1960). Imagine an infant or child hearing the utterance "Gavagai!" while observing a landscape in which a rabbit is dashing across a field. In this case, the utterance might refer to multiple referents, including the whole rabbit, the rabbit's ear, the texture of its fur, or its movement. How do infants and children know what "Gavagai" refers to? One underlying process that researchers (e.g., Fazly et al., 2010; Monaghan et al., 2021; Yu & Smith, 2007) have long assumed to support learning in such ambiguous situations is statistical learning (SL), by which learners acquire regularities in the language patterns through exposure. Specifically, for word learning under conditions with referential ambiguity, learners can track the co-occurrence of the word with its referent in the environment over multiple situations (Rebuschat et al., 2021;Yu& Smith, 2007), in order to establish the intended word-referent mapping.

Learning word-object mappings through a cross-situational learning (CSL) paradigm has been found to be rapid and successful in infants (e.g., Smith & Yu, 2008), children (e.g., 4- to 7-year-olds, Benitez et al., 2020; 4- and 10-year-olds, Fitneva & Christiansen, 2017; 5- to 7-year-olds, Suanda et al., 2014; 2- to 7-year-olds, Venker, 2019;2-to 5-year-olds, Vlach & DeBrock, 2017), and adults (e.g., Yu & Smith, 2007). In these previous experiments, participants were exposed to sets of pseudowords while observing multiple objects. Within a single trial, it was not possible to correctly map a noun to its referent due to the ambiguity of possible correspondences between words and objects. However, the appropriate word-object mapping can be determined through tracking cross-situational statistics, as each word consistently appeared with its referent while the other words and objects varied over trials. Learners can use CSL to acquire words from other grammatical categories (for verb learning, see Childers et al., 2023; Scott & Fisher, 2012; for adjective learning, see Akhtar & Montague, 1999), and in the case of adults, they can rely on CSL to acquire multiple grammatical categories simultaneously (e.g., Monaghan et al., 2015; Rebuschat et al., 2021).

However, the typical CSL paradigm, which focuses on words from a single grammatical category, all occurring with their referents, is a simplification that does not apply to naturalistic language, where scenes and utterances are more complex (e.g., Yu & Ballard, 2007). Furthermore, there is a close interdependence in the meaning and grammatical roles of words within an utterance (Fisher et al., 2010; Gleitman, 1990; Monaghan et al., 2023). This bootstrapping of word learning and syntax has been a topic of theoretical interest in language acquisition research (Abend et al., 2017; Höhle & Weissenborn, 2001), but a clear demonstration of how words and syntax are acquired simultaneously has been rarely observed. One reason for this is practical: learning a language with sufficient complexity to incorporate both vocabulary from different grammatical categories and syntactic structure is a substantial challenge. The rare exceptions, however, tend to pretrain learners on vocabulary, or using already known words, before exposing them to multi-word sentences (e.g., Amato & MacDonald, 2010; Friederici et al., 2002; Hu, 2017; Morgan-Short et al., 2014; Spit et al., 2022).

The possibility of simultaneous acquisition of vocabulary and grammar without prior vocabulary training was recently demonstrated in studies with adults (e.g., Monaghan et al., 2019, 2021; Rebuschat et al., 2021; Walker et al., 2020), where adult learners were exposed to a complex artificial language consisting of transitive sentences presented alongside dynamic scenes relating to the sentences. However, whether this CSL is accessible to children learning a language remains unclear. Vlach and DeBrock (2017) investigated multiple factors that underlie effective CSL of nouns in children aged 2 to 5. They found that children's declarative memory ability (i.e., visual and auditory recognition memory) and language skills (i.e., receptive vocabulary) were strong predictors of learning. Vocabulary learning has been related to declarative memory ability (Ruiz et al., 2018; Ullman, 2004; Walker et al., 2020), consistent with Vlach and DeBrock's

(2017) finding that it relates to CSL noun learning. However, learning syntax has been related to procedural memory ability (Morgan-Short et al., 2014). The developmental trajectories of these memory systems are very different (PiliMoss, 2021). Procedural memory tends to reach maturity at an earlier stage of the life span (i.e., infancy and early childhood), while declarative memory matures more slowly, starting to develop in childhood and not becoming fully functional until early adulthood (Bauer, 2008; Hulstijn, 2015; Ullman, 2004). Lum et al. (2010) found that procedural memory skills were relatively stable from ages 5 to 6 years, though declarative memory performance was changing substantially, and a similar pattern was found for ages 6 to 10 by Finn et al. (2016), who found procedural memory skills were similar to adults by these ages, though declarative memory skills were significantly lower. Thus, when children younger than 10 years old are faced with learning both vocabulary and syntax from a novel language, we might expect syntax, served by the procedural memory system, to be acquired more effectively, with greater variation in vocabulary learning possible due to expression of individual differences in the development of declarative memory.

In the current study, we investigate the effect that the complex environment that children experience, where there are multiple words in sentences and many possible referents around them in the environment, has upon children's simultaneous learning of vocabulary and syntax. We exposed children aged 8 to 9 years old to the complex utterances and complex scenes adapted from Rebuschat et al. (2021). We focused our investigation on children aged 8 to 9 years to meet the gap in statistical language learning studies of children of this age (Isbilen & Christiansen, 2022), and also because of this being a point in development where divergence in procedural and declarative memory skills development is observed (Ferman & Karni, 2010;Finnetal.,2016;Lumetal.,2010; Meulemans et al., 1998).

We predicted that children would be able to learn the sentence-scene correspondences, due to their ability to track cross-situational statistics for simpler word-referent mappings (e.g., Childers et al., 2023; Scott & Fisher, 2012; Vlach & DeBrock, 2017). We also predicted that they would be able to acquire syntax from cross-situational statistics, as this was readily acquired by adults (e.g., Rebuschat et al., 2021) and supported by the earlier maturing procedural memory system, providing insight into the bootstrapping process of acquisition of vocabulary and syntax.

Method

Participants

Twenty participants (mean age = 9.1 years, *SD* = 4 months, 13 female) aged from 8;11 to 9;10 at a primary school in Greater Manchester UK, participated in this study. The school is in a moderate socio-economic area (the 40% least deprived areas in England, English Indices of Deprivation, 2019) with a relatively high education level (the 60% least deprived areas in England): 65% of the parents held qualifications above university undergraduate degree, 25% had completed education up to school or college (up to age 18), and 10% held a FE college diploma. Seventeen participants were monolingual native speakers of English, two spoke English and Urdu and one spoke English, Russian, and Portuguese[3]. All had normal vision and hearing.

Materials

Artificial language

The artificial language was adapted from Rebuschat et al. (2021), with some simplifications to make the language potentially easier to acquire. Specifically, we excluded the adjectives in the artificial language in Rebuschat et al. (2021).

Vocabulary: There were 12 pseudowords, 10 of which were content words (6 nouns and 4 verbs) and 2 of which were case markers indicating the grammatical role (i.e., either subject or object) of the preceding noun. These words were read and

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[3] Note that Urdu is a verb-final language just like the artificial language used in this study. For this reason, we conducted separate analyses for the two Urdu-English bilingual children in our sample. These are reported in the Supplementary Materials.

recorded separately by a female native English speaker in monotone and presented using E-prime with a 250 ms pause between each word. The pseudowords can be found in the Supplementary Materials.

Syntax: The syntax of the artificial language was based on Japanese, with a fixed position of the verb phrase (VP), always appearing at the end of the sentence, while the subject noun phrase (NP) and object NP could alternate between the initial and second positions. The VP contained only the verb, whereas the NPs always comprised a noun followed by a post-nominal case marker, which reliably indicated whether the preceding noun was the agent or the patient in the sentence. Half of the sentences were in SOV order, and the other half were OSV. A total of 112 unique sentences were generated by E-prime by concatenating pseudowords, with a 250 ms pause between each word, as demonstrated in the following example.

(1) Cheelow tha bimdah noo dingep.
Animal$_1$ SUBJECT Animal$_2$ OBJECT pushes.
'Animal$_1$ pushes animal$_2$'.

We balanced the frequency of vocabulary, subject and object assignment, and word order across blocks.

Visual stimuli: The visual stimuli used in the current study consisted of a series of animated scenes generated by E-prime (2.0 Psychology Software Tools, Pittsburgh, PA). In these scenes, six cartoon animals (elephant, cow, chicken, turtle, zebra, and owl) were selected as the referents of the six nouns in the artificial language, performing one of the four actions (hiding, jumping, lifting and pushing) as the referents of the four verbs. We randomly allocated the mapping of the words to the animal characters and actions for each participant to avoid the association of certain sounds to objects and actions (Rebuschat et al, 2021). The animal characters are presented in the Appendix.

Procedure

Parental questionnaires and consent forms were distributed and collected by the Deputy headteacher before the experiment. Children were then trained and tested on the artificial language on two consecutive days, with each session lasting about 30 minutes. The procedure was identical on each day.

Cross-situational learning task

Participants were told they would learn an alien language spoken by "friends from a distant planet". Two practice trials were then presented in which participants had a chance to familiarise themselves with the task, observing two animated scenes (see Figure 2.1 for example), listening to artificial language sentences (e.g., *Cheelow tha bimdah noo dingep*.), and responding by pressing the keys on the keyboard associated with which scene they felt matched the sentence. An "L" sticker for the left scene and an "R" sticker for the right scene were placed over the keys "1" and "2", respectively, on a computer keyboard. Animal characters and pseudo-words contained in practice trials were not included in the main part of the study.

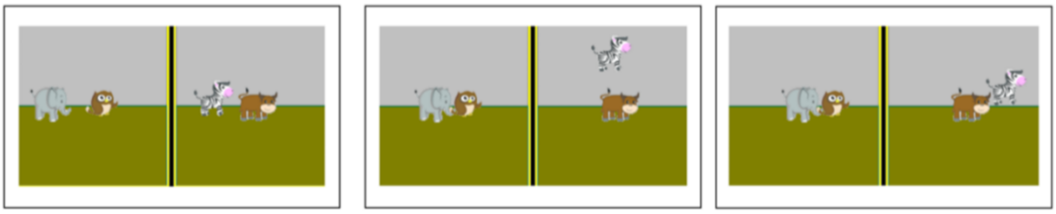


Figure 2.1 Example of a training trial of the CSL task, illustrating screenshots of the animated scenes. The left scene in this example trial depicts an elephant (agent) pushing an owl (patient), and the right scene shows a zebra (agent) jumping over a cow (patient).

The CSL task on each day comprised six blocks. Each block contained 12 training trials, different for each block, but balanced such that the occurrence of each word and visual stimulus occurred an equal number of times. A total of 72 sentences were used across the six training blocks, with 12 sentences in each block.

In each trial of this task, children observed two animated scenes, each depicting two of the six animal characters performing one of four actions. The two scenes differed in terms of the animals, the actions, and the agent and patient roles of the animals performing the action present in each scene. After the action was displayed once, the corresponding sentence was played. For example, children might see, on the left screen, an elephant jumping over an owl, and on the right a zebra hiding behind a cow, while hearing the artificial sentence “Cheelow tha bimdah noo dingep” (see Figure 2.1 for an example). The actions then repeated in a loop until participants entered their response, at which point the experiment advanced to the next trial without delay. After responding, participants received no feedback, with the task proceeding to the next trial immediately after a response was made.

In blocks 3 and 6, the 12 training trials were intermingled with 28 vocabulary testing trials, which were again balanced in terms of occurrence of words and visual stimuli. In each block there were 6 test trials for nouns, 4 for verbs, and 4 for marker words. The test trials were identical to the training trials, except the two scenes were identical except for one feature. To test nouns, the scenes varied by one animal, to test verbs, the scenes varied by the action only, and to test the marker words, the scenes varied in terms of which animal was the agent and which the patient of the action. Each noun was tested once per block, each verb once, and the marker words were tested four times.

Grammaticality judgement task

After the final block for the CSL task, there was a Grammaticality Judgement Task (GJT) block, which tested the acquisition of syntax (in terms of knowledge of word order). This consisted of 12 trials, each of which comprised one sentence occurring with one scene. All words corresponded with their referents in the scene, but in half the sentences the syntax of the language was followed (either OSV or SOV), while the remainder contained syntactic violations, with word order either VSO, VOS, SVO or OVS. There were 3 verb initial trials, and 3 verb medial trials. None of the testing sentences were used in training trials.

Participants were informed that sentences would now be spoken by an alien from another planet who was also learning this "alien language," and they had to determine whether the sentence sounded "good" or "funny" based on the sentences they had heard earlier. One of the researchers clarified “good” and “funny” to each participant one by one to make sure children understood that this referred to whether it sounded like or unlike the previous sentences. A label with "good" covered the 9 and a label "funny" covered the 0 key on a computer keyboard.

After completing the study on day 1, children returned the following day for the second training and test session at approximately the same time of day. Note that the vocabulary tests were included twice per session, and the GJT at the end of the training session. This design was so that potential subtle differences in order of acquisition of vocabulary items (e.g., nouns learned before or after verbs) could be tracked through the training, with the vocabulary test trials not interrupting exposure to the language because these test trials were identical in form to the training trials. The GJT required a different presentation and response, and so was positioned after the end of training on each day so as not to disrupt the learning.

Results

As noted above, two of our participants were Urdu-English bilingual children. Since Urdu is an SOV language, we conducted separate analyses to find out if this affected the results. The analyses can be found in the Supplementary Materials, and the results are similar to those presented here for the whole group of participants.

Performance on the cross-situational learning task

Accuracy on the training trials

The descriptive statistics of performance across training trials on two consecutive days (6 blocks each) are displayed in Table 2.1 and Figure 2.2. First, in descriptive statistics, whether performance across training trials was greater than chance (0.5) was determined by one-sample *t*-tests (see Table 2.1). For training on day 1, we observed significant learning effects over blocks 1, 4 and 5, and marginal significant learning effect over blocks 3 and 6. However, for day 2, a learning effect was only found in block 2.

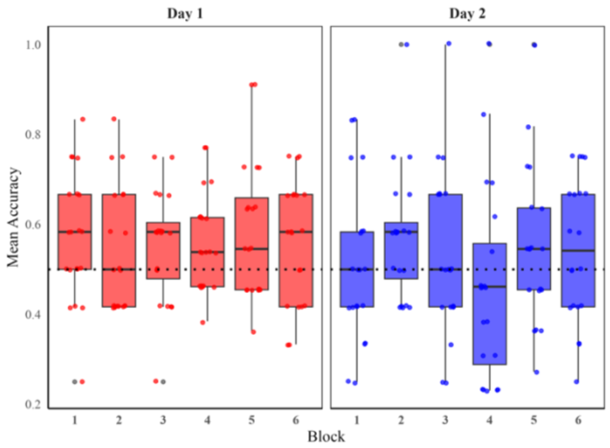
To further investigate whether learning was affected by training block and day, generalized linear mixed effects modelling was used with accuracy (0 or 1) as dependent variable, employing the binomial logistic function. We tested potential non-linear effects of learning using orthogonal polynomials for the block predictor. We constructed mixed effects models starting with a null model predicting accuracy with the binomial logit link function. Models included random intercepts for participant and item. However due to singularity, the random slopes for the within-participant predictors were not included. We then compared this model against models that incrementally added fixed effects: linear (ot1), quadratic (ot2), and cubic (ot3) polynomial terms for Block, then adding day, and their interaction. Log-likelihood comparisons were used to test whether each of the fixed effects improved model fit. Results showed that the intercept was significant, such that accuracy was slightly above chance averaged across all training trials, estimate = 0.184, *SE* = 0.076, z = 2.42, *p* = .016, odds ratio = 1.20. Adding the fixed effects of ot1 ($\chi^2(1) = 0.12$, *p* = .727), ot2 ($\chi^2(1) = 0.51$, *p* = .476) and ot3 ($\chi^2(1) = 0.17$, *p* = .683) did not significantly improve model fit. Similarly, adding the fixed effect of day ($\chi^2(1) = 3.43$, *p* = .064) did not significantly improved model fit. The interaction between block and day was not significant ($\chi^2(1) = 0.67$, *p* = .414), indicating no evidence for changing pace of learning on day 2 compared to day 1.

For the performance across test trials (i.e., vocabulary and syntax tests), in our descriptive statistics we conducted one sample t-tests to determine whether the accuracy of vocabulary (i.e., nouns, verbs and markers) and syntax (i.e., word order) test trials in each block was significantly above chance level. The descriptive statistics and results are presented in Tables 2.2 and 2.3 and Figure 2.3 and 2.4.

Table 2.1 Descriptive statistics for training trials in CSL task in the six blocks on two days. Showing t-test values compared against chance performance.

	Block											
	Day 1						**Day 2**					
	1	2	3	4	5	6	1	2	3	4	5	6
M	0.57	0.54	0.55	0.56	0.59	0.56	0.51	0.58	0.53	0.46	0.55	0.55
SD	0.14	0.14	0.13	0.11	0.15	0.14	0.18	0.15	0.19	0.22	0.17	0.16
t	2.20	1.21	1.79	2.52	2.50	2.04	0.21	2.31	0.70	-0.79	1.29	1.29
p	0.040	0.243	0.090	0.021	0.022	0.056	0.834	0.032	0.491	0.439	0.212	0.212
d	0.49	0.27	0.40	0.56	0.56	0.45	0.05	0.52	0.16	-0.18	0.29	0.29

Figure 2.2 Accuracy for training trials in CSL task for days 1 and 2. The box indicates the median (horizontal line) and interquartile range, with dots indicating individuals' accuracy. Dotted line indicates chance level (0.5).



Accuracy on the test trials

For vocabulary acquisition, results from the *t* tests showed no evidence of a learning effect of nouns, verbs and markers in all vocabulary tests (see Table 2.2 for test results). To determine whether block and day had a significant effect on vocabulary acquisition for nouns, verbs, and markers, we used generalized linear mixed effects models similar to the analysis conducted on training trials. The models included block and day as fixed effects, and the maximal random-effects structure that allowed models to converge without singularity warnings. Specifically, for noun test trials, a random intercept for item was included; for verb test trials, a random intercept for participant was included; for models testing marker test trials, random intercepts for participant and item were included. Random slopes for block and day were not included due to the singularity warnings. Results indicated that neither the fixed effect of block nor day improved the model fit for any of the vocabulary types (model results can be found in Supplementary Information).

For syntax (word order) acquisition, *t* tests results showed significant learning effects on both day 1 and day 2 (see Table 2.3 for test results). To determine whether day had significant effect on syntax acquisition, we again tested generalized linear mixed effects models in the same way as for the vocabulary test trials, except only with day as a predictor for accuracy (note that syntax was only tested once per day so block was not relevant to this analysis). The intercept of the model with no fixed effect was significant (estimate = 0.427, *SE* = 0.156, z = 2.74, *p* = .006, odds ratio = 1.53), indicating that the overall accuracy in the syntax test was greater than chance. However, we did not find that adding day significantly improved fit ($\chi^2(1) = 0.75$, *p* = .387).

Table 2.2 Descriptive statistics for vocabulary test trials in CSL task in block 3 and 6 on days 1 and 2. T-test values are compared against chance.

		Blocks			
		Day 1		Day 2	
		3	6	3	6
Nouns	*M*	0.54	0.52	0.48	0.52
	SD	0.22	0.22	0.22	0.22
	t	0.86	0.32	-0.32	0.32
	p	0.398	0.741	0.733	0.741
	d	0.19	0.07	-0.08	0.07
Verbs	*M*	0.54	0.54	0.56	0.53
	SD	0.31	0.25	0.25	0.26

	t	0.55	0.68	1.10	0.44
	p	0.591	0.505	0.287	0.666
	d	0.12	0.15	0.25	0.10
Markers	*M*	0.51	0.54	0.49	0.54
	SD	0.24	0.31	0.26	0.27
	t	0.24	0.55	-0.21	0.62
	p	0.815	0.591	0.834	0.545
	d	0.05	0.12	-0.05	0.14

Table 2.3 Descriptive statistics for syntax test trials in CSL task on days 1 and 2. T-test values are compared against chance.

	Day 1	Day 2
M	0.58	0.62
SD	0.15	0.22
t	2.30	2.42
p	0.033	0.026
d	0.51	0.54

Figure 2.3 Mean accuracy performance by vocabulary test trials in CSL task, for day 1 (left) and day 2 (right). Error bars represent the standard error of the mean for each block. The dotted horizontal line at 0.5 indicates chance.

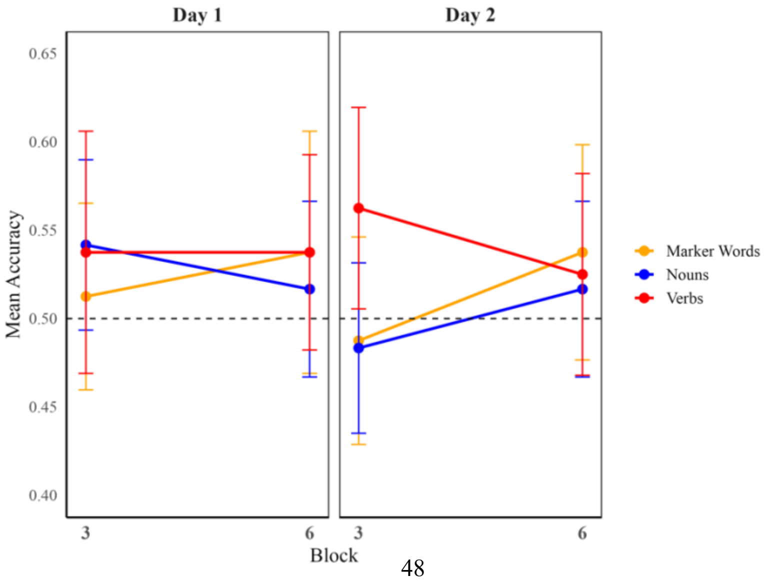
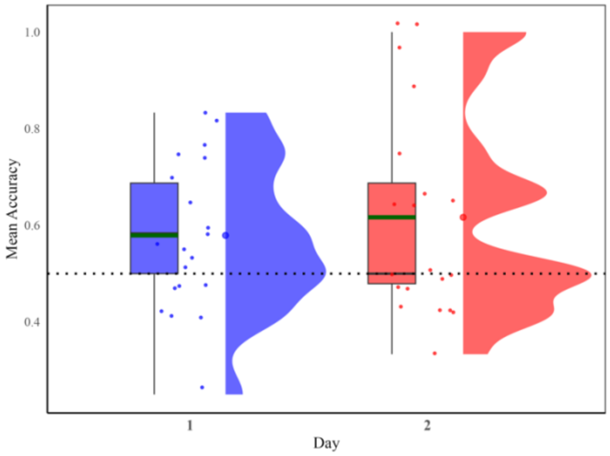


Figure 2.4 Mean accuracy performance by syntax test trials in CSL task for days 1 and 2. The box indicates the median (horizontal line) and interquartile range, with dots indicating individuals' accuracy.



Discussion

The current study explored what features of an artificial language children aged 8-9 years old can acquire through CSL. Our results indicated, for the first time, that when acquiring a novel language comprising previously unknown syntax and vocabulary, the conjunction of sentences and scenes to which they refer was navigable by children in order to effectively acquire the syntax (i.e., word order knowledge). However, in contrast there was evidence that children had only just begun to make a start on learning individual vocabulary items. Whereas overall performance on training trials (which required the coordination of words in the sentences and referents in the scenes) was above chance, accuracies for the individual vocabulary types (i.e., nouns, verbs and case markers) were not found to be significantly above chance. This difference likely reflects the distinct demands of the two tasks: the training trials required sentence-level matching between an utterance and two scenes, whereas the vocabulary test trials required more precise item-level mappings between individual word forms and their referents.

When referential ambiguity is minimised, i.e., restricted to only noun-object and verb-action mappings, children are able to learn vocabulary with relative ease (Childers et al., 2023; Scott & Fisher, 2012; Smith & Yu, 2008; Vlach & DeBrock, 2017). Furthermore, when vocabulary is pre-trained, children can also respond to the syntax of the language (Spit et al., 2022). However, in our study, when the learning environment mimicked the natural language situation by incorporating greater syntactic complexity and referential ambiguity, we found that acquiring the vocabulary through cross-situational statistics was a challenge for children. In previous studies with adults, acquiring both the syntax (word order) and the vocabulary simultaneously during learning was found to be possible (Monaghan et al., 2021; Rebuschat et al., 2021; Walker et al., 2020). In order to ascertain whether there were quantitative differences in learning between adults and children, we compared the children's performance in the current study to the adult "implicit" condition from Monaghan et al. (2021). This condition was an adult study that was qualitatively similar to the current study, though note that the language was somewhat more complicated because it contained also adjectives and more vocabulary items.

Using equivalence tests, we found that there was a significant difference in learning for verbs (adults mean accuracy = 0.82 (*SD* = 0.22), *t*(36.4) = 4.16, *p* < .001), but not nouns (adults mean accuracy = 0.60 (*SD* = 0.16), *t*(32.54) = 1.45, *p* = .157) and marker words (adults mean accuracy = 0.46 (*SD* = 0.12), *t*(23.73) = -1.23, *p* = .232. There was also a significant difference in learning for syntax (adults mean accuracy = 0.85 (*SD* = 0.16), *t*(33.02) = 4.07, *p* <.001). Thus, adults were able to learn both vocabulary and syntax more readily than children, with evidence of learning both simultaneously. Children, however, showed evidence for learning syntax, but no evidence for learning of vocabulary. It must be noted that this null effect for vocabulary is not the same as providing evidence that children did *not* learn vocabulary learning, however, there is a difference between adult and child learning in that adults could learn verbs to a level equivalent to that of syntax, whereas there was considerable disparity for children. What might result in this possible child-adult distinction in cross-situational learning?

