Statistical learning of non-native morphology in adult learners: effects of L1 morphological richness, redundancy, and salience

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Abstract

A body of statistical learning studies supports the view that language development is influenced by learners' sensitivity to the frequency and distributional properties of linguistic features in their input (see review: Saffran, 2020). Grammatical morphemes, based on this view, pose unique learning challenges: they are often acoustically subtle, redundant with other cues, and lack transparent form-meaning mappings, making it difficult to extract reliable patterns from the input (Ellis, 2022). Additionally, prior language experience may shape the ease with which morphological features are acquired (Van der Slik et al., 2019). While these factors have typically been identified through correlations with acquisition order (DeKeyser, 2005) or examined in isolation through tasks based on single sensory processing such as reading or auditory processing (Ellis & Sagarra, 2011), the current thesis explores their effects within a cross-situational statistical learning (CSL) paradigm, where audio-visual processing ability was examined. Learners track co-occurrent patterns between audio and visual cues, across multiple exposures, solving the referential ambiguity, and learned the meanings of linguistic forms indicated by co-occurring visual referents. To date, CSL has provided robust evidence for adults' statistical learning ability to acquire novel words by keeping track of words and their visual referents (Yu & Smith, 2007; Ge et al., 2025). However, whether similar mechanisms can support the learning of more complex morphological cues in sentences remains less thoroughly investigated. To address the gaps outlined above, this thesis, across three studies, examines whether adults can acquire grammatical morphology in a novel language through exposure to sentence-level input under a CSL paradigm. In addition to this overarching goal, the thesis also explores how specific factors, namely L1 morphological background, cue redundancy, and perceptual salience, shape the success of morphological learning. Each of these factors is examined in a dedicated

study, allowing for a systematic investigation of their individual and comparative influence on non-native morphological acquisition within a CSL framework.

The key features of the CSL paradigm simulate the referential ambiguity problem typical in natural language learning. In each CSL trial, participants were exposed to two visual referents and an auditory sentence in an artificial language. The artificial language contained nouns and verbs, and morphologically marked tense and number, with a subject-verb agreement on number cues. Participants were asked to infer the referential meaning of the sentence by selecting the image that best matched it, thereby simulating the referential ambiguity problem typical in natural language learning. No explicit instruction or feedback was provided throughout the learning phase.

Study 1 examined the influence of L1 morphological complexity on morphological learning. Participants were native speakers of Mandarin, English, and German - languages that vary in morphological richness. The results indicated that all groups were able to track statistical regularities and acquire both lexical and morphological patterns in the artificial language, demonstrating robust statistical learning ability. However, differences emerged in relation to L1 background: morphological learning outcomes were significantly higher for German-L1 speakers compared to Mandarin-L1 speakers, suggesting a possible facilitative effect of L1 morphological richness. Interestingly, the English-L1 group did not conform to this trend, showing learning performance that did not align neatly with their intermediate position on the morphological richness scale. This deviation may reflect the influence of additional factors such as prior non-native learning experience or overall linguistic proficiency, which potentially modulate the impact of L1 structure in CSL contexts.

Study 2 investigated the effects of cue redundancy and availability. Based on the artificial language built in study 1, sentences in study 2 included an additional adverbial cue for temporal reference, which either occurred consistently with the morphological tense marker or variably across trials. Results indicated a blocking effect: the presence of a temporal adverb reduced reliance on morphological tense cues. The learning was overall better in the consistent condition. However, the availability of cues did not modulate the blocking effect.

Study 3 explored the roles of cue salience. Morphological cues were systematically manipulated in their phonological prominence and structural transparency. Learners demonstrated significantly greater success in acquiring syllable cues (e.g., /ti/) compared to the single-consonant cues (e.g., /d/), indicating that perceptual salience significantly affects the accessibility of morphological information. However, the variance of results cannot be explained simply by the syllabicity of the cue, which is discussed in study 3.

Overall, the findings demonstrate that while adults can rapidly extract morphological regularities through cross-situational exposure, learning outcomes are shaped by cue salience, cue competition, and cue availability (Ellis, 2006). Contrary to predictions from L1 transfer accounts, L1 morphological complexity did not robustly explain variance in learning success, underscoring the view of L1 being a dominant transfer source.

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 publishable papers. The following pages contain the authorship statements signed by all co-authors of each paper.

Authorship statement

The article “Learning morphology from cross-situational statistics” is currently in press in *Studies in Second Language Acquisition* with authors Liuqi Zhu, Patrick Rebuschat, Jessie S. Nixon and Padraic Monaghan. Liuqi Zhu was responsible for conceptualisation and design, carrying out the research, formal analysis and writing up the article. Jessie Nixon was responsible for collecting part of the data and providing comments on the text. Padraic Monaghan and Patrick Rebuschat were responsible for supervision, conceptualisation and design, guidance on formal analysis, and providing comments on the text.