One possible explanation might lie with the different memory system required for language learning to proceed. Neurobiological evidence showed that procedural memory, which relates more closely to processing of syntactic regularities, tends to mature in early childhood (Pili-Moss, 2021). Declarative memory which supports vocabulary and grammar learning tends to reach maturity later in adolescence (Gomez & Edgin, 2016; Morgan-Short et al., 2014; Ullman, 2004). This is consistent with the current study as the syntactic regularity (i.e., word order) was the first, and only, language property learned to a significant level by the children.

The results suggest that, when neither syntax nor vocabulary are known to the child, knowledge about syntax, in terms of word order constraints, quickly becomes available to the learner. This provides an indication for how syntactic information may become available to the child to help scaffold and support vocabulary acquisition. Syntactic bootstrapping is thus available to children to acquire vocabulary items whose meaning can be in part dependent upon their syntactic role (Babineau et al., 2024; Gleitman, 1990; Höhle & Weissenborn, 2001; Monaghan et al., 2023).

Limitations and further directions

The current study is the first to investigate children's simultaneous acquisition of vocabulary and grammar through CSL. However, the sample size in this study is relatively small (n=20), and the age range is relatively constrained (8-9 years), which might limit the generalizability of our findings as it may not fully capture the variability in CSL performance across a broader population of children. Extending this study to a larger age range may provide us with fuller insight into how learning vocabulary and learning syntax inter-relate in children’s language development.

Our study also did not fully encapsulate the individual differences that were driving children’s performance. Note that in Figures 2.2 and 2.4 there is a large range in accuracy for individual children, indicating that whereas some children were able to acquire both vocabulary and syntax, other children failed to gain a foothold in learning the language at all. Future research that includes cognitive skill measurements (in particular, procedural memory and declarative memory) will be a useful extension to determine how memory systems relate to different aspects of language learning, when learning a language immersively. Existing adult data using a similar paradigm (Walker et al., 2020) indicated that learning vocabulary and syntax simultaneously may not relate neatly to abilities in declarative and procedural memory systems. Walker et al. (2020) found that learning all aspects of a language from cross-situational statistics (both vocabulary and syntax) related to procedural memory ability early in training, and, as learning advanced, declarative memory became more important as a predictor of syntax and verb learning accuracy. Ferman and Karni (2010) found that language learning associated with procedural skills also improved slightly with age from 8 to 12 years, to adulthood. Hence, there may be crucial stages of learning as the interactions between syntax and vocabulary emerge through exposure, each relating to different memory systems at different stages of learning, and children's mastery of vocabulary, and syntax, may well require the later-developing declarative memory system.

As revealed in Isbilen & Christiansen (2022), the effect size of SL in child population is significantly affected by test types, with processing-based tests yielding a larger effect size than reflection-based tests, and production and recall tests yielding larger effect sizes than forced-choice tests. Furthermore, testing implicit knowledge, such as syntax, is more appropriately tested through implicit, online measures, whereas testing explicit knowledge, such as vocabulary, can be measured effectively using explicit tests (Isbilen et al., 2022). The current study used such an explicit measure, requiring a forced choice. A blend of online and offline measures, then, would be a valuable extension of the current study in order to explore in greater detail the quality and quantity of children's language learning.

A further advantage of online tasks, such as eye-tracking, would enable us to determine children's attention to different elements of the scenes during learning. One possibility for children's greater learning of syntax than vocabulary may have been due to children reducing attention to the visual scene, and focusing more processing on the auditory stimuli. It is the case that the syntax test could be solved without requiring processing of the scene at all, as it tested sensitivity to the word order within sentences. However, our task was designed to keep children's focus on the screen, by providing a visual reward of a coin for correct answers during training and requiring a response for each trial, which could only be accomplished by processing the relations among auditory sentences and visual scenes. Eye tracking would enable us to confirm how children use the visual information in conjunction with the auditory input. Note, however, that performance did not change from day 1 to day 2 for either the overall training trials, nor for the syntax tests, and so there were no evident quantitative changes in children's performance over the task. Furthermore, there was above chance performance on the training trials, though at a level substantially below that of the syntax trials. Thus, word order information was available and processed more readily by children than the vocabulary information, and this highlights that potential information for syntactic bootstrapping is available to help support subsequent vocabulary acquisition. The benefit of the current paradigm is that it can offer opportunities for investigating all these issues, including effects of type of task, as well as environmental exposure, cognitive effects, and language background effects on children's early language development.

Previous studies of cross-situational word learning have established that children can use these statistics to acquire new vocabulary (e.g., Vlach & DeBrock, 2017). We are not claiming that children are unable to do this, only that, from input that involves novel syntax and vocabulary, children seem to pick up on the syntax more readily than the vocabulary. The lower levels of learning of vocabulary observed in our study compared to previous cross-situational studies with children likely rests with the greater complexity entailed by multiple words relating to multicomponent scenes. For instance, in previous simpler cross-situational studies, all objects and all words tend to be present in each learning situation. Then, the conditional probability of an object appearing with a word is 1, and the conditional probability of another object appearing with a word is 1/(n-1) where n = number of word/object pairings. So, for learning 6 words, the difference in frequency of cross-situational mappings is 1 versus 1/5 for intended versus unintended pairings. In our paradigm, however, as there are multiple words and two possible scenes occurring in each trial, the difference in frequency of mappings between intended and unintended pairings is smaller.

Table 2.4 shows the conditional probabilities for mappings, for nouns and for verbs. Adapting our paradigm to reduce the scene and sentence complexity would likely result in more successful word learning. We contend that with this simpler sentence structure, children would still be more successful at acquiring the word order, because of the earlier maturation of their procedural memory systems. This, however, is a matter for future investigation.

Table 2.4 Conditional probabilities of noun-object and verb-action pairings in our study, with probabilities also shown for a standard cross-situational learning study for 6 noun-object pairings.

Conditional	Our study's probability	e.g., Vlach & DeBrock (2017) 2 words x 2 objects, 12 pairings probability
p(noun | target object)	0.5	1
p(noun | foil object)	0.3	1/12
p(target object | noun)	1	1
p(foil object | noun)	0.3	1/11
P (verb | target action)	0.5	
P (verb | foil action)	0.17	
P (target action | verb)	1	
P (foil action | verb)	0.33	

In conclusion, we showed that children aged 8 to 9 were able to learn syntax (i.e., word order) through tracking the co-occurrence of target sentences and referential scenes with no need of prior vocabulary knowledge. However, there was no evidence that cross-situational statistics alone were sufficient to support robust simultaneous early-stage acquisition of both vocabulary and syntax in children at this age, as it has been shown to do in adults.

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Supplementary materials

Appendix A

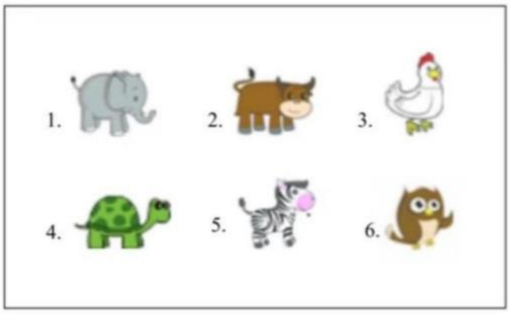
Pseudoword lexicon used in the experiment (adapted from Monaghan and Mattock, 2012).

The six bisyllabic content words used as nouns were: *barget, limeber, jeelow, goorshell, nellby, bimdah.* The four bisyllabic content words used as verbs were *dingep, fisslin, rakken, makkot*. The two monosyllabic words used as grammatical role markers (subject/object) were *tha* and *noo*.

Appendix B

Animal characters used in training and testing blocks.

Animal characters occurred across the experiment with equal frequency.



Appendix C Supplementary Tables

Table S2-1 Mixed-effects model results for noun test trials. Null model contains only a random intercept for item. Model 1 includes block as a fixed effect. Model 2 includes day as a fixed effect.

	Predictor	Estimate	*SD* Error	*Z*	*p*
null model	Intercept	0.059	0.103	0.572	0.567
model 1	Intercept	0.034	0.327	0.103	0.918
	block	0.006	0.069	0.082	0.934
model 2	Intercept	0.237	0.325	0.728	0.467
	day	-0.118	0.206	-0.576	0.565

Best-fitting model specification (null model): Number of observations: 480, Item, 24. AIC = 668.3, BIC = 676.7, log-likelihood = -332.2. R syntax: glmer(accuracy ~ 1 + (1 | item), data = noun_test_data, family = "binomial").

Table S2-2 Mixed-effects model results for verb test trials. Null model contains only a random intercept for participant. Model 1 includes block as a fixed effect. Model 2 includes day as a fixed effect.

	Predictor	Estimate	*SD* Error	*Z*	*p*
null model	Intercept	0.170	0.147	1.151	0.25
model 1	Intercept	0.288	0.374	0.769	0.442
	block	-0.026	0.076	-0.344	0.731
model 2	Intercept	0.130	0.374	0.348	0.728
	day	0.026	0.229	0.115	0.909

Best-fitting model specification (null model): Number of observations: 320, Participants: 20. AIC = 442.6, BIC = 450.2, log-likelihood = -219.3. R syntax: glmer(accuracy ~ 1 + (1 | participant), data = verb_test_data, family = "binomial").

Table S2-3 Mixed-effects model results for marker test trials. Null model contains only random intercepts for participant and item. Model 1 includes block as a fixed effect. Model 2 includes day as a fixed effect.

	Predictor	Estimate	*SD* Error	*Z*	*p*
null model	Intercept	0.078	0.150	0.521	0.602
model 1	Intercept	-0.155	0.464	-0.335	0.738
	block	0.052	0.098	0.530	0.596
model 2	Intercept	0.154	0.468	0.330	0.741
	day	-0.051	0.296	-0.172	0.863

Best-fitting model specification (null model): Number of observations: 320, Participants: 20, Item: 16. AIC = 446.7, BIC = 458.0, log-likelihood = -220.3. R syntax: glmer(accuracy ~ 1 + (1 | participant) + (1 | item), data = marker_test_data, family = "binomial").

Appendix D Analysis Omitting the Two Urdu Speakers

Table S2-4 Descriptive statistics for training trials in CSL task in the six blocks on two days. Showing t-test values compared against chance performance.

	Block											
	Day 1						Day 2					
	1	2	3	4	5	6	1	2	3	4	5	6
M	0.57	0.52	0.56	0.56	0.59	0.58	0.50	0.56	0.52	0.44	0.56	0.53
SD	0.14	0.14	0.13	0.11	0.16	0.14	0.17	0.15	0.19	0.21	0.18	0.16
t	1.90	0.72	1.84	2.22	2.37	2.46	-0.12	1.76	0.51	-1.13	1.30	0.75
p	0.074	0.482	0.083	0.040	0.030	0.025	0.907	0.097	0.618	0.274	0.211	0.462
d	0.45	0.17	0.43	0.52	0.56	0.58	-0.03	0.41	0.12	-0.27	0.31	0.18

Table S2-5 Descriptive statistics for vocabulary test trials in CSL task in block 3 and 6 on days 1 and 2. Showing t-test values compared against chance performance.

		Blocks			
		Day 1		Day 2	
		3	6	3	6
Nouns	*M*	0.57	0.51	0.47	0.52
	SD	0.20	0.22	0.22	0.23
	t	1.57	0.18	-0.53	0.34
	p	0.134	0.859	0.604	0.734
	d	0.37	0.04	-0.12	0.08
Verbs	*M*	0.53	0.54	0.57	0.56
	SD	0.32	0.26	0.27	0.25
	t	0.37	0.68	1.10	0.94
	p	0.717	0.507	0.288	0.361
	d	0.09	0.16	0.26	0.22
Markers	*M*	0.50	0.56	0.46	0.54
	SD	0.24	0.29	0.25	0.27
	t	0.00	0.81	-0.72	0.64
	p	1.000	0.430	0.483	0.528
	d	0.00	0.19	-0.17	0.15

Table S2-6 Descriptive statistics for syntax test trials in CSL task on days 1 and 2. Showing t-test values compared against chance performance.

	Day 1	Day 2
M	0.58	0.63
SD	0.16	0.22
t	2.19	2.46

p	0.043	0.025
d	0.52	0.58

3 Submitted paper 2: The role of age and instruction in statistical learning of vocabulary and grammar

Page number: 65-118

Abstract

It is generally assumed that children and adults learn language through fundamentally different mechanisms: children predominantly rely on implicit learning, while adults utilize more explicit strategies (Lichtman, 2016). However, little is known about when and how learners begin to benefit from explicit instruction in the course of language development. Addressing this gap, the present study responds to DeKeyser's (2012, 2013) call to investigate age-treatment interactions (ATIs) under highly controlled experimental conditions. Using a cross-situational learning (CSL) paradigm, we trained 150 learners aged 8 to 13 to acquire both vocabulary and grammar in a complex artificial language under two instructional conditions: implicit and explicit. The results revealed that implicit grammatical information becomes amenable to explicit instruction only from the age of 12. These findings shed light on the developmental stage at which explicit instruction may become beneficial for children's non-native language (L2) learning.

Keywords: Age-treatment interaction, implicit instruction, explicit instruction, statistical learning, cross-situational learning, child second language acquisition

Introduction

Children acquire their first language(s) without substantial explicit instruction (Lichtman, 2016). Through extended exposure to language and interaction with caregivers and other speakers, children gradually learn which words map onto which features of the environment (e.g., Smith & Yu, 2008), and how words relate to one another within syntactic structures (e.g., Gleitman, 1990). It is widely assumed that this process relies largely on implicit learning (Rebuschat, 2022; Williams & Rebuschat, 2023). In contrast, classroom-based foreign language learning typically involves a significant degree of explicit instruction (R. Ellis, 2009). This raises a critical question: How does the shift from immersive, implicit exposure to explicit instruction about language affect children's L2 learning?

In this study, we investigated how explicit instruction interacts with children's implicit statistical learning of language under conditions designed to approximate immersive learning. We examined how both CSL ability and instruction influence the acquisition of vocabulary and grammar in a novel language, and how age affects children's ability to integrate metalinguistic knowledge provided through explicit instruction with the structural properties of the language. The findings clarify when children are most responsive to explicit instruction and which aspects of L2 learning (vocabulary or grammar) are more amenable to instructional support.

Native language learning

In acquiring their native language(s), children respond to the statistical properties of the linguistic environment to learn multiple levels of language structure (Ambridge et al., 2015). This sensitivity to statistical regularities, which emerges through exposure, supports the acquisition[4] of various linguistic components: the sound structure of words

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[4] For the purposes of this study, the terms language learning and language acquisition were used interchangeably. Although some traditions reserve learning for formal, instructional contexts and acquisition for naturalistic or implicit development, this distinction is not strictly upheld here. Instead, both terms refer to the process of gaining knowledge of a L2, whether through exposure, instruction, or interaction.

(e.g., Ge et al., 2025b; Johnson & Tyler, 2010; Teinonen et al., 2009), the mappings between words and potential referents in the environment (e.g., Monaghan et al., 2019; Smith & Yu, 2008), grammatical word categories (Aslin & Newport, 2014), and syntactic structure (Gómez & Gerken, 1999; Walker et al., 2020).

Learning word-referent mappings can be supported by accumulating distributed statistics across multiple learning experiences (e.g., Monaghan et al., 2021; Roembke et al., 2023; Yu & Smith, 2007), referred to as cross-situational learning (CSL). There is substantial evidence that CSL supports word learning for various lexical classes across developmental stages. For example, infants aged 12 to 14 months (Smith & Yu, 2008), children aged 2 to 8 years (e.g., Bunce & Scott, 2017; Crespo & Kaushanskaya, 2021; Hu, 2017; Suanda et al., 2014; Vlach & DeBrock, 2017), as well as younger and older adults (e.g., Yu & Smith, 2007; Ge et al., 2025a) can learn nouns through CSL. There is also evidence that cross-situational statistics may support word-referent mapping for grammatical categories beyond nouns (e.g., adjectives: Akhtar & Montague, 2007; verbs: Scott & Fisher, 2012).

However, where the field remains divided, is how far CSL extends beyond basic word learning. Many CSL studies simplify the complexity of natural language acquisition by using novel words from the same grammatical category. This reduction in ambiguity and variation makes the task more tractable but less representative of the challenges faced during real-world language learning. Expanding artificial languages to include multiple grammatical categories increases the complexity of learning tasks, while also providing opportunities to investigate how vocabulary and grammar learning interact (Gleitman, 1990). Previous studies that examined the learning of both vocabulary and grammar often separated the two processes, for instance, by first training participants on the vocabulary before introducing new syntactic structures, or by using familiar words within novel grammatical frames (e.g., Amato & MacDonald, 2010; Friederici et al., 2002; Hu, 2017; Morgan-Short et al., 2014; Ruiz et al., 2018; Spit et al., 2022). For example, Spit et al. (2022) trained 50 kindergartners (Mean age = 5 years, 5 months) on an artificial language incorporating proper names, verbs, grammatical number markers, conjunctions, and nouns. The children were initially trained on vocabulary before being exposed to scenes and sentences. Based on CSL principles, the children demonstrated sensitivity to syntax, particularly word order, and successfully learned the function of the number marker. Thus, it remains unresolved in the field of CSL studies that whether vocabulary and grammar can be learned simultaneously through tracking input statistics.

Most recently, there is evidence that adults can learn both vocabulary and syntax simultaneously from cross-situational statistics in immersive artificial language contexts (Monaghan et al., 2015). Rebuschat et al. (2021) trained adults on an artificial language comprising transitive sentences of nouns, verbs, adjectives, and case marker words and dynamic visual scenes to which they referred. Participants could acquire nouns, verbs, case markers, and syntactic knowledge, including sensitivity to word order constraints, through exposure to cross-situational statistics. However, much less is known about the extent to which children can simultaneously learn different language features through CSL. One exception is Savarino et al. (2025), who tested school-aged children's simultaneous learning of vocabulary and morphophonological rules. In this study, 7- to 11-year-old children showed capability of establishing noun-object mappings through tracking cross-situational statistics, but found it difficult to detect the morphophonological rules (the two markers indicating animacy).

The role of explicit and implicit instruction in cross-situational learning

The CSL paradigm reflects the immersive language experience of learners, in that no explicit information about the language is provided, and learning occurs through exposure. However, two theoretical accounts have been proposed to explain the mechanisms underlying cross-situational statistical learning: Hypothesis Testing and Associative Learning. The former assumes that learners form a hypothesis about a specific word-object mapping, which is then either confirmed or rejected based on subsequent co-occurrences. This process involves strategic reasoning and typically requires conscious awareness (Kachergis et al., 2014). In contrast, the latter (e.g., McMurray et al., 2012; Yu & Smith, 2012) posits that learning emerges gradually through accumulated associative strength with less reliance on explicit knowledge and conscious awareness (Roembke et al., 2023). Thus, these two accounts diverge in their assumptions about the role of awareness and explicit information.

This theoretical distinction therefore leads to a question: what is the interface between CSL and explicit information from sources such as instruction? Adult studies suggest a potential positive role of explicit learning during statistical learning tasks more broadly and in cross-situational tasks more specifically (Hamrick & Rebuschat, 2012; Kachergis et al., 2014). In these studies, learning of individual word-referent mappings was promoted when participants' attention was directly drawn to learning certain targets. For instance, Monaghan et al. (2019) showed that explicit instruction about marker words improved adults' learning of nouns and verbs in the paradigm where (artificial) intransitive sentences appeared with animated scenes. By contrast, Monaghan et al. (2021) found no instruction effect when sentences became more complex (complex transitive sentences).Thus, these mixed findings can suggest that under some circumstances, explicit instruction can assist in promoting cross-situational word learning, and this may be more powerful when information pointing to grammatical category information may be available. They also indicate that the existing evidence regarding the effectiveness of explicit instruction is context-dependent and thus warrants further investigation.

Explicit instruction in children's language learning

As children transition from acquiring their first language(s) to learning additional languages, there is a marked shift from implicit learning through natural exposure to more explicit, formal instruction (e.g., in classroom settings). This shift raises important practical and theoretical questions about the role of explicit instruction in language acquisition. Practically, it concerns how best to support children's learning in educational contexts; theoretically, it speaks to the fundamental issue of how explicit instruction interacts with implicit statistical learning processes. Understanding this interface is crucial for informing both pedagogical approaches and models of language development.

Children are often assumed to be primarily implicit language learners (DeKeyser, 2000; R. Ellis, 2005, 2009; Lichtman, 2016), meaning that their learning typically occurs without conscious awareness of "the statistical properties and the degree of regularity in the linguistic stimuli to which (s)he is exposed" (Hulstijn, 2015, p. 30). However, Lichtman (2013) argued that this assumption may reflect differences in learning environments rather than inherent cognitive limits, as there is little direct evidence comparing children's implicit and explicit L2 learning capacities. Older learners typically receive more explicit instruction, whereas younger learners are more often exposed to whole-language activities such as songs and stories. Thus, the shift from implicit to explicit learning may partly reflect environmental rather than developmental factors, which highlights the need to integrate both the internal factors (e.g., age and memory capacities) and external factors (e.g., explicit instruction and feedback) in understanding the developmental shift in L2 acquisition.

The current study adopts the notion that instruction is a deliberate intervention that modifies learning mechanisms (e.g., attention) and/or the conditions under which learning takes place by directing attention to specific features or structures in the input (de Graaff & Housen, 2009; Ruiz et al., 2025). In particular, explicit instruction, which provides metalinguistic explanations or encourages rule discovery, may enhance awareness by prompting learners to notice linguistic regularities, thereby facilitating language acquisition (DeKeyser, 1995; Ruiz et al., 2025; Schmidt, 1990). The current study therefore examines the extent to which children in implicit versus explicit conditions developed metalinguistic awareness of syntactic rule of the target artificial language, and whether such awareness predicted more successful learning.

Despite broad consensus that instruction supports L2 development (Goo et al., 2015; Norris & Ortega, 2000), children under 12 remain underrepresented in instructional studies, which have largely focused on adolescents and adults (Roehr-Brackin, 2024). The several recent exceptions, however, have demonstrated that explicit instruction can positively impact both vocabulary (Yeung et al., 2020; Yousefi & Biria, 2018) and grammar learning (Pawlak, 2021) in children. For example, Lichtman (2016) trained children aged 5 to 7 years, as well as adult participants, on an artificial language composed of nouns, verbs, and gender determiners. In the explicit instruction condition, participants also received direct instruction on the language's word order rule (VSO). The results showed that both the implicit and explicit groups were able to learn the structure of the artificial language. However, only the children in the explicit instruction group were able to articulate explicit knowledge of the word order rule, while adults, regardless of instructional condition, were able to develop this knowledge.

Spit et al. (2022b) investigated the extent to which kindergartners benefit from explicit instruction when learning grammatical markers in an artificial language. Children were first trained on the vocabulary and then exposed to the full language, in which sentences were paired with pictures depicting their meanings. Those in the explicit instruction group were explicitly taught the meaning of grammatical markers indicating noun number. While no significant effect of instruction was found in terms of accuracy in selecting the picture that matched the sentence, differences emerged in the eye-tracking data: children in the instruction group showed earlier predictive eye movements toward the target image. These findings suggest that children are capable of responding effectively to explicit instruction. However, what remains unclear is whether explicit instruction can support children's ability to integrate metalinguistic knowledge with input statistics in contexts where vocabulary and grammar must be learned simultaneously, a challenge that closely mirrors real-world immersion settings (e.g., DeKeyser & Larson-Hall, 2005; Paradis, 2009).

Some studies have shown that older children demonstrate advantages in L2 learning (e.g., Snow & Hoefnagel-Höhle, 1978; Snedeker et al., 2012), both in laboratory settings and in real-life immersion contexts, often displaying a steeper initial learning trajectory (e.g., Jia & Fuse, 2007). Given that age captures a range of co-developing factors, such as cognitive maturation, literacy, schooling, and learning experience (Birdsong, 2018; Flege, 2019; Unsworth, 2016), it is plausible that older children gain an advantage through, for example, the matured memory capacities, their ability to engage in explicit learning strategies and transfer their first language literacy skills (Hartshorne, 2022; Lightbown, 2003). These suggest that the effectiveness of explicit instruction may depend on age. In other words, the interaction between instructional environment and age is not incidental but central to understanding children's L2 learning. This possible interplay between learning environments and age aligns with DeKeyser's (2012) call for further investigation into age-treatment interactions. However, as this is a relatively new area of research, direct empirical evidence testing these interactions remains limited (DeKeyser, 2012). DeKeyser (2013) further emphasized the need for research designs with tight control over the quality and quantity of input, such as those using artificial but complex languages. The present study takes up this challenge by employing a rich, yet highly controlled, artificial language to investigate how age-treatment interactions influence the acquisition of both vocabulary and grammar within a CSL learning paradigm.

Middle childhood through adolescence is characterized by significant developmental changes shaped by not only the maturation of cognitive capacities (e.g., working memory) but also the increased exposure to different learning environments (e.g., formal instruction). Nevertheless, this particular population remains underrepresented in both L2 acquisition and CSL studies, largely due to the practical constraints (e.g., young children are less accessible for research participation than university students; Roehr-Brackin, 2024). A recent meta-analysis of statistical learning studies highlights this gap: out of 175 studies on auditory statistical learning of language, 105 focused on adults (mean age = 25.15 years) and 46 on infants (mean age = 12.33 months), while only 24 studies included young children, with a mean age of 7.83 years (Isbilen & Christiansen, 2022). Children aged approximately 2 to 7 years are typically considered distinct from older children in the context of L2 learning, as the development of literacy and cognitive skills in older children contributes to the emergence of metalinguistic awareness and more advanced problem-solving abilities (Philp, 2008). This underrepresentation leaves unresolved the key question of when, and under what conditions, explicit instruction begins to meaningfully support children's L2 learning. Therefore, studies focusing on this certain population can advance our understanding of the developmental ambiguity in children's ability to integrate metalinguistic knowledge into the navigation of statistical input. Considering this, our study focused on children aged 8 to 13 years, both to address the scarcity of research in this specific age range and to span the developmental window during which a critical period for language learning has been proposed (Hartshorne et al., 2018). This age range also marks a stage where the maturation of metacognitive abilities may begin to qualitatively influence language learning processes.

The present study

In this study, we investigated the interplay between age and explicit instruction on language structure in school-aged children's and adolescents' cross-situational statistical learning of vocabulary and grammar. We employed a CSL paradigm designed to simulate an immersive language environment, with participants either receiving explicit instruction about the language's structure prior to the learning phase or engaging in the learning phase without such explicit instruction.

Conceptually, this study was designed to address key gaps at the intersection of CSL and second language acquisition (SLA), particularly regarding when and how, across middle childhood through early adolescence, explicit knowledge gained through instruction begins to influence L2 learning. Methodologically, through adopting a laboratory-based experimental paradigm, the study enables the examination of the widely debated topics (i.e., age effect and role of explicit instruction) in SLA research under highly controlled environments.

The study addressed the following research questions.

RQ1: How does cross-situational learning of vocabulary and grammar change across children's development?

We predicted that CSL would improve with age, given that developmental increases in attention and memory (Vlach & DeBrock, 2017), as well as in statistical learning abilities (Arciuli & Simpson, 2011), are well-documented. However, we anticipated that this improvement might differ across linguistic features. Specifically, we expected that vocabulary learning would show more age-related variation than syntax learning (e.g., sensitivity to word order), as procedural memory, which is typically associated with syntactic learning, matures earlier than declarative memory, which in turn supports vocabulary acquisition (Ullman, 2004).

RQ2: To what extent does explicit instruction about the syntactic structure of the language affect children's learning of L2 vocabulary and grammar through immersive cross-situational learning, and how does this impact vary across different age groups?

We predicted that explicit instruction would enhance learning outcomes (Lichtman, 2012), particularly for the aspects of the language that are explicitly taught, in this case, word order. However, given the interactive nature of vocabulary and grammar learning (e.g., Gleitman & Gleitman, 1992), we also considered the possibility of spill-over effects, whereby instruction on grammar might indirectly support vocabulary acquisition. Furthermore, we expected that the effectiveness of explicit instruction might vary with age, as older children may be more capable of benefiting from metalinguistic information due to their developing cognitive and literacy skills.

RQ3: To what extent do children develop explicit knowledge of the language, and how is this related to instruction and learning outcomes?

We examined whether children who received explicit instruction about the syntactic structure of the language were more likely to verbalize their syntactic knowledge. If so, we aimed to determine whether awareness of syntactic information had an effect on overall L2 learning. We predicted that explicit awareness would be more common among children who received instruction and who performed well on the task. Furthermore, we expected this awareness to be specifically related to the instructed features of the language, namely the verb-final word order and verb meanings rather than to vocabulary or other grammatical elements that were not explicitly taught.

Methods

Participants

One hundred and fifty children aged 8 to 13 years participated in the study, with 50 participants in each of three age groups: 8-9, 10-11, and 12-13 years. Participants were recruited through primary school teachers from two schools in Northern China. All were native speakers of Mandarin who had been learning English as a second language for one to three years and had no prior experience with verb-final languages. Participants were pseudo-randomly assigned[5] to one of two instruction conditions: an implicit group or an explicit group. Power analyses, based on the effect size reported in Monaghan et al. (2021)[6], indicated that a sample size of 25 participants per condition per age group would provide a statistical power of 0.88 to detect learning effects in the artificial language task. This resulted in six experimental groups, summarized in Table 3.1.

Table 3.1 Number of participants by instruction type and age group.

Instruction Type	Age Group (Years)	n
Implicit	8–9	25
	10–11	25
	12–13	26
Explicit	8–9	25
	10–11	25
	12–13	24

Informed consent was obtained from both parents and children prior to participation. The study was approved by the Ethics Review Panel of the Faculty of Arts and Social Sciences at Lancaster University and was preregistered on the Open Science Framework (OSF, please follow link).

Materials

Artificial language

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[5] The assignment was not fully randomized. For logistical reasons, participants were grouped by their schoolteacher prior to the lab sessions. To the best of our knowledge, there was no intentional grouping based on ability or background. Group sizes and age distributions were balanced across conditions, but individual-level randomization was not implemented.

[6] We tested a medium-small effect size, slightly smaller than in Monaghan et al. (2021), with accuracy estimates in our simulation-based power analysis of 0.75 (explicit) and 0.60 (implicit), assuming lower learning success for younger children than adult participants. With 25 participants per condition per age group, this yielded an estimated power of 0.88 to detect a medium-sized effect.

Vocabulary. The artificial language used in this study was adapted from Rebuschat et al. (2021) and consisted of 12 pseudowords: 10 bisyllabic content words (comprising six nouns and four verbs) and two monosyllabic grammatical case markers, which indicated whether the preceding noun referred to the subject or the object of the sentence (for the full list of stimuli, see Appendix A). In this artificial language, a noun followed by a post-nominal case marker formed a noun phrase (NP). Although learning of markers was tested in vocabulary test trials and therefore analyzed alongside vocabulary items in the current study, these markers functioned as morphosyntactic cues that signal grammatical relations within the sentence. All words were read and recorded individually by a female native speaker of English in a monotone voice.

Grammar. The word order of the artificial language was modeled on Japanese grammar, featuring a verb-final structure with variable word order. Specifically, the positions of the subject and object noun phrases (NPs) were flexible, but the verb always appeared at the end of the sentence. Thus, sentences followed either a subject–object–verb (SOV) or object–subject–verb (OSV) word order.

A total of 72 unique sentences were generated and distributed across six training blocks, with each block containing 12 sentences. Sentence stimuli were presented using E-Prime, with a 250 ms pause between each word. To assess participants' sensitivity to word order, we also constructed six ungrammatical word sequences that violated the verb-final syntax of the artificial language by altering the verb's position: three followed VSO or VOS word orders, and three followed SVO or OVS word orders. In addition, six novel grammatical sentences that conformed to the language's syntax but were not used during training were created. These grammatical and ungrammatical test sentences were used in the post-training phase to evaluate learners' syntactic knowledge.

An example sentence is provided in (1).

(1) cheelow tha bimdah noo dingep.
Animal$_1$ SUBJECT Animal$_2$ OBJECT pushes.
'Animal$_1$ pushes animal$_2$'.

Half of the sentences followed SOV word order, and the other half followed OSV. Vocabulary frequency, subject–object assignments, and word order were balanced across the six training blocks to ensure equal distribution of linguistic features.

Visual referents. Six cartoon animals (cow, chicken, turtle, zebra, elephant, owl) served as the referents for the nouns in the artificial language (for images, see Appendix B). These animal characters were shown performing one of four actions (hiding, jumping, lifting, pushing) which served as the referents for the verbs in the animated scenes. The mappings between the pseudowords and the animal characters or actions were randomly assigned across several versions of the study to minimize potential biases arising from systematic associations between specific speech sounds and referents (Rebuschat et al., 2021).

Procedure

Data collection took place at the children's schools using two experimental platforms: E-Prime 2.0 was used for the 8-9 age group, and Gorilla was used for the 10-11 and 12-13 age groups. Children were invited to a designated classroom equipped with laptops or desktop computers and noise-cancelling headphones. Testing was conducted in groups, with the number of participants per session varying based on the school timetable (up to a maximum of 25 children at a time). Importantly, children within each experimental condition and age group were always tested together.

Cross-situational learning task

Participants were first informed that they would be learning an alien language spoken by "friends from a distant planet" and were instructed to make choices as quickly as possible based on their intuition during the experiment. Children assigned to the explicit instruction condition then received information about the verb-final word order in the alien language. The instruction, translated from Chinese, was as follows: "In Chinese, if we want to say 'The dog pushes the pig.', we say the animal who does this action first, the dog in this case; and then we say the action word, pushes in this case, and we finally say the animal who is being pushed, the pig in this case. But in the alien language, aliens say the two animals first, and the action word always goes to the end of the sentence: the dog the pig pushes, or the pig the dog pushes. Remember, the action word is always at the end of the sentence. But the two animals' positions varied". While listening to this instruction, children were shown an image of the animal characters (a dog pushing a pig) to support comprehension. Participants' understanding and memory of the grammatical rule were checked right after the instruction, by asking them to repeat the rule. This oral check was judged directly by the researcher administering the task, and once they could accurately repeat the rule, they proceeded to the CSL task. This procedure was used as a brief comprehension check rather than a formal dependent measure; the number of repetitions required was not systematically recorded, and inter-rater reliability was therefore not assessed.

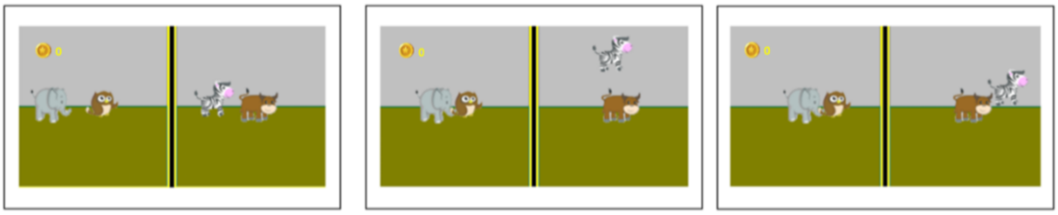
Each trial in the CSL task presented two dynamic scenes side by side on a computer screen. Each scene featured two cartoon animal characters performing different actions. While the scenes were displayed, children heard a sentence in the artificial language that corresponded to one of the two scenes. The audio was played only once, and children could respond only after the sentence had finished playing. The animations continued looping until the child provided a response by pressing a key on the keyboard corresponding to their selected scene. The experiment then proceeded immediately to the next trial. Children were instructed to match the sentence to the scene it described as quickly and accurately as possible. Correct responses were followed by an increase in an on-screen coin counter accompanied by a coin sound effect, which was included to maintain engagement during the task. Figure 3.1 illustrates an example of a training trial.

Before the training began, children completed two practice trials designed to familiarize them with the task. In each practice trial, they observed two animated scenes while listening to a sentence in the artificial language, which matched one of the scenes. The animal characters and pseudowords used in the practice trials were not included in the main study.

Training trials The CSL task consisted of six training blocks, followed by a grammaticality judgment task in a final test block (Block 7). Blocks 1, 2, 4, and 5 included only training trials, while Blocks 3 and 6 interleaved training and vocabulary testing trials to assess learning progress throughout the task. There were 72 training trials in total, distributed evenly across the six training blocks (12 trials per block). Each trial presented two animated scenes that varied in the animal characters, the actions being performed, and the assignment of agent and patient roles to the animals.

Vocabulary test trials Vocabulary test trials were used to assess participants' learning of nouns, verbs, and grammatical markers, and were interspersed within training Blocks 3 and 6. To minimize participants' awareness of being tested, these test trials were visually identical to training trials from the learner's perspective. In each trial, participants listened to a sentence and viewed two animated scenes, with the target and distractor scenes differing only in the feature being tested. In noun test trials, the scenes differed in one of the animal characters; in verb test trials, the distinction lay in the action being performed; and in marker test trials, the scenes differed in the assignment of agent and patient roles, achieved by reversing the roles of the two animal characters.

Figure 3.1 Example of a training trial. Screenshots were captured at the beginning, middle, and end of the trial. In the left scene, an elephant (agent) is pushing an owl (patient), while in the right scene, a zebra (agent) is jumping over a cow (patient).



Grammaticality judgment task

The acquisition of word order was assessed using a grammaticality judgment task (GJT, Block 7), which was administered immediately after the six cross-situational training blocks. In these syntax test trials, only one animated scene was presented alongside an auditory sentence in the artificial language. Participants were instructed to judge whether the sentence, spoken by “an alien from another planet who is also learning this alien language,” sounded good or funny, based on the sentences they had heard during training.

Before the task began, the distinction between good and funny was explained clearly to ensure all children shared the same judgment criteria. Children were asked to press a key labeled with a sticker marked good if they believed the sentence conformed to the alien language, or a key labeled funny if the sentence sounded incorrect. Of the 12 sentences presented, half (6) contained syntactic violations, while the other half were grammatically consistent with the artificial language.

Retrospective verbal reports

Finally, all children completed a series of debriefing questions designed to probe their explicit knowledge of the language. These questions assessed their understanding of the function of the marker words, as well as their knowledge of the typical positions of nouns and verbs within the sentence structure. Specifically, they were first asked to describe the word order of the sentences (i.e., positions of the nouns and verbs). If children did not provide an answer in this open question, then the follow-up prompts asking whether the relevant words typically appeared at the beginning, in the middle, or at the end of the sentence. In evaluating responses concerning word order, the critical issue was whether participants identified the correct sentence word order; therefore, child-friendly expressions such as verb, action word, doing word, or references to a specific action word (e.g., push word) were all treated as acceptable descriptions. Responses were later coded for awareness of the verb-final rule.

Statistical Analysis

For both training and vocabulary test trials of the CSL task, accuracy was treated as a binary outcome, with responses categorized as either correct or incorrect. For the trials of the GJT (i.e., syntax test trials), performance was evaluated using d' values and similarly tested against chance using t-tests.

Generalized linear logistic mixed-effects modeling (Baayen et al., 2008; Jaeger, 2008) was then conducted for statistical analysis. We constructed mixed-effect models for the training and testing phases separately, starting with the null model (containing random effects of participant and item with intercepts and slopes for each fixed effect) to models where we incrementally added fixed effects (i.e., block, age group, condition, then two-way, and finally the three-way interaction) with log-likelihood tests on model fit. For the syntax test trials, we used linear regression models for statistical analysis on d' values. The variables Age and Condition were entered into the models as categorical variables with three (8-9, 10-11 and 12-13) and two (Implicit and Explicit) levels, respectively. For Age, 8-9 age group served as the initial reference group. In follow-up analyses, we additionally re-referenced the factor to use the 10-11 age group as the reference level in the best-fitting models to make direct comparisons between 10-11 and 12-13 as well. For Condition, the Implicit group was reference group. Block was entered as a continuous variable, indexing progression through training.

For the retrospective verbal reports, we first constructed logistic regression models with awareness as the binary outcome, with age group (reference = 8-9 years) and condition (reference = implicit) as categorical predictors. Then awareness was added as a fixed effect into the best fitting logistic mixed-effects models of training trials, vocabulary test trials and syntax test trials respectively and compared model fit using likelihood ratio tests.

Analyses were pre-registered, please follow this link.

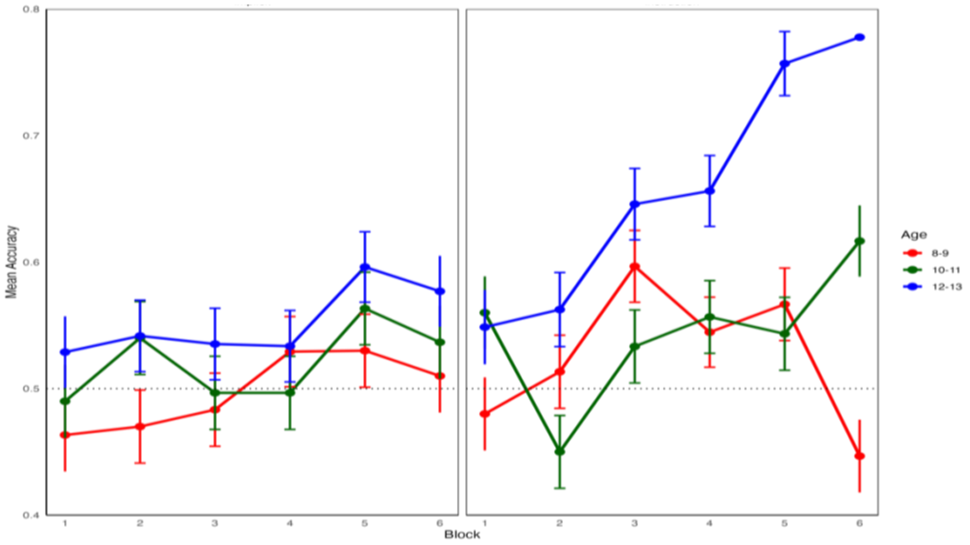
Results

In this section, we first report descriptive results, and then turn to mixed-effects modeling for confirmatory analyses which examined whether block, age or experimental condition predicted learning outcomes, and whether these effects interacted.

Performance during training trials of the CSL task

Performance on the training trials of the CSL task is summarized in Figure 3.2. Detailed descriptive statistics are reported in Table S3-1.

Figure 3.2 Performance on training trials of the CSL tasks, across six blocks of exposure by learning conditions. Dotted lines at 0.5 represent chance performance. Error bars indicate standard error of the mean. The left panel shows performance in the implicit condition and right one shows performance in the explicit condition.



These descriptive patterns shown in Figure 3.2 suggest a possible three-way interaction between age, block, and condition (i.e., 12-13 instruction group showed a robust boosted learning across six training blocks). This observation is formally tested in the mixed-effects models reported in the following section.

In line with our preregistration, to examine whether block, age or experimental condition contributed to a better learning, and whether the effect depends on each other, we conducted binary logistic mixed-effects modelling. We constructed models starting with a null model, the model with the maximum random effects that converge. Slopes for item were training block, age, experimental condition, and their interactions, and slope for participant was block. We then added fixed effects of training block, age, experimental condition, then two-way interactions (i.e., the interactions between training block and age, training block and experimental condition, and age and experimental condition), and then the three-way interaction between training block, age, and experimental condition to test whether they improve model fit.

We found that adding the fixed effect of block significantly improved model fit compared to the null model ($\chi^2(1) = 17.87, p < .001$). Adding the fixed effect of age group ($\chi^2(2) = 11.10, p = 0.004$) and condition ($\chi^2(1) = 7.80, p = 0.005$) further improved model fit. Thus block, age group and condition were included into the subsequent models. In addition, the interaction between block and age group ($\chi^2(2) = 6.70, p = 0.035$) also improved model fit. However, the interaction of training block and experimental condition did not improve model fit ($\chi^2(1) = 2.66, p = 0.103$), and neither did the interaction between age and condition ($\chi^2(2) = 2.64, p = 0.267$). Thus, these two interactions were not added into the following models.

Crucially, the three-way interaction among block, age and condition ($\chi^2(3) = 11.55$, $p = 0.009$) provided a significant improvement in fit and thus this main effect was included in the model. Table 3.2 presents the best-fitting model summary, which indicated a significant three- way interaction with a small effect size[7] (*OR* = 1.15, 95% CI [1.06, 1.25]). This significant (though small) effect indicated that instruction enhanced learning for the 12-13 age group, and this improvement increased as training proceeded, to a greater extent than for the other age groups.

Table 3.2 Best fitting model for accuracy in training trials, showing fixed effects.

Fixed Effects	Estimate	SD Error	Z	*p*
(Intercept)	-0.108	0.095	-1.136	0.256
block	0.035	0.033	1.042	0.297
age10-11	-0.028	0.138	-0.205	0.838
age12-13	0.005	0.123	0.044	0.965
conditioninstruction	0.056	0.096	0.586	0.558

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[7] We followed Rosenthal's (1996) benchmarks for interpreting odds ratios as indicators of effect size. Specifically, odds ratios of 1.5, 2.5, 4.0, and 10 are considered to reflect small (weak), medium (moderate), large (strong), and very large (very strong) effects, respectively. Odds ratios were computed by exponentiating the coefficients: exp (logged odds).

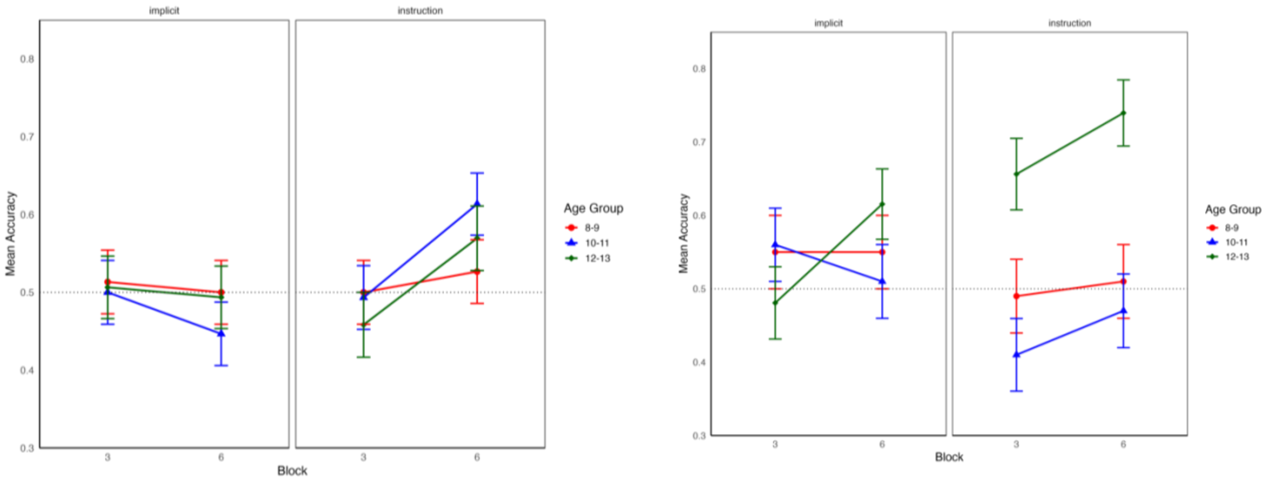
block:age10-11	0.026	0.048	0.550	0.582
block:age12-13	0.051	0.044	1.139	0.255
block:age8-9:conditioninstruction	0.011	0.042	0.273	0.785
block:age10-11:conditioninstruction	0.009	0.040	0.221	0.825
block:age12-13:conditioninstruction	0.143	0.042	3.414	<.001***

Number of observations: 10851, Participants: 150 , Item, 106 . AIC = 14761.7, BIC = 15425.3, log-likelihood = -7289.8. R syntax: glmer(accuracy ~ block + age + condition + block:age + block:age:condition + (1 + block| participant) + (1 + block * age * condition | item), data = dat_training, family = "binomial", control = ctrl).

Performance on vocabulary test trials of the CSL task

The vocabulary test trials were used to measure the acquisition of nouns, verbs, and marker words. Detailed descriptive statistics, including comparisons against chance level, are displayed in Table S3-2 and Figure 3.3. For nouns, significant learning was observed only in the 10-11-year-old group under the explicit instruction condition. For verbs, significant learning emerged in the 12-13-year-old group across both the implicit and explicit instruction conditions, while no significant effects were found in the younger age groups. For marker word learning, no significant learning effect were found.

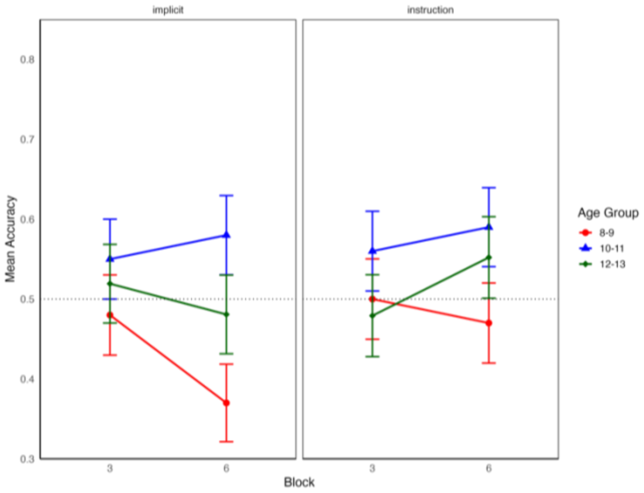
Figure 3.3 Mean accuracy on the vocabulary test trials of the CSL task by learning conditions. These trials only occurred in Blocks 3 and 6. Dotted lines at 0.5 represent chance performance. Error bars indicate standard error of the mean. The left panels show performance in the implicit condition and right ones show performance in the explicit condition.



A. Mean Accuracy for Noun Test

B. Mean Accuracy for Verb Test

C. Mean Accuracy for Marker Test



In line with our preregistration, generalized linear mixed-effects modeling was conducted to examine whether testing block, age group, experimental condition, and their interactions significantly predicted learning outcomes (see Table S3-3 for best fitting model summary and formula).

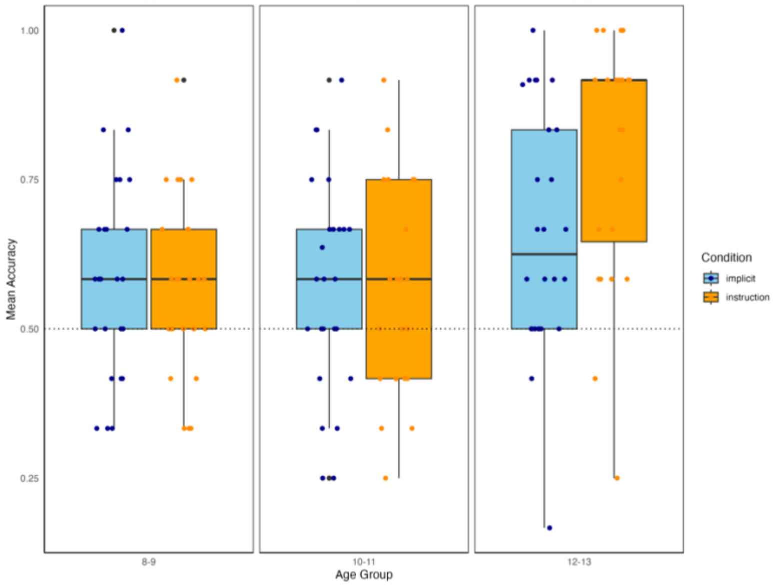
For noun learning, adding neither block, age, condition nor their interactions improved model fit. For verb learning, adding block, age group, instructional condition, or their interactions did not significantly improve model fit, indicating no reliable main effects of either age or instruction. However, the model coefficients suggested a robust effect of age and instruction: 12-13-year-olds in the instruction condition significantly outperformed all other groups (estimate = 0.99, *SE* = 0.22, $p < .001$; *OR* = 2.69, 95% CI [1.74, 4.16]). Regarding marker learning, adding the main effect of age did not significantly improve model fit, indicating that age did not serves as a global factor that predicted marker learning across all the groups. However, the model coefficients suggested a specific developmental contrast: with a significant higher accuracy of 10-11 age group than 8-9 (estimate = 0.473, *SE* = 0.16, $p = .002$; *OR* = 1.60, 95% CI [1.18, 2.17]), whereas no significant difference with the 12-13 (estimate = -0.27, *SE* = 0.16, $p = .088$) age group. No other main effects and interactions improved model fit.

Performance on syntax test trials

Participants' acquisition of syntax (i.e., word order) was assessed by the grammaticality judgment task. Significant learning was observed in both implicit and explicit instruction conditions for the 8-9 and 12-13 age groups, and marginal effects were detected for the 10-11-year-old group (for the detailed descriptive statistics including comparisons against chance level, see Table S3-4 in Appendix and Figure 3.4).

Linear regression models found that adding the fixed effect of age significantly improved model fit compared with the null model, $\chi^2(2) = 23.27$, $p < .001$, $\Delta R^2 = .13$, $f^2 = .15$, indicating a medium effect of age. However, adding the fixed effect of condition did not improve model fit ($\chi^2(1) = 1.54$, $p = .225$), and thus was not included in the best-fitting model. In addition, adding the interaction of age and experimental condition ($\chi^2(2) = 5.76$, $p = .059$) did not improve model fit significantly. However, the model summary indicates a specific contrast: that there was a significant effect of instruction for the 12-13 age group (estimate = 0.87, *SE* = 0.40, $p = .033$). See Table S3-5 for best-fitting model summary.

Figure 3.4 Performance on the grammaticality judgement task (i.e., syntax test trials) across age groups and instruction type.

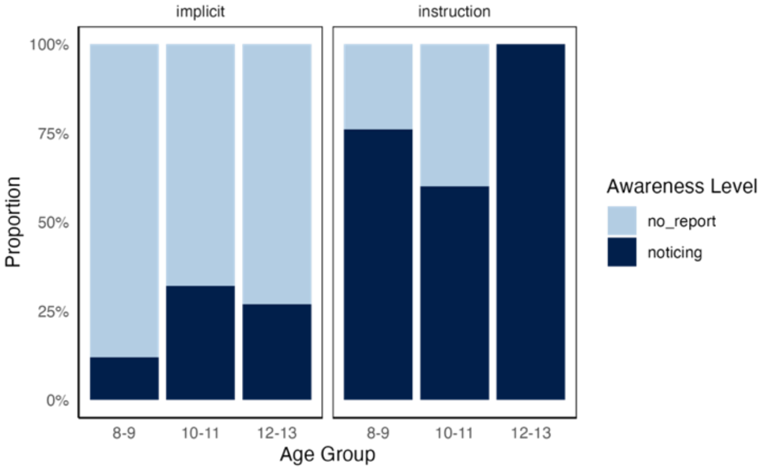


In sum, we observed a non-linear developmental trajectory of CSL learning: 12-13-year-old children outperformed their younger peers in verb and syntax learning, showing greater sensitivity to explicit instruction.

Retrospective verbal reports

Responses to the debriefing questions concerning participants' knowledge of the syntax (i.e., the verb-final word order knowledge) of the artificial language were coded into two categories according to their awareness (Lichtman, 2016). Participants were coded as "Noticing" if they provided responses indicating that verbs are placed at the sentence final position. Participants whose responses did not include this description were coded as "No report". Cohen's κ indicated high inter-rater reliability (κ = 0.973; 98.7% agreement). The proportion of children in each category, across the implicit and explicit instruction groups, is presented in Figure 3.5.

Figure 3.5 Proportion of children who were aware or unaware of the learning target, based on their retrospective verbal reports.



We first employed logistic regression models to examine whether the development of explicit awareness of the syntactic structure could be predicted by age, experimental condition, and their interaction. Awareness (i.e., noticing and no report) was entered as a binary outcome, with age group and condition as fixed effects. The results revealed a significant main effect of age. Compared with the youngest group (8-9 age group), children in the 10-11 age group (estimate = 1.24, *SE* = 0.07, *p* < .001, with a moderate effect size, *OR* = 3.45, 95% CI [3.01, 3.97]) and the 12-13 age group (estimate = 1.00, *SE* = 0.07, *p* < .001, with a moderate effect size, *OR* = 2.72, 95% CI [2.36, 3.13]) were more likely to notice the verb-final word order. Furthermore, condition also significantly predicted the development of awareness with a large effect size, *OR* = 23.22, 95% CI [20.14, 26.78]: participants in the explicit instruction group were significantly more likely to demonstrate awareness than those in the implicit group (estimate = 3.15, *SE* = 0.07, *p* < .001).

Next, we examined whether awareness significantly affected accuracy in both training and test trials, beyond the effects of group and condition already included in the mixed-effects analyses. For training trials, adding awareness did not improve the model fit of the best-fitting model (Model 7; $\chi^2(1) = 0.23$, *p* = 0.629). For the vocabulary test trials, awareness had a significant effect on verb learning with a small effect size ($\chi^2(1) = 8.92$, *p* = 0.003; *OR* = 1.58, 95% CI [1.22, 2.05]), but no significant effects were found for noun learning ($\chi^2(1) = 0.15, p = 0.702$) or marker learning ($\chi^2(1) = 1.91, p = 0.167$). In terms of the syntax test trials, awareness was a significant predictor in addition to age, $\chi^2(1) = 204.94, p < .001$, although the effect size was very small ($\Delta R^2 = .008$, $f^2 = .009$).

In sum, we found that the awareness of the verb-final word order knowledge increased with age and was substantially boosted by explicit instruction, with a ceiling effect in the 12-13-year-old instruction group. In addition, awareness predicted verb and syntax learning, but not the learning of nouns and marker words, suggesting that the effect of awareness may vary depending on the linguistic feature being learned..

We further conducted exploratory analysis to examine whether the effect of awareness varied across age groups and learning conditions by adding the interaction terms age×awareness and condition×awareness to the best-fitting models for training and testing phases using a nested model comparison strategy. Results found that adding these two interaction terms did not significantly improve the model fits for vocabulary learning trials. In contrast, syntax learning (GJT scores) was significantly predicted by both age×awareness and condition×awareness, indicating that the effect of awareness on GJT depended on age and learning conditions: awareness significantly predicted syntax learning for 12-13-year-old group, $\chi^2(2) = 28.81, p < .001$, and under explicit instruction $\chi^2(2) = 33.01, p < .001$ (See Supplementary Materials for the detailed model-building procedures and full results).

Discussion

It is widely assumed that children and adults acquire language through fundamentally different mechanisms: children primarily rely on implicit learning, while adults tend to engage more with explicit strategies (Lichtman, 2013). The aim of this study was to investigate when and how, over the course of development, learners begin to benefit from explicit instruction to support language acquisition. Our findings revealed a significant interaction between age and instruction during immersive L2 learning, suggesting that the effectiveness of explicit instruction varies across developmental stages.

Developmental trajectories in cross-situational learning of language

Our first research question examined how cross-situational learning develops across childhood and adolescence. As predicted, we observed a significant effect of age in the acquisition of sensitivity to the verb-final word order during the navigation of sentence-scene correspondence, indicating that older children were more capable of extracting language structure through tracking input statistics. This finding aligns with Arciuli and Simpson's (2011) evidence of increasing statistical learning ability between the ages of 5 and 12, challenging the view that statistical learning is age-invariant (e.g., Saffran et al., 1997; Moreau et al., 2022). Our results also correspond with the maturation of cognitive skills (e.g., working memory) that typically emerge around the age of eight and beyond (e.g., Schneider, 2010; Vuontela et al., 2003), and which are likely to support more successful language learning. However, it is important to note that this age-related improvement was most evident in testing performance, including syntax and marker tests, rather than in the overall training accuracy, where age effects were largely explained by the interaction with instructional condition.

The developmental trajectory observed in our study was nonlinear. While syntax acquisition remained relatively stable between the ages of 8 and 11, a significant improvement emerged in the 12-13 age group. This pattern is less consistent with the Critical Period Hypothesis, which posits that younger learners have an advantage in acquiring a L2 through implicit mechanisms (Johnson & Newport, 1989; Hartshorne et al., 2018), and more in line with alternative accounts suggesting a "the-older-the-better" trend during childhood and adolescence (Muñoz, 2006; Snedeker et al., 2012; Snow & Hoefnagel-Höhle, 1978).

Nevertheless, there was an exception to the overall "the-older-the-better" trend observed in the current data. Notably, 10-11-year-olds showed comparatively better acquisition of marker words than both younger (8-9) and older (12-13) peers, despite markers typically being difficult to learn even for adults (e.g., Monaghan et al., 2021).

In the artificial language used here, these markers function as morphosyntactic cues signaling subject and object roles of the nouns within the sentence, and therefore contribute to learners' understanding of sentence structure in addition to the verb-final word-order constraint. Within the implicit condition, we also observed relatively higher rates of noticing in the 10-11 group, suggesting that even without explicit instruction, children at this age may be better at abstract sentence structure through navigating sentence-scene correspondences. This non-linear, peak at 10-11 years of age profile aligns with developmental work showing that children around age 11 outperformed nearby age groups on several morphophonological measures, before performance dipped again in mid-adolescence (Reed, Griffith, & Rasmussen, 1998). Note that Savarino et al. (2025) showed that children at the younger age range of our study – aged 7 to 11 years – had difficulty in acquiring morphonological rules involving markers of animacy on words in an artificial language, consistent with the development of this ability throughout childhood.

We emphasize that the present study did not collect individual differences measures (e.g., attention, working memory, metalinguistic skill), so we cannot identify the underlying mechanisms of this shift at around 10 years of age. Future work should test whether such factors predict marker learning, particularly for features lacking concrete referents but carrying abstract semantic/pragmatic cues (as in our markers). In adult learners, awareness of marker words has been linked to outcomes (e.g., Ruiz et al., 2025), suggesting that rule articulation may play a role that warrants targeted assessment in children. Taken together, our data support treating 10-11 years as a developmental transition point for learning morphosyntactic cues, rather than as a simple "older is better" effect, while reserving definitive causal claims for studies that include direct cognitive and awareness measures.

Our findings further suggested a qualitative difference between vocabulary and syntax learning across development. Sensitivity to the verb-final word order constraint appeared more consistent across age groups, with even the youngest children (aged around 8) showing significant above-chance performance on GJT task. By contrast, the youngest learners failed to learn word-referent mappings, and the successful learning of marker words and verbs was only observed in older learners (aged 10-11 and 12-13 respectively). Though we did not directly compare vocabulary and syntax learning, because of the different ways in which these measures are analysed, this pattern could suggest a developmental shift in vocabulary learning during middle childhood to early adolescence. These results reflect those of Zhang et al. (2025), who found that children aged 8 in the UK were able to acquire word order knowledge but struggled with vocabulary learning.

The observed advantage in word learning for older children is likely linked to developmental improvements in memory capacity, particularly in the declarative memory system associated with vocabulary learning. Previous work suggests that procedural memory, which supports syntax acquisition, reaches maturity earlier than declarative memory (Ullman, 2004). Given that declarative memory continues to develop through adolescence, the age range targeted in our study, spanning the transition from childhood to adolescence, provides valuable insight into this cognitive shift. In doing so, our findings complement existing research on cross-situational word learning (e.g., Fitneva & Christiansen, 2017; Benitez & Li, 2024; Vlach & DeBrock, 2017), offering new evidence on how memory systems and linguistic features interact across development. However, the current study did not collect direct data on learners' individual differences in cognitive abilities, which limits the extent to which our interpretation can be empirically supported. Nevertheless, we highlight this as an important direction for future work: investigating how the development of cognitive abilities shapes the effectiveness of instruction, particularly during the transition from middle childhood to early adolescence.

Effects of explicit instruction and developmental differences

Our second research question explored the extent to which explicit instruction about syntactic structure influenced children's learning of L2 vocabulary and grammar. As predicted, we found that explicit instruction enhanced L2 learning performance. This finding supports recent evidence (e.g., Lichtman, 2016) that challenges the long-held assumption that children acquire language primarily through implicit mechanisms

(Lichtman, 2013). Our paradigm extends this line of research by demonstrating that children can benefit from explicit instruction even when required to acquire vocabulary and grammar simultaneously in an immersive learning context.

However, contrary to our initial prediction, the benefits of explicit instruction were not uniform across age groups. Rather, the effectiveness of instruction was interacted with learners' age. Specifically, children aged 12-13 years showed a marked openness to explicit instruction, leading to better performance on both vocabulary and grammar learning tasks. A similar shift was noted in Lichtman (2013), where sixth-grade learners (around age 12) exhibited a sudden improvement in learning outcomes, coinciding with the introduction of explicit instruction in their school curriculum. While Lichtman attributed this shift solely to instructional exposure, our findings suggest that cognitive maturation may also play a central role.

In addition, these findings conform with Chen et al.'s (2017) argument that the simultaneous learning of multiple linguistic components from CSL may be affected by learners' (selective) attention and cognitive capacities. In line with this perspective, the present study showed that although children struggled to acquire vocabulary and grammar simultaneously through CSL, performance improved when explicit instruction directed their attention to specific linguistic features and promoted their awareness of the underlying rules. Notably, this effect was most evident for older children, suggesting that developmental increases in cognitive resources such as working memory and attentional control may determine who benefits from explicit instruction. This interpretation is also in line with West et al., (2021), who found that the sustained attention, rather than procedural learning per se, was a critical predictor of 7- to 8-year-olds' grammatical skills. Hence, developing attentional resources, rather than procedural memory skills, may be the driver of statistical learning ability contributing to language learning. Distinguishing attention from memory skills in future studies can highlight which may be most critical in language learning.

Our study provides evidence of a qualitative developmental shift driven by the interaction between age and instructional input. One explanation for this shift is the increasing capacity for explicit learning strategies as cognitive abilities mature. N.C.

Ellis (2002) suggested that such strategies become increasingly important with development, particularly as working memory improves. Supporting this, prior research has found that the effectiveness of explicit feedback (Yilmaz, 2013; Li, 2013) and explicit instruction (Suzuki & DeKeyser, 2017) is moderated by working memory, which itself develops significantly between ages 6 and 13 (Vuontela et al., 2003).

Our findings also emphasize the need to consider moderating variables such as age, rather than focusing exclusively on instructional technique when evaluating pedagogical effectiveness (Norris & Ortega, 2000). This study also contributes to the emerging field of age-by-treatment interaction, as called for by DeKeyser (2012). While his theoretical claims were based on combining data from immigrant and foreign language learning contexts, direct empirical evidence was lacking at the time. Our results offer empirical support for DeKeyser's account by directly testing age-treatment interactions in a relatively large sample (N = 150).

Relatedly, our study also responds to Roehr-Brackin's (2024) call for research into whether explicit learning can facilitate the learning process that proceeds without conscious awareness. The CSL paradigm adopted in the current study provides an appropriate context for this question because it is widely considered to rely on implicit statistical learning, in which learners extract distributional regularities merely from the co-occurrences in the input, often without awareness (e.g., Kachergis et al., 2010). By embedding explicit instruction within this immersive CSL context, we show that instruction can enhance learning from statistical input under specific conditions. Previous studies with adults have suggested a potential benefit of instruction in CSL (Kachergis et al., 2014; Monaghan et al., 2019), but the outcomes appear to depend on the linguistic feature being targeted. For example, Monaghan et al. (2021), using a nearly identical artificial language and CSL paradigm, found that explicit instruction on marker words ("tha" and "noo", also used in the present study) had no effect on learning. In contrast, our study showed that explicit instruction on sentence structure, specifically, verb-final word order, significantly enhanced learning, suggesting that the focus of instruction matters greatly in determining its impact on L2 learning.

The instruction we provided closely related to the syntax learning that we tested in the GJT, i.e., sensitivity to the word order. Learners could perform well on this task if they became aware of the identity and position of the verb at the end of the sentence. Future studies could extend this approach by examining other syntactic structures, such as subject-verb agreement and number marking. For instance, learners might be guided to attend to number or role distinctions in the input without being explicitly told the grammatical rule. Researchers could then examine whether such guidance supports transfer to structurally related but untaught constructions, thereby testing whether instruction facilitates broader grammatical abstraction rather than feature-specific learning.

Nevertheless, our findings contribute to broader debates on the interface between explicit and implicit learning in terms of developmental effects and whether there is any possibility at all of interactions between explicit and implicit knowledge (Ellis, 2015). We show when, across development, explicit instruction could penetrate implicit learning. We also provide evidence of the interface itself: our learners do apply explicit information to support acquisition of implicit knowledge.

It is important to note, however, that we do not claim that explicit learning can *only* support implicit learning around puberty. Rather, what our findings demonstrate is a clear interface of explicit and implicit learning, though the specific developmental point observed here is likely to be task-dependent. Future work should systematically investigate the interface between explicit and implicit learning across a wider range of linguistic features, experimental designs, and wider age groups (e.g., from early childhood through adolescence) to gain a comprehensive understanding of when and how explicit learning interfaces with implicit learning. Furthermore, the instruction we provide closely related to the syntax learning that we tested in the GJT, i.e., sensitivity to the word order. Learners could perform well on this task if they became aware of the identity and position of the verb at the end of the sentence. Testing a wider range of syntactic structures in future studies, and examining whether indirect information about syntax, testing transfer to acquisition of other structures, would be a point for interesting departure from the current study.

The role of awareness in vocabulary and syntax learning

Our third research question examined the relationship between awareness of language structure and L2 learning outcomes. As predicted, children as young as eight years old demonstrated an ability to verbalize the syntactic rule (i.e., word order) after receiving explicit instruction, and greater awareness was associated with better performance in verb and syntax learning. These findings align with those of Lichtman (2016), who found that children aged 5-7 in an explicit instruction condition developed greater awareness of the structural features of a mini-language.

Notably, the present study found that awareness accounted for a small but significant portion of variance in verb learning performance. The variable of awareness but not condition itself emerged as the only significant main effect in the final model indicated that the successful verb learning might not be merely the receipt of instruction, but rather the learner's awareness of the instructional target, underscoring the role of awareness in children's cross-situational learning of vocabulary. This aligns with findings from Ruiz et al. (2025), who also reported that awareness, but not memory capacity or instruction type, best predicted vocabulary learning outcomes in adult learners under similar experimental conditions. These findings highlight the importance of considering awareness not only in research but also in practical L2 classroom instruction.

In addition, the awareness measure used in the current study (i.e., the ability to articulate the rule) may reflect children's declarative memory for the taught grammatical rule, which itself may contribute to learning performance. Declarative memory supports the encoding and retrieval of explicit knowledge, including facts and rules (Ullman, 2004), and therefore may underlie participants' ability to verbally report the structural regularity of the artificial language, and therefore may underlie participants' ability to verbally report the structural regularity of the artificial language. As such, the observed association between awareness reports and learning outcomes may partly reflect the contribution of declarative memory rather than awareness alone.

This interpretation is also consistent with the broader findings of the current thesis. In Study 3, declarative memory was identified as a significant predictor of grammar learning under explicit instruction, suggesting that learners with stronger declarative memory may be better able to retain and apply explicitly instructed linguistic knowledge. As the current study did not include a control group where learners had rule instruction but no subsequent exposure to the target language and then were asked to recall the rule again, it is difficult to determine the extent to which participants' awareness reports reflect rule recall versus awareness that developed during the CSL task. The interpretation of the current findings relating to awareness should therefore be treated with caution until further evidence becomes available.

Taken together, these findings support that awareness facilitates both verb and syntax learning, the language features that directly covered in the explicit instruction; and that the role of awareness in GJT scores indicated that children could apply consciously noticed rules to grammatical judgments.

Practical implications

Our findings offer practical insights for designing age-appropriate L2 instruction. As DeKeyser and Larson-Hall (2005) argued, the widely held belief that "earlier is better" does not apply uniformly across all L2 learning contexts. In formal educational settings, such as classroom-based L2 instruction, our findings support a more nuanced interpretation of the critical period hypothesis. Rather than assuming that younger learners always benefit more, we emphasize the importance of aligning explicit instruction with learners' cognitive and developmental readiness. The effectiveness of instruction, in this view, depends not only on what is taught, but when and to whom it is taught. Moreover, the finding that metalinguistic awareness significantly predicted verb and syntax learning highlights the importance of fostering and monitoring learners' conscious understanding of grammatical rules in real classroom settings.

Taken together, these findings have implications for teachers, curriculum designers, and educational policymakers seeking to optimize language instruction. Aligning pedagogical approaches (e.g., explicit instruction) with learners' developmental readiness and promoting metalinguistic awareness can help create more effective, age-sensitive L2 learning environments.

Limitations and future directions

The present study provides support for a maturational account of L2 learning in children aged 8 to 13. However, we did not directly examine the role of individual cognitive abilities (such as memory) in the learning process. Prior research by Vlach and DeBrock (2017) suggests that memory abilities, rather than age, are the strongest predictors of vocabulary learning in younger children (ages 2 to 5). Future research should aim to disentangle the effects of procedural, declarative, and working memory from chronological age, and examine how these memory systems interact with explicit instruction in additional language learning.

A second limitation concerns our reliance on offline testing measures. Incorporating a combination of online and offline methodologies could yield a more comprehensive understanding of the learning process. For example, Spit et al. (2022b) found that the effect of instruction on children's grammatical marker acquisition was detectable only through eye-tracking data, not through standard accuracy measures. Future studies should therefore consider integrating online processing-based measures (e.g., eye-tracking, reaction times) to capture more subtle, implicit learning effects, alongside offline explicit assessments (e.g., untimed grammaticality judgment tasks), which allow learners to reflect on and apply their explicit knowledge (R. Ellis, 2005). Furthermore, the syntax learning in the current study was assessed with only a single grammaticality judgment task. While this provided evidence of children's explicit knowledge of the word order rule, it offers a relatively narrow perspective on syntactic competence. Complementary tasks, such as sentence-picture matching, would help triangulate syntactic knowledge in a more ecologically robust way and provide stronger evidence about the depth and durability of syntactic learning.

Although participants' understanding and memory of the grammatical rule was checked immediately after instruction through a recall test, this procedure does not constitute a standardized assessment, and thus could limit our finding regarding effect of instruction and awareness. Future research would benefit from implementing standardized rule knowledge check both before and during exposure, though we recognize that such checks during the task may risk interfering with the learning process.

Another concern is the absence of direct measures of task motivation, which can affect learners' attention during the task. Although the coin-based task feature was designed to maintain attention and encourage active participation, we cannot determine whether it was equally motivating across different age groups. Furthermore, though the on-screen coin counter and sound effect was not intended to simulate the kind of communicative or interpersonal feedback that may accompany successful understanding in natural language learning, it is possible that this structure had indirectly shaped learning by reinforcing successful responses or encouraging pattern spotting. Therefore, future research should consider incorporating alternative measures of motivation (e.g., self-reports) alongside online methods such as eye-tracking, which can capture real-time attention allocation during learning. This multimethod approach would offer a fuller picture of how, when, and for whom explicit instruction facilitates L2 learning.

Last but not least, while the artificial language paradigm allows for tight experimental control over linguistic and instructional input, we acknowledge that it differs from natural L2 learning which contains, for example, opportunities for shared attention or meaning negotiation, limiting the ecological validity of our findings.

Conclusion

This study provides insights for developmental changes in children's receptivity to explicit instruction in L2 learning across middle childhood and adolescence. The findings carry important methodological, theoretical, and practical implications. Methodologically, this study is the first to examine L2 instruction within a highly controlled yet relatively more immersive learning environment, offering greater ecological validity than many artificial vocabulary or grammar learning studies while retaining experimental precision. Theoretically, our results point to a critical developmental window around age 12, during which explicit instruction begins to play a more dominant role in L2 learning. The study contributes to theoretical models of cross-situational learning by showing that explicit knowledge can support learning, particularly for older children. We further propose that CSL may begin as an associative process but becomes increasingly strategic and metacognitively driven as learners approach puberty. Finally, our findings offer important practical insights for L2 instructional design, highlighting when and for which language features the explicit instruction is most effective.

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Supplementary materials

Appendix A

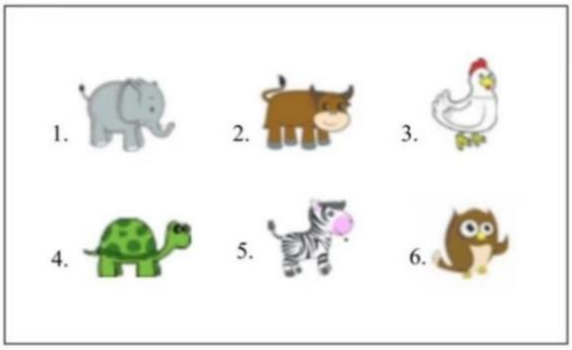
Pseudoword lexicon used in the experiment (adapted from Monaghan and Mattock, 2012).

The six bisyllabic content words used as nouns were: *barget, limeber, jeelow, goorshell, nellby, bimdah.* The four bisyllabic content words used as verbs were *dingep, fisslin, rakken, makkot*. The two monosyllabic words used as grammatical role markers (subject/object) were *tha* and *noo*.

Appendix B

Animal characters used in training and testing blocks.

Animal characters occurred across the experiment with equal frequency.



Appendix C Supplementary Tables

Table S3-1a Summary of descriptive statistics on mean accuracy for each training blocks in 8-9 aged implicit and instruction group

Block	1	2	3	4	5	6
Implicit (n = 25)						
Mean	0.46	0.47	0.48	0.53	0.53	0.51
SD	0.13	0.17	0.14	0.14	0.18	0.19
Explicit (n =25)						
Mean	0.48	0.51	0.60	0.54	0.57	0.45
SD	0.14	0.18	0.17	0.16	0.15	0.15

Table S3-1b Summary of descriptive statistics on mean accuracy for each training blocks in 10-11 aged implicit and instruction group

Block	1	2	3	4	5	6
Implicit (n = 25)						
Mean	0.49	0.54	0.50	0.50	0.56	0.54
SD	0.19	0.16	0.18	0.14	0.17	0.17
Explicit (n =25)						
Mean	0.56	0.45	0.53	0.56	0.54	0.62
SD	0.13	0.15	0.15	0.17	0.19	0.23

Table S3-1c Summary of descriptive statistics on mean accuracy for each training blocks in 12-13 aged implicit and instruction group.

Block	1	2	3	4	5	6
Implicit (n = 26)						
Mean	0.53	0.54	0.54	0.53	0.60	0.58
SD	0.16	0.15	0.17	0.17	0.17	0.16
Explicit (n =24)						

Mean	0.55	0.56	0.65	0.66	0.76	0.78
SD	0.16	0.19	0.16	0.21	0.20	0.19

Table S3-2a Summary of descriptive statistics and one-sample *t* tests on mean accuracy for each vocabulary test block for the 8-9 age group.

	Implicit (n = 25)		Explicit (n = 25)	
	Test1	Test2	Test1	Test2
Nouns:				
M	0.51	0.50	0.50	0.53
SD	0.21	0.20	0.21	0.16
t value	0.31	0.00	0.00	0.81
p value	0.759	1.000	1.000	0.425
Cohen's *d*	0.06	0.00	0.00	0.16
Verbs				
M	0.55	0.55	0.49	0.51
SD	0.24	0.23	0.33	0.28
t value	1.04	1.10	-0.15	0.18
p value	0.307	0.284	0.882	0.862
Cohen's *d*	0.21	0.22	-0.03	0.04
Markers				
M	0.48	0.37	0.50	0.47
SD	0.28	0.22	0.24	0.25
t value	-0.36	-2.98	0.00	-0.59
p value	0.723	0.006	1.000	0.559
Cohen's *d*	-0.07	-0.60	0.00	-0.12

Table S3-2b Summary of descriptive statistics and one-sample *t* tests on mean accuracy for each vocabulary test block of the 10-11 age group.

	Implicit (n = 25)		Explicit (n = 25)	
	Test1	Test2	Test1	Test2
Nouns:				
M	0.50	0.45	0.49	0.61
SD	0.19	0.20	0.16	0.16
t value	0.00	-1.32	-0.20	3.60
p value	1.000	0.200	0.840	0.001
Cohen's *d*	0.00	-0.26	-0.04	0.72
Verbs				
M	0.56	0.51	0.41	0.47
SD	0.23	0.23	0.26	0.34
t value	1.30	0.21	-1.74	-0.44
p value	0.207	0.832	0.095	0.664
Cohen's *d*	0.26	0.04	-0.35	-0.09
Markers				
M	0.55	0.58	0.56	0.59
SD	0.20	0.20	0.29	0.26
t value	1.22	1.99	1.03	1.74
p value	0.233	0.058	0.313	0.095
Cohen's *d*	0.24	0.40	0.21	0.35

Table S3-2c Summary of descriptive statistics and one-sample *t* tests on mean accuracy for each vocabulary test block of the 12-13 age group.

	Implicit (n = 26)		Explicit (n = 24)	
	Test1	Test2	Test1	Test2
Nouns:				
M	0.51	0.49	0.46	0.57

SD	0.22	0.19	0.17	0.24
t value	0.15	-0.17	-1.19	1.45
p value	0.882	0.866	0.247	0.162
Cohen’s *d*	0.03	-0.03	-0.24	0.30
Verbs				
M	0.48	0.62	0.66	0.74
SD	0.23	0.24	0.26	0.26
t value	-042	2.48	2.90	4.51
p value	0.678	0.020	0.008	0.000
Cohen’s *d*	-0.08	0.49	0.59	0.92
Markers				
M	0.52	0.48	0.48	0.55
SD	0.28	0.28	0.25	0.30
t value	0.35	-0.35	-0.40	0.84
p value	0.731	0.731	0.692	0.410
Cohen’s *d*	0.07	-0.07	-0.08	0.17

Table S3-3a Best fitting model (null model) for accuracy in noun test trials, showing fixed effects.

Fixed Effects	Estimate	SD Error	Z	*p*
(Intercept)	0.049	0.057	0.874	0.397

Number of observations: 1800, Participants: 150, Item, 23. AIC = 2639.2, BIC = 3089.8, log-likelihood = -1237.6. R syntax: glmer(accuracy ~ (1 + block| participant) + (1 + block * age * condition | item), data = dat_noun, family = "binomial", control = ctrl).

Table S3-3b Best fitting model (null model) for accuracy in verb test trials, showing fixed effects.

Fixed Effects	Estimate	SD Error	Z	*p*
(Intercept)	0.102	0.073	1.402	0.161

Number of observations: 1200, Participants: 150, Item, 15. AIC = 1778.0, BIC = 2195.4, log-likelihood = -807.0. R syntax: glmer(accuracy ~ (1 + block| participant) + (1 + block * age * condition | item), data = dat_verb, family = "binomial", control = ctrl).

Table S3-3c Best fitting model (null model) for accuracy in marker test trials, showing fixed effects.

Fixed Effects	Estimate	SD Error	Z	*p*
(Intercept)	0.043	0.063	0.687	0.492

Number of observations: 1200, Participants: 150, Item, 16. AIC = 1816.1, BIC = 2233.4, log-likelihood = -826.0. R syntax: glmer(accuracy ~ (1 + block| participant) + (1 + block * age * condition | item), data = dat_marker, family = "binomial", control = ctrl).

Table S3-4a Summary of descriptive statistics and one-sample *t* tests on mean accuracy for syntax test block.

Aged 8-9	Implicit (n=25)	Explicit(n=25)
M	0.59	0.57
SD	0.17	0.15
t value	2.62	2.37
p value	0.015	0.026
Cohen’s *d*	0.52	0.47
Aged 10-11	Implicit (n=25)	Explicit(n=25)
M	0.57	0.57
SD	0.18	0.17

t value	2.02	1.92
p value	0.054	0.067
Cohen’s *d*	0.40	0.38
Aged 12-13	Implicit (n=26)	Explicit(n=24)
M	0.66	0.80
SD	0.20	0.21
t value	4.03	6.98
p value	0.000	0.000
Cohen’s *d*	1.43	1.43

Table S3-5a Best fitting model for accuracy (*d’*) in syntax test trials, showing fixed effects.

Predictor	Estimate	SD Error	*t*	*p*
(Intercept)	0.453	0.145	3.124	0.002**
age 10-11	-0.059	0.205	-0.289	0.773
age 12-13	0.804	0.205	3.926	<.001***

4 Submitted paper 3: Individual differences in children's response to explicit instruction: Effects of age and memory ability

Page number: 120-156

Abstract

This study investigated how declarative, procedural and working memory capacities support additional language (L2) learning under explicit instruction from middle childhood to early adolescence, a period marked by substantial cognitive development yet is underrepresented in L2 research. 50 learners aged 8 to 13 were trained on an artificial language composed of transitive sentences with animated scenes in a cross-situational learning paradigm. Vocabulary and grammar learning required tracking co-occurrences between features of sentences and scenes, and integrating an explicitly instructed grammar rule (i.e., sentence word order), presented prior to exposure. We found that declarative memory was a predictor of grammar learning with explicit instruction, while procedural memory related positively to grammar learning only for older children. Furthermore, phonological short-term memory predicted grammar rule learning, while complex working memory predicted verb learning which became more pronounced in older learners. The results suggest that curriculum design, in particular the use of explicit instruction, should be tailored to children's age and cognitive abilities.

Keywords: Age-aptitude interaction, individual differences, procedural memory, declarative memory, working memory, explicit instruction, cross-situational learning, child second language acquisition

Introduction

Acquiring an additional language (L2) often results in substantial variability in learning outcomes (R. Ellis, 2004; Robinson, 2001; Tagarelli et al., 2016). These outcomes can be affected by both individual differences in cognitive abilities, such as memory systems, and the instructional input learners receive (Tagarelli et al., 2016). In particular, working memory, declarative memory, and procedural memory have been found to play a key role in L2 acquisition (e.g., Baddeley, 2010; Morgan-Short et al., 2022) and in use of explicit instruction in language learning (Ruiz et al, 2025). While a substantial body of research has explored these factors in adult L2 learners, much less is known about how they operate during childhood and early adolescence, a critical developmental period during which the key memory systems undergo rapid and significant changes. In this study, we investigated how short- and long-term memory systems (working memory, procedural memory and declarative memory) affect learning of vocabulary and grammar interactively with age across middle childhood to adolescence. The findings clarify which memory systems are most responsive to explicit instruction, and whether different language features (i.e., vocabulary and grammar) are governed by different memory systems across development.

Memory and language learning

A fundamental challenge that all language learners face is to determine which words map onto which features of the environment and how words relate to one another within syntactic structures. Recent research suggested that such difficulties can be solved by accumulating distributed statistics across multiple learning experiences (e.g., Monaghan et al., 2021; Yu & Smith, 2007), referred to as cross-situational learning (CSL). However, there is individual variation in learning from CSL (Isbilen et al., 2022; Vlach & deBrock, 2017; Walker et al., 2020).

Declarative and procedural memory affect L2 learning (see Morgan-Short et al., 2022; Ullman & Morgan-Short, 2023, for reviews). According to the declarative/procedural (D/P) model (Ullman, 2004; Ullman & Morgan-Short, 2023), two distinct long-term memory systems, declarative memory and procedural memory, underlie the learning and use of different aspects of language. Specifically, declarative memory is a domain-general neurocognitive system that supports the conscious recall of factual information (semantic memory) and events (episodic memory). It also supports the rapid learning and retention of arbitrary associations (Morgan-Short et al., 2022; Ullman, 2020). In contrast, procedural memory is a general-purpose system involved in the implicit learning of motor skills, habits, and actions. Procedural memory tends to function outside of conscious awareness, resulting in knowledge which is not easy to verbalize (Ullman, 2020). Unlike declarative memory in which learning can occur very rapidly after a single exposure of information, learning within the procedural memory tends to occur more slowly and gradually.

Ullman's D/P model (2001; 2004) associates the learning of certain language properties to declarative and procedural memory systems separately, and the associations seem to differ across development. For children learning their L1, Ullman (2001) proposes that declarative memory underpins the acquisition of vocabulary. Procedural memory, on the other hand, subserves the learning of mental grammar (e.g., rule-based morphology and syntax). For adults learning their L2, declarative memory subserves both vocabulary learning and at least the initial learning of grammar (Hamrick, 2015).

However, neither theoretical accounts nor empirical findings based on L1 and adult L2 acquisition can simply be generalized to child L2 learners. One reason is the distinct developmental trajectories of D/P memory systems (Pili-Moss, 2021). Procedural memory develops early, reaching functional maturity in infancy and early childhood, while declarative memory develops slowly, continuing to mature and becoming fully functional in early adulthood (Ullman, 2004). Empirical studies have shown that children between the ages of 5 and 10 possessed adultlike procedural memory skills, yet their declarative memory abilities remain underdeveloped compared to adults (e.g., Lum et al., 2010).

Zhang et al. (2025) and Zhang et al. (under review) showed that grammar learning of an artificial language in children aged 8 to 13 may be age-invariant, whereas vocabulary learning showed significant age-related gains, with only children aged 10 and above demonstrating successful word learning via CSL. These differential developmental trajectories in the acquisition of grammar and vocabulary may possibly reflecting the underlying development of procedural and declarative memory, but these studies did not include direct memory assessments. Pili-Moss (2021) found that procedural but not declarative memory was a predictor of grammar learning in 8- to 9-year-old children. However, it remains an open question whether and how these memory systems support the acquisition of vocabulary and grammar across childhood and early adolescence.

In addition to the long-term memory systems (i.e., procedural and declarative memory), working memory (WM) has also been identified as a predictor of language learning outcomes (Linck et al., 2014; Williams, 2015). WM refers to the cognitive capacity to store, maintain, and process information in ongoing tasks (Li, 2022), and is generally distinguished into 'phonological short-term memory' involving storage of speech information, and 'complex working memory' involving both storage and processing of speech (Li, 2017). WM is associated with L2 vocabulary and syntax learning (Martin & Ellis, 2012). For L2 learning under instruction 7- to 8-year-olds showed that phonological short-term memory correlated with L2 vocabulary, while complex WM predicted L2 grammar (Engel de Abreu & Gathercole, 2012). For children's L2 leaning under implicit, uninstructed conditions, Verhagen and Leseman (2016) found associations between phonological short-term memory and vocabulary and grammar, while complex WM only predicted grammar learning (see also Sia et al., 2023; Zhou et al., 2024). In childhood, WM undergoes significant and rapid changes (Ahmed et al., 2022) and so developmental change may affect its role in learning.

Explicit instruction and memory

Though children are often assumed to be implicit language learners (DeKeyser, 2000; Lichtman, 2016), child L2 learning of both vocabulary and grammar have been shown to be open to and boosted by explicit instruction (e.g., see Pawlak, 2021 for classroom-based studies and see Lichtman, 2016; Spit et al., 2022 for lab-based studies). This positive role of instruction is affected by learners' age (Zhang et al., under review), due to the increasing ability for explicit learning as cognitive capacities mature (see also Ellis, 2002).

The role of declarative and procedural memory appears to vary across instructional conditions. Declarative memory tends to predict learning under more intentional and explicit learning conditions (e.g., Robinson, 1997; Ruiz et al., 2021). Procedural memory, on the other hand, tends to be more engaged in implicit learning conditions (Granena & Yilmaz, 2019).

Regarding WM, it is more likely to be engaged in initial stages under explicit and conscious learning conditions, while it is less likely to be implicated in implicit and unconscious learning contexts (Goo, 2012; Li, 2017; Ruiz et al., 2021; Yilmaz & Granena, 2019). Individual differences may thus be more likely to account for learning variance in explicit than implicit learning conditions (Linck et al., 2014).

The present study

In this study, we investigated how declarative memory, procedural memory, and working memory (both storage and manipulation components) interact with explicit instruction to shape L2 vocabulary and grammar acquisition in children aged 8 to 13 years. We adopted a well-established language-learning paradigm (Rebuschat et al., 2021) designed to simulate an immersive learning environment, and tested the extent to which individual differences in memory affected the learning of vocabulary and grammar from cross-situational statistics under explicit learning instructions, and whether memory influences depended on age.

In line with the D/P model (Ullman, 2004), we first predicted that procedural memory ability would related to grammar learning and declarative memory relate more closely to vocabulary learning. Second, given the explicit knowledge delivered by explicit instruction, we predicted that declarative memory would also predict grammar learning (Morgan-Short et al., 2022). Third, we predicted that working memory would be a robust predictor for both vocabulary and grammar learning (Engel de Abreu &

Gathercole, 2012; Li, 2022). Finally, we hypothesized that the effects of declarative and working memory would depend on learners' age, while the effect of procedural memory would stay stable across development, reflecting the ongoing developmental changes of memory capacities across 8 to 13 year olds (e.g., Ahmed et al., 2022; Ullman, 2004). The study design and analysis was pre-registered prior to data collection (OSF, https://osf.io/6j29a/overview?view_only=5d01443edb8846eeb2e17612affd9fa4).

Methods

Participants

Fifty children[8] aged from 8 to 13 (mean age = 10.14 years, *SD* = 1.77, 20 girls) participated in the current study. They were recruited via schoolteachers in Northern China. All participants were Chinese native speakers, who had been learning English as a second language for 2 to 5 years and had no learning experience of word-final languages.

The study was approved by the ethics review panel of the Faculty of Arts and Social Sciences at Lancaster University and was preregistered on the Open Science Framework (OSF) platform (https://osf.io/6j29a/overview?view_only=5d01443edb8846eeb2e17612affd9fa4).

Tasks and Materials

All task instructions were delivered in Chinese, translated where necessary from other language original versions.

Artificial language

The artificial language was adapted from Rebuschat et al. (2021) and has been used previously in both adult and child studies (Zhang et al., 2025).

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[8] The target sample size (N = 50) was determined with reference to Ruiz et al. (2025), who examined the effect of individual differences in memory in adults using the same CSL paradigm. In that study, each experimental group included 37 participants, with comparable within-subject trial structures and outcome measures.

Vocabulary. There were 12 pseudo-words in the artificial language, including 10 bisyllabic content words (6 nouns and 4 verbs) and 2 monosyllabic grammatical case markers functioned as morphosyntactic cues and indicating if the preceding noun referred to the subject or object of the sentence (for a full list of stimuli, see Appendix A). In the artificial language, a noun phrase (NP) consisted of a noun and a post-nominal case marker. The words were recorded separately by a female native English speaker with monotone and presented in sequence by E-prime with a 250 ms pause between each word.

Grammar. The word order of the artificial language was modeled on Japanese grammar, with the verb consistently positioned at the sentence-final position, while the positions of subject and object noun phrases (NPs) varied. Specifically, the sentence order could either be subject-object-verb (SOV) or object-subject-verb (OSV). A total of 72 unique artificial sentences were generated, half SOV and half OSV word order, allocated into six training blocks (12 sentences each). The frequency of vocabulary, subject and object assignment, and word order were balanced across blocks. An example sentence is shown in (1).

(2) cheelow tha bimdah noo dingep.
Animal$_1$ SUBJECT Animal$_2$ OBJECT pushes.
‘Animal$_1$ pushes animal$_2$’.

We also constructed 12 artificial sentences to measure learners’ syntactic knowledge (verb-final word order knowledge) in the post-training phase. Six of them were ungrammatical artificial sentences that violated the word order. They were constructed by moving the position of the verb, three with word order VSO or VOS, and 3 with word order SVO or OVS. Another six of them were consistent with the syntax of the language which were not used in training trials.

Visual referents. We used six cartoon animal characters (cow, chicken, turtle, zebra, elephant, and owl) serving as the referents to nouns in the artificial language (for images, see Appendix B). Four actions (hiding, jumping, lifting, and pushing) performed by the cartoon animals served as the referents of verbs of the artificial language in animated scenes. Mappings were randomised across several versions of the study to avoid biases between certain speech sounds and referents (Rebuschat et al., 2021).

Cross-situational learning task

Participants learned the artificial language via a cross-situational learning task. Participants were first informed that they would be learning an alien language spoken by “friends from a distant planet”. Then they were explicitly instructed of the verb-final word order structure of the target artificial language by the researcher. The instruction was delivered in Chinese, and its English translation is as follows: “In Chinese, if we want to say ‘The dog pushes the pig.’, we say the animal who does this action first, the dog in this case; and then we say the action word, pushes in this case, and we finally say the animal who is being pushed, the pig in this case. But in the alien language, aliens say the two animals first, and the action word always goes to the end of the sentence: the dog the pig pushes, or the pig the dog pushes. Remember, the action word is always at the end of the sentence. But the two animals’ positions vary.” While listening to this instruction, the researcher also presented an image of the animal characters (a dog pushing a pig) to assist children’s comprehension. To ensure participants remembered the instructed grammar rule prior to training, the researcher asked a comprehension check question: “Which word is always at the final position?” Children were allowed to proceed to the CSL task only if they answered this question correctly. If a child gave an incorrect response, the instruction was repeated, and the question was asked again until the correct answer was provided.

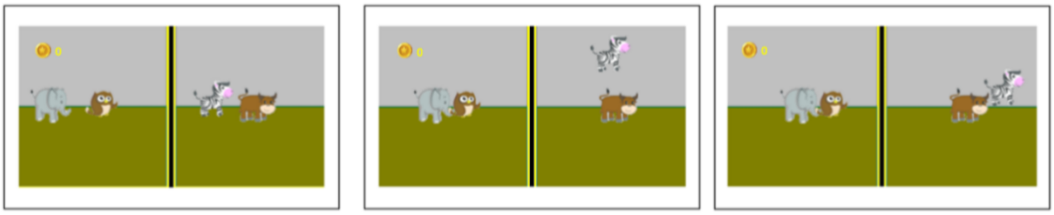
In each trial of the CSL task, participants heard an artificial sentence while observing two animated scenes presented side by side on a laptop screen. Each scene featured two cartoon animal characters performing one of the four actions, and the sentence corresponded to one of the two scenes. The audio was played only once, and children could give responses only after the sentence had finished playing. The animations continued looping until the participant provided a keyboard response, after which the task proceeded immediately to the next trial. An increase in an on-screen coin counter with a coin sound effect was given to maintain attention and encourage active participation. Figure 4.1 illustrates an example of a training trial.

Before the training trials of the CSL task, children were given two practice trials, comprising animal characters and pseudowords not included in the main study.

The CSL task consisted of six training blocks, followed by a grammaticality judgment task in a final test block (Block 7). Blocks 1, 2, 4, and 5 included only training trials, while Blocks 3 and 6 intermingled training and vocabulary testing trials to assess learning progress throughout the task.

The 72 training trials each comprised two animated scenes varying in the animals, actions, and the assignment of agent and patient roles to the animals. A total of 28 test trials were used to assess children's learning of vocabulary (12 for nouns, 8 for verbs and 8 for markers). They were intermingled in training blocks 3 and 6. In each test trial, the target and distractor scenes differed only in the feature being tested. Specifically, in noun test trials, the difference lay in one of the animal characters; in verb test trials, the scene differed in the action; and in the marker test trials, the roles of the two animal characters were reversed for the distinction in the assignment of agent and patient roles.

Figure 4.1 Example of a training trial. Screenshots were captured at the beginning, middle, and end of the trial. In the left scene, an elephant (agent) is pushing an owl (patient), while in the right scene, a zebra (agent) is jumping over a cow (patient).



Grammaticality judgment task

A grammaticality judgment task (GJT) was administered immediately after the cross-situational training blocks to assess the acquisition of grammar (in terms of knowledge of word order). A total of 12 syntax test trials were included in GJT, each of which included only one animated scene occurring with one auditory artificial language sentence. Six sentences were grammatically correct, following either OSV or SOV word order, while 6 contained syntactic violations (either VSO, VOS, SVO or OVS) with three verb initial sentences and three verb medial sentences. None of the syntax test sentences were used in training trials.

Children were instructed to determine whether the sentence they heard, spoken by “an alien from another planet who is also learning this alien language,” sounded good or funny. They were told to make judgment based on the sentences they heard earlier during training. The researcher clarified “good” and “funny” to each participant to ensure all children shared the same judgement criteria before the task began. Children were asked to press a key labeled with a sticker marked “Good” if they believed the sentence conformed to the alien language, or a key labeled “Funny” if the sentence sounded unlike the previous sentences.

Continuous Visual Memory Test

We used the Continuous Visual Memory Task (CVMT; Larrabee et al., 1992) as a measure of declarative memory (e.g., Morgan-Short et al., 2022). It has acceptable reliability (e.g., Ruiz et al., 2019 [Cronbach’s alphas of .63 and .67 for laboratory-based and web-based versions of CVMT, respectively]. The split-half reliability was 0.57 for the current data set, lower than the split-half reliabilities reported for adult samples (e.g., .61-.70 in Baños et al., 2001). However, lower reliability is not unusual in child cognitive-task data, where performance may be more affected by developmental variability, task difficulty, and attentional fluctuation.

Participants were presented black-and-white pictures of complex figures and were tested on their recognition memory. There were 112 learning trials in the CVMT, including 49 target trials (7 target pictures, each repeated seven times) and 63 foil trials (63 pictures, each appearing once). The whole test lasted about 8 minutes.

Alternating Serial Reaction Time Task

The Alternating Serial Reaction Time Task (ASRT; Howard & Howard, 1997; Howard et al., 2004) is a widely used measurement of procedural memory (e.g., Morgan-Short et al., 2022), with moderate to good reliability (split-half reliability =~ .42, Buffington & Morgan-Short, 2019; Cronbach's alpha [.75, .79], Norris et al., 2015). The ASRT used in the current study was adopted from Szücs-Bencze et al. (2023). Children saw a drawing of a dog head appear in one of the four horizontal circled positions. Participants' task was to response to the structured sequences, presenting by the occurrence of the "dog head" across the four circled positions, by pressing the corresponding keys as quickly and accurately as possible. The location of the target was determined by a probabilistic eight-element sequence, and procedural memory was scored as the improvement in reaction time for patterned versus random trials (e.g., Brill-Schuetz & Morgan-Short, 2014).

Digit span tasks

Working memory, as conceptualized in the present study, follows the multi-component model proposed by Baddeley and Hitch (1974), which posits a central executive system responsible for attentional control, along with domain-specific subsystems: the phonological loop for verbal information, the visuospatial sketchpad, and the episodic buffer that integrates information across modalities and interfaces with long-term memory. Based on this model, the Digit Span Forward and Digit Span Backward tasks, adapted from the Wechsler Adult Intelligence Scale-Revised (WAIS-R; Wechsler, 1981), were used to assess two core aspects of WM: phonological short-term memory (PSTM) and complex WM, respectively (Li, 2017; Verhagen & Leseman, 2016).

The digit span tests were adjusted to range from 3 to 11 digits for the forward test and 2 to 10 digits for the backward digits, given the potential cross-language effect caused by the shorter digit articulation time in Mandarin than in English (Chen et al., 2009). In the Digit Span Forward, participants were required to immediately recall a series of digits, spoken by the researcher at the rate of one per second, in the same order accurately. In the Digit Span Backward, participants were asked to repeat the digits in reverse order accurately, thereby engaging both the phonological loop and the central executive, as successful performance requires storage and manipulation. Each digit length included two trials. The highest digit length that the participant repeated correctly on at least one trial was used as the score of working memory.

Procedure

Data collection took place in a quiet classroom at the participants' school. Children were invited to a designated room equipped with laptops and noise-cancelling headphones. Testing was conducted either individually or in pairs. After signing the informed consent, participants completed the cross-situational learning task, and then proceeded onto the CVMT task, followed by the ASRT task. These three tasks were launched on Gorilla. Participants then did the digit span tasks individually with the researcher.

Statistical Analysis

For the training and vocabulary test trials, performance was evaluated by mean accuracy as a binary outcome, and for the grammaticality judgement task, performance was evaluated by d' values.

For statistical analysis of training and test trials, we conducted generalized linear logistic mixed-effects modeling (Baayen et al., 2008). In line with our preregistration, we constructed models starting with the null model (containing random effects of participant and item with intercepts and slopes for maximum fixed effects that could converge without singularity issues), then tested potential non-linear effects of block (i.e., learning over time) using orthogonal polynomials for the block predictor (ot1 = linear, ot2 = quadratic, and ot3 = cubic), then age, declarative memory (CVMT score), procedural memory (ASRT score), working memory (digit span forward score; digit span backward score) and two-way interactions between age and each memory score. Log-likelihood comparisons were used to test whether each of the fixed effect improved model fit. Models were constructed for training and testing phases separately.

For the syntax test, linear regression models were used for statistical analysis on *d*' values. We centered and scaled variables of age and scaled variables of memory scores for model converge.

Due to a technical issue, CSL data from one participant were not recorded and missing for training blocks 5 and 6. This participant was retained in the analysis using available data from blocks 1 to 4.

Results

Performance during training trials of the CSL task

Detailed descriptive statistics are reported in Table S4-1.

Adding the fixed effect of linear block (ot1) significantly improved model fit ($\chi^2(1) = 9.26, p = .002$), but fixed effects of quadratic block (ot2, $\chi^2(1) = 1.14, p = .286$) or cubic block (ot3, $\chi^2(1) = 0.993, p = .319$) did not improve model fit, thus indicating a linear effect of learning. Including age did not improve model fit ($\chi^2(1) = 3.72, p = .054$), nor did procedural memory, declarative memory, and working memory, or the interaction between age and declarative memory. Crucially, the interaction between age and procedural memory significantly improved model fit, ($\chi^2(1) = 6.68, p = .010$) (see Figure 4.2). Post hoc analysis using *simple slopes analysis* (Aiken & West, 1991) indicated that age significantly predicted training performance at average (estimate = 0.11, $SE = 0.04, p = .003$) and high levels of procedural memory (estimate = 0.18, $SE = 0.05, p < .001$), but not at low levels of procedural memory (estimate = 0.05, $SE = 0.05, p = .310$).

Age and digit span backward score (the measurement of complex WM) was also significant ($\chi^2(1) = 4.33, p = 0.038$) (see Figure 4.3). Simple slopes analysis showed that the effect of working memory was significant only for older children (approximately 12 years, estimate = 0.29, $SE = 0.08, p < .001$), but not for children at (estimate = 0.14, $SE = 0.07, p = .052$) or below mean age for the group (estimate = –0.02, $SE = 0.11, p = .849$).

See Table S4-2 for the summary of the best fitting model.

Figure 4.2 Two-way interaction between age and procedural memory. The left panel shows the effect of age for learners with average to high procedural memory scores; the right panel shows the effect for learners with low procedural memory. Shaded areas indicate 95% confidence intervals; the dotted horizontal line indicates chance-level performance (0.5).

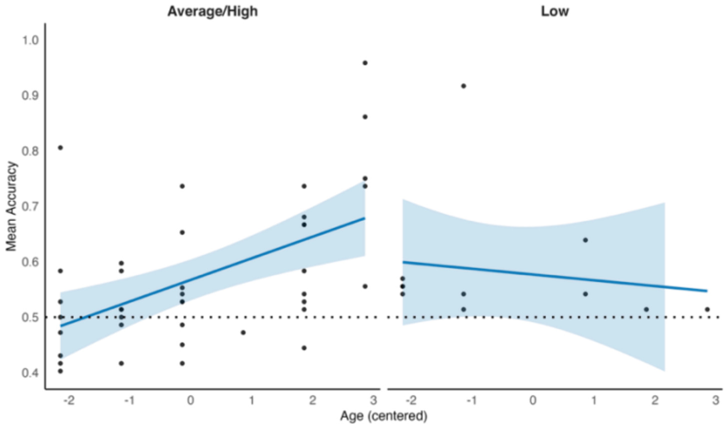
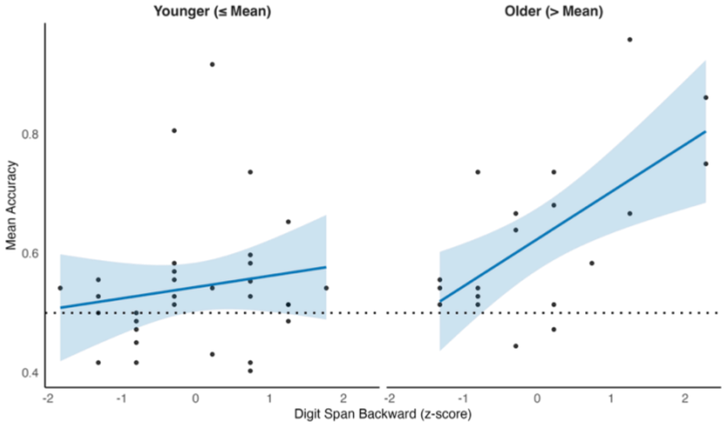


Figure 4.3 Two-way interaction between age and complex working memory. The left panel shows the effect of working memory (measured by Digit Span Backward) for younger learners. The right panel shows the effect for older learners. Shaded areas indicate 95% confidence intervals; the dotted horizontal line indicates chance-level performance (0.5).



Performance on vocabulary test trials of the CSL task

Detailed descriptive statistics are summarized in Table S4-3. One-sample *t* tests showed that performance was significantly above chance (.50) for verbs (block3: *M* = 0.59, *p* = .018; block6: *M* = 0.58, *p* = .028) and marker words (block3: *M* = 0.61, *p* = .003; block6: *M* = 0.59, *p* = .013), whereas noun learning remained at chance across both tests.

For noun learning, there were no significant effects of block, age, memory scores, or their interactions. For verb learning, there were again no significant main effects for block, age, procedural memory (ASRT scores), or declarative memory (CVMT scores). Adding the fixed effect of working memory (digit span backward scores) into the mixed-effects model resulted in singular fit, and thus we instead using linear regression with log-likelihood tests on model fit. Digit span backward score was a significant predictor, *F*(1, 97)= 17.07, *p* < .001. None of the interactions were significant. For marker word learning, we again used linear regression, instead of generalized linear logistic mixed-effects modeling, for statistical analysis of marker test data due to singular fit. However, there were no significant predictors of marker word learning.

Performance on the grammaticality judgement task

Detailed descriptive statistics are summarized in Table S4-4 and Figure 4.4.

In terms of syntax learning, adding age, *F*(1, 586) = 147.62, *p* < .001, declarative memory, *F*(1, 584) = 42.06, *p* <.001, and PSTM (measured by digit span forward), *F*(1, 583) = 11.27, *p* =.001, were significant. Procedural memory, and Complex WM (measured by digit span backward) were not significant, but the interaction between age and procedural memory was significant, *F*(1, 582) = 9.84, *p* =.002 (see Figure 4.5). Post hoc analyses indicated that the effect of procedural memory was significant only for older children (one standard deviation above the mean age, around 12 years old), estimate = 0.30, *SE* = 0.08, *p* < .001, but not for mean age (approximately 10.14 years), estimate = 0.11, *SE* = 0.06, *p* = .055, or younger children (one standard deviation below the mean, approximately 8 years), estimate = -0.08, *SE* = 0.07, *p* = .292.

The interaction between age and declarative memory was also significant, *F*(1, 582) = 5.186, *p* =.023. Post hoc analyses revealed that the positive effect of declarative memory on syntax learning was strongest for younger children (1 SD below the mean age, approximately 8 years), estimate = 0.44, *SE* = 0.07, *p* < .001; and was weaker but still significant at the mean age (approximately 10.14 years), estimate = 0.32, *SE* = 0.06, *p* < .001; and for older children (1 SD above the mean, approximately 12 years), estimate = 0.20, *SE* = 0.08, *p* = .020.

The interaction between age and working memory was not significant. The final model summary is provided in Table S4-5.

Figure 4.4 Performance on the grammaticality judgement task. Individual dots represent participants' accuracy scores; the boxplot shows the median and interquartile range, and the violin plot illustrates the score distribution. The dotted horizontal line at 0.50 indicates chance performance. The figure shows above-chance group performance alongside individual variability.

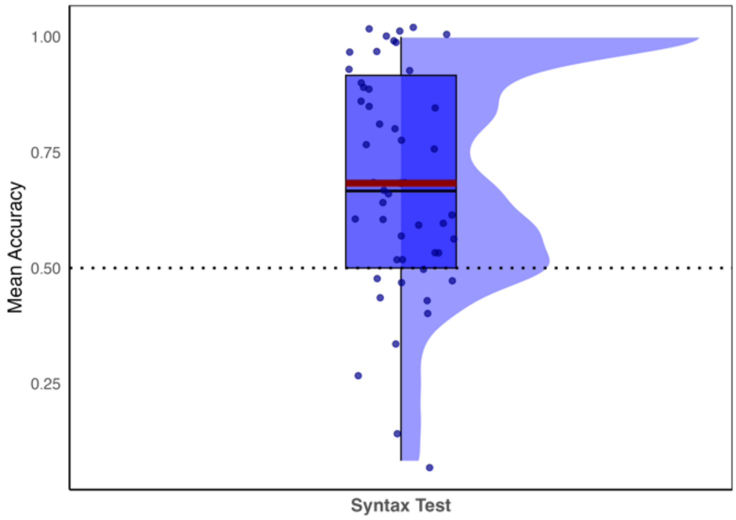
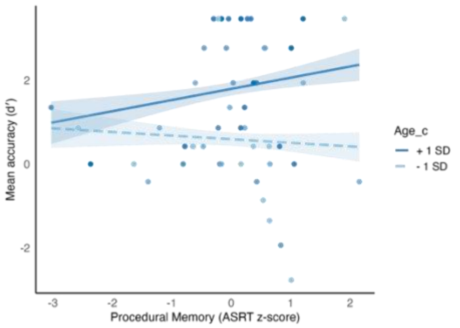
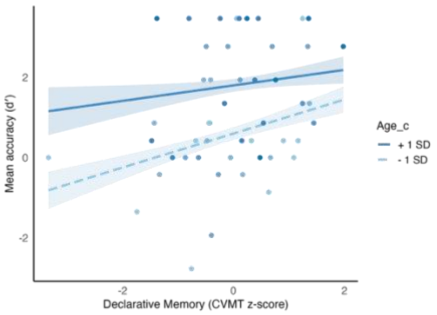


Figure 4.5 Effect of the interaction between age and procedural memory (left figure) and between age and declarative memory (right figure) on syntax learning. Predicted probabilities are plotted separately for younger (−1 SD; approximately age 8.5) and older (+1 SD; approximately age 12.5) children based on centered age values (range: 8-13 years). Shaded areas represent 95% confidence intervals.





Discussion

Middle childhood through early adolescence represents a critical developmental transition. Internally, children's cognitive systems, particularly memory systems, undergo substantial maturation (e.g., Ahmed et al., 2022; Ullman, 2004); externally, language learning becomes increasingly responsive to explicit instruction (e.g., DeKeyser, 2012). The current study investigated how procedural memory, declarative memory, and working memory interact with children and adolescence early stages of L2 exposure in a CSL context where explicit grammar knowledge (word order) penetrated the acquisition of a novel language. Our research questions examined how individual differences in procedural memory, declarative memory and working memory capacities might interact with the learning of vocabulary and grammar from cross-situational statistics, and whether the associations are moderated by age.

Association between procedural and declarative memory with language learning under explicit instruction

Based on the D/P model (e.g., Ullman, 2004; Ullman & Morgan-Short, 2023), our first prediction was that procedural memory would support the acquisition of grammatical features, specifically, marker words and word order, because these elements do not map onto single concrete referents in the scene (i.e., animal characters or the actions they are performing) in the same direct way as nouns and verbs, and instead require abstract pattern extraction (Ullman, 2020). In contrast, we expected declarative memory to support the learning of nouns and verbs, which involve forming direct associations with referents presented in the scenes (Ullman, 2020). This prediction was only partially supported. We found no significant relationship between declarative memory and vocabulary learning, but procedural memory positively predicted older children's sensitivity to the verb-final word order. This association between procedural memory and grammar learning is in line with Pili-Moss (2021), in which 8- to 9-year-old children's learning of L2 word order was predicted only by procedural memory (with a small effect size).

As noted by Ullman and Morgan-Short (2023), more input promotes reliance on procedural memory whereas limited or instructed input leads to reliance on declarative memory. The learning of word-referent mappings in the current CSL paradigm, was ambiguous, requiring learners to accumulate statistical regularities over time, rather than consciously remembering the target information within a single trial. In this sense, the cross-situational learning of vocabulary in the current task may have engaged procedural memory to some extent (Ruiz et al., 2021; Ullman, 2004).

Declarative memory was, however, identified as a predictor of sensitivity to the verb-final constraint across age groups, in line with our second prediction, and consistent with Morgan-Short et al.'s (2022) view that explicitly instructed grammar knowledge relies on declarative memory (see also Walker et al., 2020). Our study showed that instructional context plays a critical role in modulating the contribution of memory systems in early stages of children's grammar learning.

The role of working memory in vocabulary and grammar learning under explicit instruction

Our third prediction that working memory would predict both vocabulary and grammar learning was also confirmed, for verb and grammar learning. We found that the manipulation and storage components of working memory operated as distinct constructs that modulate the early stages of L2 learning. Manipulation skills (digit span backward) were associated with greater verb learning, and storage capacity (digit span forward) was linked to higher performance in syntax (word order) learning. This finding fits well with earlier studies showing that different aspects of working memory play distinct roles in language acquisition (e.g., Engel de Abreu & Gathercole, 2012; Ellis & Sinclair, 1996; Martin & Ellis, 2012; Verhagen & Leseman, 2016).

In contrast to some prior research showing a link between PSTM and vocabulary acquisition (e.g., Engel de Abreu & Gathercole, 2012; Verhagen & Leseman, 2016), we found that verb learning was predicted not by the storage component of working memory but by complex WM, which involves both the phonological loop and the central executive (Perez, 2020; Ruiz et al., 2021). It is possible that explicit instruction triggered the involvement of memory systems during learning. Among the three vocabulary categories consisting of our novel language, only verb acquisition was significantly predicted by complex working memory. Prior to exposure, participants were explicitly taught the verb-final word order rule of the artificial language, which likely directed their attention to the final word in each sentence and to the action being performed in the corresponding scenes. Yet, in a similar CSL paradigm without such instruction with adults (Walker et al., 2020), complex WM did not predict vocabulary learning. Explicit instruction may increase the role of the executive component of working memory.

In our study, children with higher complex working memory capacity were better equipped to store and integrate co-occurrence cross-modal associations (i.e., audio words and visual referents) across ambiguous situations. In an audio-visual vocabulary learning study, Perez (2020) demonstrated that complex working memory significantly contributed to vocabulary learning in incidental learning conditions, whereas phonological short-term memory did not. Together, these studies support Ellis and Sinclair's (1996) claim that working memory plays a crucial role in forming cross-modal associations between linguistic and visual input.

For grammar learning, we found phonological short-term memory, rather than complex working memory, predicted performance, reflecting previous studies (French & O'Brien, 2008; William and Lovatt, 2005). Our GJT task could be completed solely by learners' sensitivity to word order within sentences, without any need to process semantic information from the visual scenes. This fits well the account that phonological short-term memory supports sequence learning when there is no need of semantic analysis or top-down processing (Williams & Lovatt, 2005).

Complex working memory, involving attentional control and simultaneous storage and processing, is likely to be engaged when instruction imposes a high online processing load, such as during interactional feedback or recasts that require learners to rapidly interpret, compare, and revise linguistic forms in real time (e.g., Li et al., 2019). In contrast, the current study provides evidence that when explicit instruction is pre-exposure and learners' tasks are to retain and apply a previously taught syntactic rule across learning trials, the storage component of working memory may serve as the primary cognitive resource.

Age-aptitude interaction in grammar and vocabulary learning under explicit instruction

Our initial prediction regarding the age-aptitude interaction was that the effects of declarative and working memory would be moderated by age, while the effect of procedural memory would remain relatively stable across development. This prediction was partially supported. Consistent with our hypothesis, we found that working memory and declarative memory indeed interacted with age. However, contrary to our initial prediction, procedural memory also interacted with age.

The positive two-way interaction between age and complex working memory during the training phase suggested that as children become more cognitively mature (around 10 to 12 years of age in the current study), those with greater complex working memory capacity started to show an advantage in processing linguistic input, involving noticing and pattern identification (Skehan, 2002). Previous CSL studies focusing on younger children (aged around 3.5 to 7 years, e.g., McGregor et al., 2022; Sia et al., 2023) have found no association between working memory and cross-situational word learning, whereas Zhou et al. (2024) has found 6- to 12-year-olds's learning associated with working memory. While the core structures of working memory are in place by around 5 years of age, its functional capacity continues to improve steadily through middle childhood and adolescence (Ahmed et al., 2022).

In addition, we found that the role of procedural memory was modulated by age during both training and grammar testing phases.We also observed a negative two-way interaction between age and declarative memory for grammar learning outcomes. These interactions suggest a developmental shift in the contribution of declarative/procedural memory systems in early stages of L2 learning.

For procedural memory capacity, while researchers (e.g., Ullman, 2004) have proposed that it matures early and remains relatively stable throughout development, our results indicate a potential child-adult difference regarding its role in initial stages of L2 learning (cf. Ruiz et al., 2025). For declarative memory, on the other hand, the interaction with age revealed a declining benefit of declarative memory across development. This finding may expand our understanding of the D/P model (Hamrick, 2015; Ullman, 2004; 2005), which posits that children learning their L1 grammar rely more on procedural memory, while adults learning their L2 grammar rely more on declarative memory. Our results suggest that for children and adolescents learning the sentence-level structural regularities in an L2 under explicit instruction, both memory systems are involved, but their influence is modulated by age.

In our data, age emerged as the strongest predictor of early L2 performance on the verb-final word order acquisition during the critical developmental window of 8 to 13 years that we tested, accounting for the largest proportion of variance. Moreover, beyond age, declarative memory ($\Delta R^2 = .05$) and working memory ($\Delta R^2 = .02$) accounted for additional variance. While memory abilities may be the primary driver of language learning variability in early childhood (Vlach & deBrock, 2017), by middle childhood and early adolescence, age becomes a more robust predictor which integrates cognitive maturity with other co-developing nonbiological factors, such as formal schooling and metalinguistic awareness, all of which are critical to success in instructed L2 learning contexts (e.g., Roehr-Brackin, 2025; Unsworth, 2016).

Taken together, these findings highlight the importance of considering the developmental changes in individual differences in cognitive abilities when examining

L2 learning processes and outcomes, in particular for the effect of explicit instruction in child populations.

Limitations and future direction

The current study identified age as the strongest predictor for early stages of L2 learning, with memory abilities explaining additional but a smaller proportion of variance. However, we did not include cognitive systems other than memory, such as analytic reasoning (e.g., Paradis et al., 2017), statistical learning ability (e.g Monaghan et al., 2023), or general language learning skills (e.g., vocabulary size, Vlach & DeBrock, 2017). Including these additional measures in addition would help fill out our understanding of developmental individual differences impacting language learning. A second limitation concerns the measurements of memory systems in child populations, which may be lower in reliability than for adults (West, 2017) due to attentional fluctuations. Future research should aim to replicate our findings using multiple measurements of declarative and procedural memory and include control measures for attention and task engagement for children. Furthermore, the current study mainly focused on memory and learning under explicit instruction. Other patterns of individual difference may give rise to advantages for implicit learning (e.g., Ruiz et al., 2025).

Conclusion

This study provides compelling evidence for the cognitive and developmental factors underlying age-related improvements in L2 learning during the critical developmental period from 8 to 13 years of age. Using a cross-situational learning paradigm with explicit pre-exposure instruction about the verb-final word order, the study examined how memory systems contributed to children’s learning of word-referent mappings and sentence-level structural regularities. The findings offer important theoretical and practical implications for the field of child L2 acquisition.

Theoretically, the current study provides empirical evidence in refining the D/P model, suggesting that the extent to which procedural and declarative memory systems are involved in the acquisition of word-referent associations or rule-based morphology can be modulated by the learners’ age. In addition, we identified that the two components of working memory, phonological short-term memory and complex working memory, serve as distinct contributors to supporting early L2 acquisition. Their contribution appeared to be modulated by developmental age as well as the cognitive demands imposed by the linguistic and instructional input.

Practically, the results suggest that brief explicit metalinguistic information may be particularly beneficial for learners who are developmentally ready to use it. For young children with higher declarative memory capacity, explicit instruction is more likely to facilitate learning of the sentence-level structural regularity tested in the current study. Conversely, for learners with lower memory capacities, such as working memory or declarative memory, our findings suggest that developmental maturation can partially compensate for early cognitive limitations, enabling them to benefit from explicit instruction as they grow older.

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Supplementary materials

Appendix A

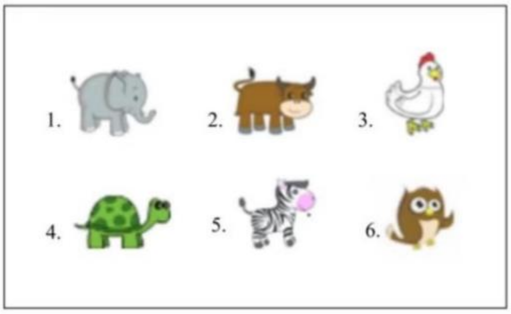
Pseudoword lexicon used in the experiment (adapted from Monaghan and Mattock, 2012).

The six bisyllabic content words used as nouns were: *barget, limeber, jeelow, goorshell, nellby, bimdah.* The four bisyllabic content words used as verbs were *dingep, fisslin, rakken, makkot*. The two monosyllabic words used as grammatical role markers (subject/object) were *tha* and *noo*.

Appendix B

Animal characters used in training and testing blocks.

Animal characters occurred across the experiment with equal frequency.



Appendix C Supplementary Tables

Table S4-1 Summary of descriptive statistics and one-sample *t* tests on mean accuracy for each training blocks.

Block	1	2	3	4	5	6
	n=50	n=50	n=50	n=50	n=49[9]	n=49
Mean	0.54	0.54	0.56	0.58	0.59	0.64
SD	0.14	0.18	0.19	0.21	0.21	0.20
t value	1.76	1.62	2.34	2.72	3.02	4.75
df	49	49	49	49	48	48
p value	0.085	0.111	0.024	0.009	0.004	<.001
Cohen's *d*	0.25	0.23	0.33	0.39	0.43	0.68

Table S4-2 Best fitting model for accuracy in training trials, showing fixed effects.

Fixed Effects	Estimate	SD Error	Z	*p*
(Intercept)	0.327	0.085	3.865	<.001
ot1	10.510	3.333	3.153	.002
Age: ASRT	0.093	0.036	2.560	.010
Age: Digitspan_Back	0.075	0.035	2.113	.035

Number of observations: 3582, Participants: 50. AIC = 4720.8, BIC = 4764.1, log-likelihood = -2353.4. R syntax: glmer(accuracy ~ 1 + ot1 + Age :ASRT + Age : Digitspan_Back + (1+ot1 | participant), data = dat_training, family = "binomial").

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[9] Due to the technical issue, one participant's data for block 5, block 6 and GJT (syntax test block) was not recorded. Block 6 was where vocabulary test 2 was posited.

Table S4-3 Summary of descriptive statistics and one-sample *t* tests of mean accuracy against chance for each vocabulary test block.

	Test1 (n=50)	Test2 (n=49)
Nouns:		
M	0.50	0.46
SD	0.50	0.50
t value	0.00	-1.41
p value	1.000	0.165
Cohen's *d*	0.00	-0.20
Verbs:		
M	0.59	0.58
SD	0.49	0.49
t value	2.45	2.27
p value	0.018	0.028
Cohen's *d*	0.35	0.32
Marker words:		
M	0.61	0.59
SD	0.49	0.49
t value	3.07	2.59
p value	0.003	0.013
Cohen's *d*	0.43	0.37

Table S4-4 Summary of descriptive statistics and one-sample *t* tests on mean accuracy for syntax (word order) test block.

Syntax (n=49[10]*)*	
M	0.68
SD	0.47
t value	5.19
p value (*d'*)	<.001
Cohen's *d*	0.76

Table S4-5 Best fitting model for accuracy in syntax testing trials, showing fixed effects

Fixed Effects	Estimate	SD Error	*t*	*p*
(Intercept)	1.196	0.056	21.511	<.001
Age	0.338	0.033	10.308	<.001
Declarative memory	0.308	0.057	5.378	<.001
Working Memory (Forward)	0.226	0.057	3.943	<.001
Age: Procedural memory	0.099	0.010	3.378	<.001
Age: Declarative memory	-0.065	0.029	-2.277	.023

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[10] Due to the technical issue, one participant's data for GJT was not recorded.

5 General discussion

5.1 Summary of key findings

This thesis examined the internal and external factors in early stages of L2 grammar and vocabulary learning, focusing on an underrepresented population, children across 8 to 13 years of age (Isbilen & Christiansen, 2022; Roehr-Brackin, 2024). Across three studies, it was uncovered that middle childhood through early adolescence was a critical period for L2 learning, which undergoes significant changes regarding the way learners' individual differences factors interacted with the linguistic input. Moreover, this project adopted an increasingly widely used CSL paradigm (Rebuschat et al., 2021) during which learners were exposed to a complex artificial language, providing a methodological possibility for an examination of multiple learning factors in a highly-controlled but more ecologically valid input environment than other artificial vocabulary or grammar learning studies (e.g., Spit et al., 2022; Yu & Ballard, 2007).

5.1.1 RQ1: How does cross-situational learning of vocabulary and grammar change across middle childhood to early adolescence?

The first research question of the current thesis taps into the developmental changes of cross-situational statistical learning of vocabulary and grammar during middle childhood through early adolescence. This question is answered together by study 1, 2 and 3. In the first study (Chapter 2), 8- to 9-year-old children were trained on the artificial language through a CSL task, without any feedback or explicit instruction. During the CSL task, children could only learn word-referent associations and grammar knowledge (sentence word order knowledge) by tracking the statistics from the input across trials. Furthermore, vocabulary and grammar could be tested for learning simultaneously as all language features were previously unknown to all participants. Note that most existing studies pretrained on vocabulary before the exposure to artificial sentences. Results showed that children at this age were able to effectively acquire the grammar knowledge through navigating the conjunction of sentences and scenes to which they refer. However, accuracies for each vocabulary type (i.e., nouns, verbs and case markers) were not observed to be significantly above chance. The results suggest a child-adult distinction in CSL: adults were able to learn both vocabulary and grammar simultaneously from similar input (Monaghan et al., 2021; Ruiz et al., 2025; Walker et al., 2020), while children only showed evidence for learning syntax, but not vocabulary.

Following up on the finding of a child-adult distinction in CSL uncovered in Study 1, Study 2 (Chapter 3) exposed children aged 8 to 13 to the same CSL task as in Study 1 to further explore the changes across development. Study 2 replicated the finding in Study 1 that young children (aged 8 to 9) found it difficult to learn word-referent associations from cross-situational statistics, but grammar is more ready to be learned. Results from Study 2 and Study 3 (Chapter 4), which adopted the same CSL paradigm as Study 1 and 2, and tested the children at the same age range as Study 2, indicated a clear developmental trajectory with older children in the current populations demonstrating a more effective CSL.

5.1.2 RQ2: To what extent does the external factor (i.e., explicit instruction) affect children's learning of vocabulary and grammar through cross-situational learning, and how does this factor interact with age?

Study 2 directly answered this question by training children aged 8 to 13 the same CSL task as in Study 1 except with half of them receiving the explicit instruction on the verb-final grammar knowledge prior to the learning task commencing. Results suggested a positive age-instruction interactional effect on CSL performance. Specifically, children aged 12-13 years showed a marked openness to explicit instruction, leading to higher accuracy on both vocabulary and grammar learning tasks.

Study 2 found evidence for a qualitative developmental change driven by the interaction between age and instructional input, reflecting a possible role of working memory maturation behind this interaction, though this was not tested in this study. It was also found in Study 2 that while vocabulary learning was affected by age, grammar learning appeared more consistent across age groups. This distinction reflected the developmental trend of declarative and procedural memory. Procedural memory which relates more closely to the learning of syntactic regularities, tends to mature in early childhood, while declarative memory which relates to vocabulary learning tends to reach maturity later in adolescence (Pili-Moss, 2021; Morgan-Short et al., 2014; Ullman, 2004).

5.1.3 RQ3: To what extent do internal factors, including age, working memory, procedural memory and declarative memory, affect children's learning of vocabulary and grammar through cross-situational learning under explicit instruction, and how do these factors interact?

Following up on the findings in Study2, Study 3 were set out to answer the third research question. Study 3 provided the same explicit instruction and focused on the same population (i.e., children aged 8 to 13 years) as Study 2. Results first demonstrated that the involvement of procedural and declarative memory in the acquisition of word-referent associations and rule-based morphology could depend on the type of linguistic input (i.e., cross-situational statistics and explicit instruction) and learners' age. The second key finding was that two components of working memory (phonological short-term memory and complex working memory) serve as distinct constructs in supporting L2 acquisition. Furthermore, their contribution was modulated by the cognitive demands imposed by the linguistic and instructional input. Specifically, for the task that requires both the storage of phonological information and tracking the word-referent associations, complex WM got involved. For the task (i.e., GJT) that required only the sensitivity towards word-order structure without the need to process semantic information from visual scenes, PSTM was engaged. Moreover, the effect of WM was also modulated by developmental age with a clear effect as a significant predictor observed only for children around 12 years old.

5.2 Cross-situational learning across development

Age-related effects have been long studied in SLA research, and has also been explored in increasing depth in CSL studies. However, there is a clear research gap in the (cross-situational) statistical learning literature: most research has focused on infants, pre-school children, and adults, with school-aged children underexplored (Isbilen & Christiansen, 2022; Rebuschat et al, in prep). The current thesis provided a way of testing age-related effects in a highly controlled yet more ecologically valid, immersive environment than traditional CSL paradigms. This CSL paradigm also allowed investigation on both online, overall learning process, and learning outcomes (e.g., GJT task). Across three studies, I addressed this gap in studies of middle childhood and early adolescence by testing a total of 220 children across 8 to 13 years of age, expanding our understanding of cross-situational statistical learning across the lifespan. Across three studies, I found cross-situational statistics powerful and effective in supporting the learning aspects of a complex artificial language for 8- to 13-year-old learners, and consistently observed a significant effect of block, meaning that learning improved as exposure proceeded. However, the power of cross-situational statistics seems to be limited for younger learners, and children became more capable of CSL during development. There were two key observations regarding age effects.

Firstly, I observed a consistent developmental trajectory of CSL across middle childhood to early adolescence across Studies 2 and 3, with older children presented a more effective early-stage L2 learning. This “the-older-the-better” trend was in line with the belief that SL ability increases with age (e.g. Arciuli & Simpson, 2011), while challenging the view that statistical learning is age-invariant (e.g., Saffran et al., 1997; Moreau et al., 2022). This finding also echoes the evidence regarding the age-related effect in SLA research, showing that older learners outperformed younger learners in the initial L2 learning stages (e.g., Jia & Fuse, 2007; Menks, 2024; Snow & Hoefnagel-Höhle, 1978; Snedeker et al., 2012).

Younger children (around 8 years old) in the current series of studies found vocabulary learning more challenging than learning the verb-final word order constraint. When these younger learners need to learn word-referent associations and the sentence structure simultaneously from cross-situational statistics without any feedback and instruction, they acquired the verb-final word order constraint successfully, but showed no evidence of vocabulary (nouns, verbs, and markers) learning. This finding was consistent in learners from Studies 1 and 2 who did not receive explicit grammar instruction. Nevertheless, existing studies (e.g., Monaghan et al., 2021) reported adults' capability of simultaneous vocabulary and grammar learning from similar statistical input. This simultaneous learning capability was only observed in the current project when children reached around puberty. Children in the 12-13 age group were more capable of tracking word-referent co-occurrence while abstracting sentence patterns merely from input statistics, and their test scores became more like adults did. Children in the 12-13 age group reached mean accuracy of 62% and 66% for verb and grammar tests respectively, similar to adult performance in learning the same artificial language which reached mean accuracy of 67% and 63% respectively in Ruiz et al. (2025).

An important question arising from these findings concerns the representational nature of what was learned about sentence structure as measured by GJT in the current thesis project. The evidence across studies suggests that sentence-level structural learning may occur at different representational depths across development. For younger learners (particularly 8- to 11-year-olds in Study 1 and 2), above-chance performance on the GJT likely reflects distributional sensitivity to recurring positional patterns in the input, as they presented above-chance performance on the GJT but no consistent evidence of verb learning. That is, learners may have detected that certain word forms consistently appeared in sentence-final position and that deviations from this pattern were unfamiliar. This form of learning is consistent with pattern extraction from cross-situational statistics and does not necessarily imply that learners represented verbs as a grammatical category. In contrast, older learners (particularly the 12-13-year-olds in Study 2 and participants in Study 3) demonstrated successful verb learning alongside above-chance performance on the GJT. In these cases, sentence-final regularities may have been supported by lexical knowledge, allowing learners to associate specific lexical items with structural roles.

Importantly, the present findings do not demonstrate the acquisition of hierarchical phrase structure or category-general syntactic rules beyond the constraints tested. Rather, they provide evidence that children and adolescents can acquire sentence-level structural regularities from cross-situational statistics, with the depth and nature of representation appearing to change developmentally. More generally, these interpretations should be understood as specific to the current CSL task, which involved a simple artificial grammar and a highly constrained forced-choice learning environment.

This age-related difference underscored in the current thesis echoes Newport (2020), who suggested that age could play a critical role in shaping how learners extract and use input statistics and in determining which language structures are more readily learnable at different developmental stages. Children and adults presented different learning behaviors of abstracting regular versus probabilistic rules from input statistics in Newport (2020). Children (aged around 5-6 years) showed their capability of rule generalization from input statistics, but they could not capture or reproduce the probabilistic variations in the input, which, however, was observed in adults' productions.

Secondly, results from the testing trials provide insight in the different developmental patterns underlying grammar and vocabulary acquisition. When acquiring a novel language comprising previously unknown syntax and vocabulary, the acquisition of vocabulary tended to depend more on age. Specifically, for vocabulary learning, learners at the age of 12-13 years successfully acquired verb-referent mappings through cross-situational statistics, while younger learners showed no evidence of this. It is important to note that I am not interpreting the null result of vocabulary learning among children in younger age groups as children's lack of ability to learn vocabulary from CSL. Previous study (e.g., Scott & Fisher, 2012, Experiment 1 showed that children as young as 2.5 years old could use cross-situational statistics to constrain the correct novel verb-action associations when novel verbs were embedded in the natural language. Indeed, what I proposed here is that when learners are exposed to complex linguistic input, the power of CSL for vocabulary learning may be limited by other individual difference factors such as age, attention, cognitive abilities, and vocabulary size, which will be further discussed in the following sections. This is reflected in Scott and Fisher's (2012) Experiment 2. This study tested 2.5-year-old children's productive vocabulary size and CSL of transitive and intransitive verbs, thereby manipulate learning complexity and enable the investigation of the limits of CSL ability. In Experiment 1, when novel intransitive verbs were placed in target sentences (e.g., "She is pimming"), no significant difference was observed between low- and high-vocabulary learners. However, when the target sentences became more complex in experiment 2, in which the novel verbs were placed in transitive frames (e.g., "She is pimming her toy") which requires the process of additional noun-phrase argument, learning performance was affected by productive vocabulary, with only high-vocabulary children showed successful learning similar to Experiment 1, while low-vocabulary children failed to do so. This is where individual differences, such as vocabulary size, or more broadly, working memory, may come into play. For vocabulary size, it may facilitate verb learning in transitive frames through inferencing: children with larger vocabularies are better able to use their existing knowledge of the nouns in the sentence, the agent and the patient, to infer the likely meaning of the novel verb, thereby reducing the referential ambiguity that the transitive frame would otherwise introduce (Scott & Fisher, 2012). For working memory, Scott and Fisher (2012) also raise the possibility that low-vocabulary children's difficulty may have partly reflected lower working memory capacity, which would limit their ability to encode, retrieve, and compare the more complex sentence-event pairings encountered in transitive frames.

Grammar learning, on the other hand, was less sensitive to age than vocabulary learning, presenting a quantitative, but not a qualitative change over development. Grammar could be effectively learned across 8 to 13 years, contrasting with the younger children's greater difficulty in vocabulary acquisition. Nevertheless, I still observed a significant positive effect of age on grammar learning consistently in both Studies 2 and

3, with older children performing with higher accuracy on GJT. This age-related effect is in line with studies such as Menks (2024), which reported a steep developmental trajectory of novel grammar learning outcomes on learners from the age of 8 to around 15.

There remain open questions that emerged from the current data with not yet enough evidence to resolve. This is mainly regarding the word-referent association learning in the current complex CSL task. Word learning from the traditional CSL paradigm has been found to be powerful and effective for both child and adult populations (e.g., Vlach & DeBrock, 2017; Yu & Smith, 2007). However, in my studies, I observed a difficulty for learning of nouns across the three studies, among the 220 participants in total (yielding 8 experimental groups), the only group of children who learned nouns successfully was the 10-11-year-old group under the explicit instruction condition. There is also an interesting pattern emerging from Study 3 concerns the dissociation between noun, verb, and marker learning. Verbs and marker words were learned significantly above chance, whereas nouns were not.

This observed difficulty of noun learning in the current CSL paradigm is likely due to the increased referential ambiguity within each trial in the adopted paradigm. Isbilen and Christiansen (2022) proposed that the existing CSL studies most rely on perfectly uniform co-occurrence information, yet these previous designs do not reflect language learning in real world which is certainly more varied regarding the linguistic and statistical properties. When referential ambiguity was increased, for example as in Benitez and Li (2024), they found that children's learning performance was worse in their two-to-one condition (learning two words for one object) than in one-to-one condition. The referential ambiguity in the current studies was even more challenging, as there are multiple words appeared with two possible scenes in each trial (for more discussion on complexity, see Chapter 2 Discussion). Even though the explicit instruction informed learners that nouns appeared at the first and second positions, this knowledge could not resolve which noun mapped onto which object. Verb learning, by contrast, benefited from two sources of support. First, referential ambiguity was substantially lower: only two actions were available as competing referents per trial, compared to four objects. Second, the explicit instruction drew learners' attention to verb-final position, providing a directly instructed positional cue. The combination of lower referential competition and explicit information likely jointly supported successful verb learning.

Another interesting finding is that, though being regarded as difficult to learn even for adults (e.g., Monaghan et al., 2021), children in Study 3 learned marker words fast and successfully at a group level. Note that, unlike verbs, markers received no explicit instruction, yet were learned successfully, in contrast to nouns, for which positional information was explicitly provided but learning still failed. This finding is consistent with evidence from artificial language learning studies with adults. For example, Marsden et al., (2013) demonstrated that even when learners' attention was directed to stem meanings rather than suffixes, above-chance suffix meaning learning still occurred. Although marker learning was analyzed as vocabulary in the current studies, the case markers in the artificial language functioned as morphosyntactic cues signaling subject and object roles within the sentence. The acquisition of markers therefore reflects sensitivity not only to word-referent mapping but also to grammatical categories and argument structure within sentences. Marker learning thus represents an additional dimension of sentence-level structural learning beyond positional regularities alone. Nevertheless, the findings regarding successful marker learning in Study 3 warrant cautious interpretation and further examination, mainly given that marker learning was significant in Study 3 but not in Study 2, despite both studies testing the same age range (8-13 years), using identical explicit instruction and identical CSL tasks.

However, I did not find any significant predictors for what makes a successful noun and marker learner. This thesis included both internal and external factors, however, neither age, memory, explicit instruction, nor their interactions could predict noun and marker word testing scores as tested in the mixed-effects models. This is broadly consistent with Marsden et al. (2013), who similarly found that the orientation of attention during training, whether directed to form or meaning, had little differential effect on the pseudoaffixation effects observed. In an adult study which adopted the similar CSL paradigm as the current thesis but included different types of instructions and memory measurements, Ruiz et al. (2025) also found no association between either learning conditions or memory abilities with marker word learning. However, the awareness of marker word knowledge (i.e., whether learners could articulate the position or function of the two case markers) was identified as a key predictor.

Therefore, for future studies, it is valuable to test the power (and also the limits) of cross-situational statistics in supporting word learning in more ambiguity and challenging input environment, as well as examining additional individual differences measures that were not included for marker learning in the current thesis, such as whether learners can verbalize the function or position of the case markers, as in Ruiz et al. (2025). This is also motivated by the finding of Marsden et al. (2013) that explicit knowledge of morphological forms was associated with higher accuracy than implicit, intuition-based responding, which suggested that the transition from implicit sensitivity to explicit awareness may be a key step in consolidating morphological learning. Including this variable can also contribute to the understanding of CSL mechanisms: whether it proceeds associatively, or alternatively, via hypothesis-testing (for more discussion, see for example, Roembke et al., 2023). If awareness predicts CSL, this would suggest that, at least for certain tasks and at initial learning stages, CSL is more dependent on awareness and thus supports the propose-but-verify (hypothesis-testing) account (e.g., Trueswell et al., 2013).

Another possible individual difference predictor can be receptive and productive vocabulary size. Findings in previous studies (e.g., Scott & Fisher, 2012; Vlach & DeBrock, 2017), which suggested that learners with higher vocabulary size showed better learning of word-referent associations under more complex learning tasks, motivates the prediction that vocabulary size, which represents general language learning abilities, plays an important role in the learning of new words. However, it is important to note that vocabulary size has also been found to associate with general cognitive abilities such as working memory (e.g., Marchman & Fernald, 2008). Therefore, future studies should be designed to jointly control vocabulary and memory to probe unique versus shared variance. Notably, in Vlach and DeBrock (2017), memory abilities served as stronger predictors in cross-situational word learning than language ability (i.e., receptive vocabulary size) for preschoolers. It is therefore particularly interesting to test whether there is a developmental change in the dominant driver of CSL. Given that neither age nor memory abilities tested in the current thesis could explain the variation of nouns and marker word learning, could it be the general language abilities that driving CSL for the current populations?

5.3 Effect of explicit instruction across development

Consistent evidence has demonstrated that explicit instruction facilitates L2 learning (e.g., Goo et al., 2015; Norris & Ortega, 2000; Spada & Tomita, 2010). However, most research exploring the effect of instruction primarily focused on adolescents and young adults, while leaving young learners' (under age of 12) ability to use explicit instruction rarely explored (Roehr-Brackin, 2024). In the current project, it was observed that explicit instruction boosted children's L2 learning, as well as the development of metalinguistic awareness. Learners who received explicit instruction over the word order knowledge presented steeper learning trajectories and reached higher accuracy than children with no explicit instruction, particularly for 12-13-year-olds. This finding indicated that children's L2 learning process can be amenable to explicit instruction, and contributes to Lichtman's (2013) instructional hypothesis, which proposes that previous assumptions that children rely more on implicit learning are simply because they are more likely to be exposed to implicit learning, and children can benefit from explicit instruction when they are exposed to it.

In the current study, children as young as eight years old demonstrated an ability to articulate the word order rule after receiving explicit instruction, while children in implicit condition could not. These findings align with Lichtman's (2016) argument that explicit instruction leads to explicit language knowledge regardless of age, making learning environment an important factor in addition to age. Furthermore, this metalinguistic awareness was identified as a key predictor for successful verb learning, particularly consistent with Schmidt's (1990) noticing hypothesis which suggested the importance of noticing the grammatical patterns so as to be able to apply them productively. Specifically, the predictor of successful learning of verb-action mappings was not merely the receipt of instruction, but rather the learners' ability to verbalize the verb-final word order knowledge. This was also reflected in a similar study on adult populations. Ruiz et al. (2025) found that learners who could verbalize the case marker rules were more successful in CSL of marker words.

The significant effect of explicit instruction on children's performance during CSL tasks may contribute to the broader debate of the implicit and explicit learning interface in SLA research, indicating that explicit knowledge can be helpful in learning process that proceeds without conscious awareness (e.g., R. Ellis, 1993; N.C. Ellis, 2015). Specifically, explicit learning engages conscious processing, particularly at the initial registration of language patterns which can then be tuned and enhanced by subsequent unconscious learning during input processing (N.C. Ellis, 2005). N.C. Ellis proposed several interesting and important questions: "What can be learned implicitly? If implicit learning is simply associationist learning and the induction of statistical regularities, what aspects of language can be so acquired? …What are the developmental paths of implicit and explicit learning abilities? ..." (2015, p.4). The current thesis provides some preliminary empirical evidence relevant to these questions, though it is important to note that awareness during learning was not directly measured, and therefore claims about the implicit nature of the learning processes observed should be interpreted cautiously. First, I found that verbs can be learned from merely tracking the cross-situational statistics, without the need of explicitly drawing learners' attention to verbs, at least for the older children under the current CSL tasks, as the reception of the verb-final word order instruction did not affect the verb testing scores. Instead, developmental factors predicted verb learning. Specifically, Study 2 underscored that 12-13-year-old learners (but not their younger peers) in both implicit and explicit conditions learned verb-action mappings successfully, and Study 3 indicated that the higher complex working memory capacity predicted verb learning. Nevertheless, Study 3 did not include an implicit condition, thus it still remains inconclusive whether working memory played its role in interaction with instruction. However given that Study 2 found that children's CSL of verbs was less dependent on explicit instruction, it may be the case that cross-situational learning of verbs by its nature is the language feature that is less sensitive to explicit instruction but more dependent on cognitive maturation.

However, it should be noted that the awareness measure in the present study assessed participants' knowledge of the word-order rule rather than their awareness of verb-action mappings. Therefore, the current data do not allow us to determine whether verb learning occurred with or without conscious awareness of the learned associations. While it remains possible that some degree of conscious knowledge of verb meanings emerged during learning, the present findings nonetheless indicate that successful verb learning did not depend on explicit instruction about verbs themselves. Rather, learners were able to acquire verb-action mappings from the cross-situational co-occurrence information available in the input. It is also important to note that the more successful learning of verbs, compared with nouns and markers in the current studies, is likely to be related with the language structure of the current artificial language, which follows either SOV or OSV (i.e., verbs are always at the end of the sentence), making verbs relatively salient within a sentence. Therefore future work adopted varied artificial language structures is needed to further explore what aspects of language can or cannot be learned through induction of input statistics.

Second, the significant age-instruction interactional effect observed in Study 2 directly responses to Ellis' question regarding the developmental path of implicit and explicit learning. The explicit instruction over the word order syntax knowledge only boosted older learners' (aged around 12 years old) syntax learning, but not younger children, who behaved similarly to those in the implicit condition.

In addition to age and explicit instruction, both the long- and short-term memory capacities explained L2 learning variations on child populations in the current project. The following sections will discuss how memory capacities affected CSL as well as how their effect shifted across development.

5.4 Effect of working memory capacity in L2 learning

5.4.1 Working memory as a main effect

The current thesis found that WM was a significant predictor to vocabulary and grammar learning outcome, consistent with the previous literature (e.g., Service, 1992; Ellis & Sinclair, 1996; Martin & Ellis, 2021). It contributes to the theoretical models of WM in which WM contains different subsystems, each serving as a distinct construct in supporting the L2 acquisition of different language features (e.g., Baddeley & Hitch, 1974; Li, 2017). Specifically, it was identified that the PSTM (i.e., the phonological loop) and complex WM (i.e., the phonological loop plus the central executive) operated as distinct constructs modulating the early stages of simultaneous L2 vocabulary and grammar learning. The complex WM was associated with greater verb learning, whereas the PSTM was linked to better performance in syntax (word order) learning, fitting well with earlier evidence indicating that different aspects of working memory play distinct roles in language acquisition (e.g., Engel de Abreu & Gathercole, 2012 ; Martin & Ellis, 2012; Verhagen & Leseman, 2016). Associations between different components of WM and different language features are likely shaped by the cognitive demands leveraged by instruction and input statistics.

A successful learning of verb-action mappings in the current CSL task required not only the storage of phonological information, but also tracking the co-occurrence of words and their visual referents (i.e., actions performed by animal characters) across situations. This learning process is likely to place substantial demands on the executive component of working memory, which enables learners to maintain and update information about form-meaning pairings across trials while inhibiting competing associations. This aligns with findings from Perez (2020), who demonstrated that complex WM supported audio-visual vocabulary learning. In addition to the statistical input, children in Study 3 also received explicit instruction over the verb-final sentence word order. This explicit information particularly favors the function of WM that enable learners to selectively focus on the relevant information and filter out irrelevant input to decrease ambiguity and thus lead to a better verb learning.

On the other hand, grammar acquisition in the current studies could be completed solely by learners' sensitivity to the verb-final word order within sentences in the GJT, without any need to process semantic information from the visual scenes. This nature of the GJT fits well the account that PSTM supports sequence learning when there is no need of semantic analysis or top-down processing (Andrade & Baddeley, 2011; Williams & Lovatt, 2005). This observation, that PSTM rather than complex WM, was associated with children's grammar learning under explicit instruction indicated that when grammar learning involves applying a taught rule in a sequence-tracking context without the need of integrating semantic cues, PSTM is engaged to support encoding and retaining of surface sentence patterns (Andrade & Baddeley, 2011).

Different types of instructional interventions may also differently engage the storage (PSTM) or manipulation (complex WM) components of working memory. Specifically, for the explicit interventions that pre-exposure and temporally spaced, such as the explicit instruction in the current series of studies, the PSTM is recruited to support the retain and apply of the previous taught rule across learning trials. In contrast, for interventions that impose a high online processing load, such as interactional feedback or recasts, complex WM, which involves simultaneous storage and processing, is likely to be engaged (e.g., Li et al., 2009; Suzuki & DeKeyser, 2016).

The current results that the two distinct working memory constructs, namely PSTM and complex working memory, engaged in the learning of different language features highlight the importance of considering cognitive demands of specific language learning tasks as well as instructional interventions in interpreting memory effects in L2 learning.

Furthermore, Robinson (1995) proposed a complement to Schmidt's (1990) noticing hypothesis, integrating the role of rehearsal in short-term memory with awareness, and highlighting their importance in subsequent learning and encoding in long-term memory. This view is substantiated by the current findings. In Study 2, metalinguistic awareness, operationalized as the ability to verbalize the verb-final word order rule, predicted successful verb learning. In Study 3, complex WM predicted verb learning performance. These results suggest a convergence between the two constructs: it is plausible that complex WM serves as a cognitive foundation for the development and application of metalinguistic awareness. That is, learners with higher complex WM may be better able to store the instruction input (the verb-final word order knowledge), sustain attention on specific learning target (focusing on verbs), manipulate statistical input, thereby facilitating rule abstraction and application. This interpretation is supported by previous research indicating that WM capacity underpins explicit knowledge development and metalinguistic processing (e.g., Brooks & Kempe, 2013), and the effect of WM tends to be more robust under explicit learning conditions (e.g., Tagarelli et al., 2011; Denhovska et al., 2016).

5.4.2 Age-working memory interaction under explicit instruction

There was a significant age-complex WM interaction during the training phase in Study 3, indicating that complex WM (phonological loop plus central executive) did not equally contribute to simultaneous vocabulary and grammar learning for learners of all ages, particularly under explicit instruction. Specifically, complex WM did not play a role for the younger children, however it emerged as a significant predictor for children around 12 years old. This age-dependent effect of WM seems to reflect the development trajectory of working memory during childhood: while the core structures of working memory are in place by around 6 years of age, its functional capacity continues to improve steadily through middle childhood and adolescence (Gathercole et al., 2004). This leads to the possibility that WM may be more actively engaged in CSL in older children, and thus provides a possible explanation for the seemingly contrasting findings in previous studies: Specifically, while some research did not find associations (e.g., McGregor et al., 2022; Sia et al., 2023), some (e.g., Zhou et al., 2024), and Study 3 in this thesis, observed that the performance in the current CSL task could be predicted by WM.

These inconsistent findings may actually further underscore the different learning mechanisms involved in (cross-situational) statistical learning between younger and older children. Learning in CSL tasks is demanding, and certain cognitive abilities, such as selective attention and inhibitory control are likely to be engaged in order to alleviate referential ambiguities, supporting tracking of plausible mappings while inhibiting irrelevant ones. However, children in their early childhood seem to lack such a cognitive strategy as shown in Sia et al. (2023). They found that 4-year-old children could learn words via cross-situational statistics successfully. However, neither attention and inhibition control, nor visual-spatial short-term memory[11] predicted these young children's cross-situational word learning. Sia et al. (2023) interpreted their finding as young children relying on an exploratory learning strategy instead of an attentional learning strategy like adults do. I thus argue that children's underlying learning mechanisms during CSL is complex and dynamic across development. There might be a shift from exploratory learning, during which they navigate the input statistics more broadly even if they were told to focus on certain features (like the explicit instruction in the current study), to a more attentional learning which enables effective integration of what was taught in the explicit instruction into CSL.

However, this is still far from a conclusive claim. The most apparent reason is that the tasks adopted in the previous studies and the current studies were not directly comparable. For example, Sia et al. (2023) used flanker task and stroop task, the two typical measurements of central executive component of complex working memory (Li, 2017), while the current adopted tasks that tapped into the similar function was backward digit span task. Moreover, the current CSL task combined both cross-situational word learning and grammar learning, while Sia et al. (2023) mainly focused on CSL of nouns. Zhou et al. (2024) did adopt comparable working memory tasks to the current studies, i.e., digit span forward and backward, yet this study tested visual statistical learning but not CSL. Therefore, future studies with comparable measurements, learning tasks and target populations are particularly needed before we can confirm whether there is an exploratory-to-attentional change of learning mechanism during CSL across development. Moreover, the adoption of online process

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[11] The term "visual-spatial short-term memory" that I used here was originally termed as working memory in Sia et al. (2023). Sia et al. adopted three tasks, namely flanker task, stroop task and Corsi block task as measurements for selective attention, inhibitory control, and working memory respectively. The current thesis adopts Baddeley and Hitch's (1974) working memory model, as well as following Li (2017), discussing working memory with a distinction between 'phonological short-term memory' and 'complex working memory'. Corsi block task is a type of visual matrix task, typically measuring visual-spatial short-term memory and the flanker task and stroop task are typically used as measurements of the central executive component of complex working memory (Li, 2017).

measures, such as eye-tracking, which enables trial-by-trial tracking of attention allocation, and EEG, which enables exploring neural responses to specific parts of the speech stream, could contribute to the further investigation of strategy use in CSL.

5.5 Effect of declarative and procedural memory capacities in L2 learning

5.5.1 Declarative and procedural memory as main effects

The current project provides empirical contributions to the D/P model, which posits declarative and procedural memory as two memory systems that supports the learning and using of different language features, by first providing unique data from children aged 8 to 13, and second through an immersive language learning environment in which vocabulary and grammar had to be learned simultaneously. Both of these two variables, age and input, are believed to modulate the engagement of procedural and declarative memory (Morgan-Short & Ullman, 2023).

Regarding declarative memory, though often being related to associative vocabulary learning in the D/P model, I did not observe any associations between declarative memory and learning of word-referent mappings. This lack of association is likely due to the role of input. Specifically, declarative memory is often regarded as enabling fast learning from limited input and is involved in the conscious retrieval of factual knowledge. However, in the current CSL paradigm, children had to learn vocabulary from complex input where word-referent mappings are ambiguous within a single trial and instead of fast learning within a single trial, accumulative learning across trials is required. This is reflected in Walker et al. (2020) where adult learners' vocabulary learning via CSL tasks was linked to procedural memory, but not declarative memory.

However, it is plausible that the construct of declarative memory in supporting fast learning and conscious recall of factual knowledge was supported by current finding of the association between declarative memory and GJT scores. The association between declarative memory and GJT scores indicated that children with higher declarative memory were better at integrating the explicitly taught knowledge into CSL. Specifically, unlike words which could only be learned through accumulating word-referent co-occurrence, learning of the word order knowledge was directly assisted by explicit instruction. Therefore, if learners could consciously recall the word order rule during exposure, grammar knowledge could be gained even within a single trial. This is in line with the existing evidence that declarative memory is more likely to associate with learning in explicit and intentional contexts, such as classroom instruction (e.g., Robinson, 1997; Ruiz et al., 2021; Yilmaz & Granena, 2021).

5.5.2 Age-declarative memory and age-procedural memory interactions under explicit instruction

Procedural and declarative memory capacities follow distinct developmental trajectories (Pili-Moss, 2021), with procedural memory reaching maturity in early childhood while declarative memory continues to develop into early adulthood (Bauer, 2008; Hulstijn, 2015, Ullman, 2004). Based on this developmental trend, I expected the effect of procedural memory in L2 learning to be more stable, while declarative memory to be more depended on age. However, results underscore the developmental shift regarding the contribution of these two memory systems in particular to grammar learning under explicit instruction. First, the negative age-declarative memory interaction suggested that though declarative memory served as a significant main effect to grammar learning, as children grow older, the reliance on declarative memory in order to exploit explicit instruction may be decreased. Older children with relatively lower declarative memory capacity had more chance to gain through explicit instruction than their younger peers. There was also an age-procedural memory interaction in GJT trials, showing that procedural memory related to learning, though only for older children in the current population.

Taken together, study 3 modeled age as a proxy for maturational changes, and examined how it interacts with working memory, declarative memory, and procedural memory to predict L2 learning across ages 8-13. Vlach and DeBrock (2017) took an innovative step and suggested that memory abilities could be the most important factor above and beyond age and vocabulary size, in driving preschool-aged children's cross-situational word learning. The current study confirms and expands Vlach and DeBrock's account, indicating that for school-aged children, memory (working memory in particular) keeps driving cross-situational word learning.

5.6 Age effect in L2 learning: revisiting Critical Period Hypothesis

A classic paradox surrounding the CPH is the "older-is-better" trend in initial learning rate and "younger-is-better" trend concerning ultimate attainment (e.g., Krashen et al., 1979). The current thesis confirms the former pattern and provides compelling evidence of the origin behind this older learners' initial advantage. Specifically, the matured memory abilities and executive control equip older child learners to an efficient integration of explicit knowledge during the language learning process. For the current population, learners at around 12 years of age showed a quicker and more successful L2 learning under explicit instruction, which was predicted by PSTM, complex WM, declarative and procedural memory, with the relative importance of each varying by linguistic features and task demands.

These findings may help explain the "older-is-better" trend observed in L2 learning in schooling situations (e.g., Pfenninger & Singleton, 2017; Singleton & Leśniewska, 2021). Adolescent beginners of language learning in these studies performed as well as, or even surpassed, younger beginners. L2 learning in classroom settings is often under limited amount of input and relies more on explicit learning (e.g., explicit instruction, corrective feedback). This is the learning condition in which learning relies more heavily on declarative memory and working memory (e.g., Doughty, 2001; Li, 2017; Ruiz et al., 2021; Yilmaz & Granena, 2021), and thus older children present advantages plausibly due to their more mature cognitive capacities, so that they are better able to maintain and consciously recall the metalinguistic information gained through instruction while processing the input statistics.

However, the current findings could not explain the “younger-is-better” pattern for ultimate attainment observed mostly in immersive situations, but proposes an interesting question for future studies to explore: Why does the early advantage of older learners, particularly brought by more mature cognitive abilities and advanced explicit learning ability, fail to translate into a long-run advantage? Or in other words, does the advantage observed for older learners in the current studies ultimately boost or hinder long-term language learning attainment, and do limited cognitive abilities in children paradoxically lead to greater success in ultimate language acquisition?

Under the “less-is-more” hypothesis (Newport, 1990), limited processing capacity can sometimes promote chunking and generalization, whereas greater analytic capacity may over-segment (e.g., morphology acquisition). Note that in the current thesis project (in study 2 specifically), I found that the marker words were the only vocabulary category that younger learners learned more successful than the older children. Therefore, it is necessary for future studies to investigate whether the changes caused by maturational and cognitive advances provide positive or negative effects for L2 learning in the long run. In other words, would there be a “more-is-less” tendency to explain why late starters face difficulties when acquiring an additional language? To test this, future studies can further manipulate the input complexity with longer training sessions.

Another possibility for why older learners’ initial advantage may not extend to long-term attainment could lie with the input quality and quantity, which is not tied to biological maturation but are confoundable with age (see also Singleton & Leśniewska, 2021). As Flege (2019) emphasizes, it is commonly assumed that a longer length of residence in an L2-speaking environment guarantees more input, but this is not necessarily the case. Immigrants may spend years primarily interacting in their first language or with accented L2 speech from within their community, resulting in limited or lower-quality exposure. In this regard, beyond maturational differences, a key difference between early and late starters in the L2 is, for example, simply the length of school education time: children who arrive early typically accrue more years of high-quality, interaction-rich classroom input than L2 learners who immigrate in adolescence or adulthood. Therefore, for a better understanding of developmental change in language acquisition mechanisms, and the driving factors behind such changes, future work should design with a tight control of input quality and quantity. In this respect, the CSL paradigm adopted in the current thesis, which enables examination of various language features (e.g., word-referent associations; sentence structure learning) while provides precise control of input, provides a unique methodological contribution towards CPH research.

5.7 Limitations and future directions

The current thesis yields vivid results regarding how explicit instruction, age, and memory capacities shape children and adolescents’ early L2 learning under a cross-situational learning paradigm. It also raises interesting yet unanswered questions and several limitations that set the stage for future work.

First of all, the studies offer empirical evidence of a qualitative shift in L2 learning strategies and outcomes from middle childhood to early adolescence. The findings consistently point towards an "older-is-better" trend at the initial stages of L2 learning, at least within this specific age range. Learners around 12-13 years presented an advantage at integrating explicit rule knowledge into navigating input statistics, plausibly due to more mature working memory and attentional control. However, these findings should be interpreted as task-specific. Although the adopted CSL paradigm is relatively more ecologically valid than many traditional artificial language learning tasks, it remains a highly simplified and controlled experimental environment. Learners were exposed to a very simple artificial grammar, a highly demanding forced-choice CSL task involving two juxtaposed scenes, and learning conditions that differed in the presence of explicit instruction and task-specific cues. These features make the paradigm well suited for isolating developmental and cognitive factors, but they also limit the extent to which the findings can be generalized to naturalistic L2 learning, where interaction, shared attention, meaning negotiation, and more varied linguistic structures are central. In addition, although the GJT provided evidence of sensitivity to the verb-final structural regularity, it did not provide definitive evidence about the exact representational level of what had been learned, for example whether performance reflected sensitivity to surface positional or syllabic patterns, familiarity with sentence-final forms, or more abstract structural knowledge. For this reason, claims about learning mechanisms in the present thesis should be understood as applying primarily to the current task and artificial language rather than to language learning in general.

Moreover, the "older-is-better" benefit identified in the current thesis project cannot be generalized to the later developmental stages of L2 learning or across all linguistic domains. The current studies comprised a laboratory-based, short-term training with the adoption of a highly controlled CSL paradigm, although with enhanced ecological validity. Nevertheless, this short-term training context differs significantly from the long-term, immersive natural language learning environments where many key hypotheses about age effects, such as the Critical Period Hypothesis have been developed, and thus future studies in more naturalistic experimental design with longer training sessions and delayed posttests could provide more comprehensive understanding of what drives the age-related effects in L2 learning.

A further limitation concerns the operationalization of explicit instruction in the current thesis. Instruction was implemented narrowly as brief pre-exposure metalinguistic information about the target structure, and learners’ uptake of this information was primarily assessed through their ability to verbalize the rule. This design was appropriate for isolating one potential mechanism of instruction, namely the directing of learners’ attention to a relevant structural feature. However, it represents only one component of instruction. In classroom settings, explicit instruction is typically accompanied by some form of guided input, output practice, repetition, interaction, or feedback, all of which may contribute substantially to learning. The current findings should therefore not be interpreted as showing how instruction in general operates in pedagogical contexts, but rather as identifying one specific mechanism through which explicit information may facilitate learning under controlled experimental conditions. Future studies should incorporate broader instructional sequences, including input- and output-based practice, in order to determine how the effects observed here extend to more classroom-like forms of teaching.

Second, though markers and nouns were difficult to learn in the current materials, there indeed were some individuals who reached a successful learning level. However, I did not observe any cognitive predictors across the two studies, neither did learning condition, nor age and memory, explain these individual differences. Two explanations are plausible: (1) the cognitive abilities measured (working, declarative and procedural memory) may not capture the variance most relevant to the learning of markers and nouns; and/or (2) the instruction focused on verb and word-order knowledge rather than directly cueing nouns and markers, and so learners were not focusing on these aspects of the language. Future work should include other individual differences such as vocabulary size and language analytic ability (e.g., Paradis, 2011) and test treatments that explicitly direct attention to noun and marker learning, for example, explicit instruction over the marker knowledge (e.g., Ruiz et al. 2025).

In addition to age and memory, this thesis also underscored a moderating role of metalinguistic awareness, and a possibility that working memory serves as the cognitive underpinning to the development of metalinguistic awareness. However, Study 3 did not collect data tapping into learners' awareness by, for example debriefing questions, making it impossible to directly test this possibility. Moreover, awareness in Study 2 was assessed through debriefing questions which ask learners to verbally reflect on what they are learning. However, such direct subjective methods can have limitations (Rebuschat, 2013), overlooking the fact that there may be awareness that exists but is difficult to articulate. Therefore, follow-up studies can explore the moderating role of awareness through indirect objective methods such as the opt-out paradigm (e.g., Spit et al., 2021) which allows for assessing the awareness that exists in a way that cannot be verbalized.

Findings in the current thesis relied on offline, explicit behavioral measurements (i.e., the left/right and good/funny forced-choice tasks) which provided evidence on whether learning occurred, but also had a limitation that these measures do not provide online data indicating how and when specific mechanisms were involved during learning (Isbilen et al., 2022). Future work on the developmental changes in L2 learning would benefit from the employment of online measurements, such as eye-tracking, which enables the online tracking of trial-by-trial shifts in visual attention during training (e.g., dwell time, gaze switches), and thus leading to a better understanding on, e.g., how attention is affected and allocated by different treatments (e.g., explicit instruction, recast), and whether such effect differs across development.

Moreover, the currently adopted CSL paradigm provides a good opportunity to test L2 learning mechanisms in a relatively more ecological valid environment with a good control of input quality and quantity. It also enables the manipulation of different variables, such as teasing apart the effect of age and learning environment. A limitation, however, is that I only included an immediate test right after training sessions, but did not include delayed posttests which measure long-term retention of language knowledge. As previous research has proposed evidence of having short-lived learning effects when treatment provided metalinguistic knowledge, e.g., after two weeks the advantage gained through negative feedback with metalinguistic information disappeared in (Lado et al., 2014). In addition, Walker et al., (2020) found different association between declarative and procedural memory to language learning regarding the immediate learning and retention overnight. Future studies which investigate memory-treatment interactions should design to include posttests which enable us to investigate whether the observed aptitude-treatment effects persist over time, or changes with consolidations.

Another constraint for the current study is the lack of first language (L1) diversity in the current sample population. In the 8-to-9-year-old groups, the sample included two distinct populations: children from the UK and from China, which partially reduces the bias by sampling (DeKeyser, 2013; Pfenninger & Singleton, 2019). A brief comparison between the descriptive statistics of the two groups, namely the English-speaking 8-9-year-old children in Study 1 and the Chinese-speaking children in the implicit 8-9 age group in Study 2, suggests a broadly similar pattern: children in both of these two groups showed above-chance performance on the GJTs but little evidence of robust vocabulary learning. This comparison tentatively suggests that the central developmental pattern identified in the thesis is unlikely to be entirely driven by L1 background. However, the studies were not designed to test L1 effects directly, and the groups differed not only in language background but also in broader testing context and study design. Moreover, the other age groups were recruited from a single city in northern China. A wider sample, including learners with typologically distinct L1s, would allow us to test whether the reported age-related effects replicate across backgrounds.

Last, I call for sustained attention by both SLA and CSL researchers to school-aged learners, from middle childhood through early adolescence. This period is characterized by rapid maturational change and shifting contextual demands, producing interactive effects on how learners attend to, interpret, and consolidate linguistic input in an additional language. It would be insightful for follow-up research to treat this age range as a distinct developmental period, moving beyond simplistic comparisons of "child" versus "adult" learners by using experimental designs that can separate maturation from learning context. Future studies focus on this population would shed light on theories of not only the age-related effects in language acquisition research, but more broadly deepen our understanding of the complex interplay between human development, brain function, and environmental input.

5.8 Pedagogical implications

The current thesis contributes to both CSL and SLA research, expanding our understanding on how age, as a proxy of cognitive abilities, could modulate L2 learning across the critical developmental window from middle childhood through adolescence. These findings may have pedagogical implications for language teaching, especially in foreign language (FL)[12] contexts, although it is acknowledged that such implications should be interpreted with caution. The instructional manipulation used in the current studies was deliberately narrow: it consisted only of brief pre-exposure metalinguistic information about the target structure, rather than the broader forms of instruction typically found in classrooms. Likewise, the artificial language and CSL task do not directly mirror everyday classroom practice.

Recent decades have shown a trend of early implement of foreign language education at the elementary school (or even pre-school) education (Muñoz & Spada, 2018). Nevertheless, this early-start movement has not yet been backed up by systematic, long-term empirical scrutiny of its effectiveness (e.g., Jaekel et al., 2017). Instead, existing empirical studies have indicated an “older-is-better” trend in FL learning in school (e.g., Jaekel et al., 2017). This contrast is also reflected in the current thesis in which the observed age-treatment interaction points to a similar “older-is-better” trend. In particular, the present results indicate that in contexts where exposure is limited and instruction is more explicit, an early start is not necessarily related to a successful learner; rather, older learners with more mature cognitive capacities are often better equipped to benefit from instruction, yielding faster and more accurate learning outcomes. Nevertheless, this finding does not imply that learning shouldn’t start at an early age in a FL context.

Acquiring a L2 at an early age can be beneficial, yet it is also conditional. What matters is not simply the learners’ age, but what teachers (and also families) can provide to children. This is particularly relevant in FL contexts, where the quantity and quality of input are typically limited relative to L2 environments (e.g., for immigrants). The findings from this thesis suggest that explicit instruction, often undervalued in early childhood education, can significantly enhance learning, particularly for learners with higher working memory and declarative memory capacities. Thus, it is overly simplistic to assume that young children should exclusively engage in implicit learning, or that

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[12] Foreign language learning refers to learning of a language that is not used either at home or in the society where learners live (Muñoz & Spada, 2018).

explicit instruction (e.g., rule explanations, corrective feedback) should be avoided for young children. On the contrary, a more comprehensive understanding that teachers should bear in mind is that when well-aligned with learners' cognitive profile, explicit instruction can serve as a powerful tool to accelerate L2 development, at least at the beginning stages. For example, study 3 showed that children as young as 8-9 years of age with higher cognitive capacities could learn successfully under explicit instruction.

Second, the observed age-aptitude interactions under explicit instruction speak to the importance of managing cognitive load in instructional tasks during teaching. The efficient learning of vocabulary and sentence structure from cross-situational statistics was observed in the current studies. However, its power could be limited by memory abilities and input complexity. When I observed learners' learning difficulty in the current CSL paradigm (Study 1), I provided external cues in Study 2 and Study 3 which draw learners' attention to certain language aspects and found that this treatment could significantly boost learning, particularly for learners with higher memory capacities or older age. For those younger children with lower working memory or declarative memory, external cues may cause extra cognitive load. Thus, instead of adding external cues for these learners, maybe simplification of input statistics is more helpful.

This has important implications for teaching practices which rely on input-rich techniques such as songs, storybooks, and cartoons in real-world language teaching. These techniques, particularly favored by teachers of young children for their immersive and implicit nature, may not be equally efficient across all learners. Based on findings from the current CSL research (and also my personal teaching experience), there are indeed young children who either fail to learn or learn very slowly from such exposure, given that not all young children are capable of tracking input statistics, solving referential ambiguities and establishing current word-referent mappings merely from receiving input. I'm not suggesting that these techniques are ineffective, they can be, if teachers know the extent to which students can benefit, and importantly, what additional support best suits individuals when they do not benefit as expected. For example, for high capacity learners (e.g., learners with higher complex working memory and attentional control), or older children (e.g., children around puberty), when there are learning difficulties (e.g., unable to solve referential ambiguity), the introduce of external cues (e.g., pre-exposure rule instruction) can be very effective in boost learning. However, for low-capacity young children (e.g., young children with lower working memory and attentional control), when the same difficulties occur, explicit cues or explanations may not be a good choice given that they are not cognitively ready to maintain and recall such cues and effectively integrate them in learning process. In this case, an alternative and more appropriate way could be reducing input complexity and ambiguity by for example, shortening the sentence length, reducing the number of new words, or constraining the variation in syntactic structures. Future work exploring the effects of aptitude-treatment interactions in children's learning from input statistics under immersive teaching techniques (e.g., songs and rhythms, cartoon videos and picture book reading) would not only be interesting but also essential for optimizing instructional approaches to align with children's individual cognitive profile.

Third, the finding that the memory capacities required by certain treatments change across development could indicate that not only "one-size-does-not-fit-all", but one size does not even fit one. This is particularly the case for learners across childhood to adolescence as this is the critical period that undergoes developmental changes in cognitive maturation as well as the response towards explicit treatment. Teachers should take into account this developmental perspective and adapt teaching accordingly to learners' developmental stages. However, I acknowledge that applying findings from individual differences research to real classrooms can be very challenging. Such application is hindered by the complexity of age-aptitude-treatment interactions, the variability across language domains, and practical constraints such as large class size, curriculum constraints, and assessment demands. Nevertheless, I argue that recent advances in artificial intelligence (AI) and large language models (LLMs) present a unique opportunity to bridge this gap. AI-powered educational technologies offer the potential for personalized and adaptive teaching and learning, tailored to learners' individual profiles and dynamically responsive to changes in their developmental trajectories (e.g., Intelligent Tutoring Systems in Morgan et al., 2020 and Tyagi, 2025). I thus call for further research on a comprehensive understanding of age-aptitude-treatment interactions, as well as exploring their implementation in real language teaching through big learner data from real-world contexts (e.g., educational apps), so that we will have a solid theoretical framework for the future design of AI-based instructional tools, which can assess learners' cognitive ability, index optimized learning and teaching techniques, and tracking changes and adapt learning accordingly.

In sum, this thesis calls for a shift away from simplistic age-based assumptions in L2 teaching practices and curriculum design, toward a more nuanced and research-based model that integrates developmental, cognitive, and contextual factors.

6 Conclusion

Across three studies, this thesis provides compelling evidence that age is a robust driving factor in L2 acquisition, and operates as a proxy for maturational change. It serves as a moderator, affecting the effect of contextual cues (e.g., explicit instruction) and cognitive ability (e.g., memory capacities) at least for the initial stages of L2 learning.

A consistent pattern emerged at 12-13 years, where learners displayed marked openness to explicit instruction. Learners at this age range presented quicker and better simultaneous learning of vocabulary and grammar, as well as a more efficient navigating of sentence-scene correspondences when given a pre-exposure explicit instruction. If, following Eubank and Gregg (1999), the critical period is viewed as a "window of opportunity" (p. 68), the present findings may point to a second, adolescent-onset window for L2 learners, one in which explicit cues can be productively integrated with distributional evidence to accelerate initial progress.

Analyses of individual differences provide clarifications. Age, memory abilities and their interactions predicted the integration of explicitly taught grammatical knowledge with cross-situational statistics. For example, children as young as eight benefited from explicit instruction when they possessed sufficient working memory capacity and could consciously articulate the sentence structure regularities. In such cases, explicit instruction facilitated even early L2 development.

The current thesis carries important methodological, theoretical, and practical implications. Methodologically, I demonstrate how age-related effects can be examined in a highly controlled yet immersive learning environment that balances ecological validity with experimental precision. Theoretically, it advances cross-situational learning accounts by specifying when and how explicit knowledge is integrated with distributional evidence, and it refines age-related effects in SLA, such as interpretations of the Critical Period Hypothesis, by empirically underscoring the developmental changes across middle childhood to early adolescence. Finally, the findings offer important practical insights for L2 instructional design. Rather than assuming that younger learners always benefit more, or that only older learners benefit from explicit instruction, I emphasize the importance of aptitude-treatment alignment: optimizing the stage at which explicit instruction is given according to individuals' cognitive profile and developmental readiness.

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