Authorship statement

I, Liuqi Zhu, have written the article "Blocking or highlighting in statistical learning: How distributional properties shape non-native morphology acquisition in adult learners" and carried out the research behind it in collaboration with Patrick Rebuschat and Padraic Monaghan. I was responsible for conceptualisation and design, carrying out the research, formal analysis and writing up the article. Patrick Rebuschat and Padraic Monaghan were responsible for supervision, conceptualisation and design, guidance on formal analysis, and providing comments on the text.

Authorship statement

The article "How salience shapes the statistical learning of non-native morphology" is currently under review in *Second Language Research* with authors Liuqi Zhu, Padraic Monaghan, and Patrick Rebuschat. I was responsible for conceptualisation and design, carrying out the research, formal analysis and writing up the article. Patrick Rebuschat and Padraic Monaghan were responsible for supervision, conceptualisation and design, guidance on formal analysis, and providing comments on the text.

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1.Introduction

Morphology acquisition has long been identified as a persistent difficulty for adult non-native language learners (Slabakova, 2014). This stands in stark contrast to first language (L1) acquisition, where, although morphological features are acquired later in development, they are eventually mastered with high accuracy and automaticity. The apparent asymmetry in attainment between L1 and non-native language learning raises fundamental questions about the nature of morphological learning and the mechanisms that support or constrain it across the lifespan.

One line of explanation focuses on the quality and quantity of linguistic input, rather than processing constraints. Children typically acquire their L1 in a rich, high-frequency language environment, where statistical regularities can be extracted through immersive exposure. In contrast, non-native language learners often receive more limited, fragmented input, which may restrict the formation of robust morphological representations (Cook & Gor, 2015; Giraudo & Dal Maso, 2018; Smith, 2016). This account underscores the need to examine whether adult learners retain the capacity to acquire morphology under input conditions that are both rich and structured. This question is particularly relevant within an emergentist, usage-based framework, which holds that language learning is fundamentally driven by sensitivity to distributional patterns in the input (Ellis, 2006, 2022). If morphological acquisition depends on detecting regularities in form-meaning mappings, then adult learners may still be capable of acquiring morphology readily, provided that the input environment supports such learning.

Cross-situational statistical learning (CSL) offers an ideal paradigm for testing the role of input in learning as a hypothesis. A seminal feature of CSL paradigm is that learners are exposed to sequences of input in which linguistic auditory forms must be mapped to semantic visual referents across multiple exposures. This paradigm simulates the referential ambiguity that characterises implicit natural language learning, where learners need to figure out the meaning of the word/sentence they heard by paying attention to the co-occurring visual world. Previous research using CSL paradigms has demonstrated that adults can successfully acquire novel lexical items through exposure to ambiguous but statistically structured input (Yu & Smith, 2007). More recent studies have extended CSL to complex grammatical structures, showing that learners can also extract case markers, word order patterns from co-occurring sentence-event pairings (Rebuschat et al., 2021). These findings support the robustness of CSL mechanisms beyond word learning, revealing their potential for broader applications in acquisition of non-native morphology. To date, the extent to which inflectional suffixes, such as tense and number marking, can be learned through CSL remains underexplored. This dissertation addresses this gap by investigating the learnability of morphology within a CSL framework, together with exploring the factors that modulate such learning, including L1 background, cue salience, and cue redundancy, over three studies. In doing so, it tests predictions from usage-based and emergentist models, which attribute learning outcomes to the interaction of cognitive learning mechanisms and input characteristics.

Findings of the three studies in this thesis contribute to our understanding of how statistical learning mechanisms operate beyond vocabulary acquisition and into more complex morphosyntactic domains. In the next chapter, I review the theoretical background of non-native morphology learning, focusing on the factors that account for morphological learning difficulty. I then discuss up-to-date evidence in CSL studies of morphological learning. Finally, I outline the critical gaps addressed in the present studies of this thesis.

2.Literature review

The acquisition of morphology is widely recognised as particularly challenging for non-native language learners. Across languages, inflectional features such as tense, number, and subject-verb agreement often remain incompletely acquired, even for advanced non-native language learners (Pica, 1983; Sagarra & Ellis, 2013). This phenomenon has been attributed to a range of factors causing morphology processing difficulty, including the inherent properties of morphological cues (e.g., low salience), distributional features (e.g., availability of a more salient cue encoding the same meaning; low contingency of form-meaning mappings), or top-down factors such as the influence of learners' L1s (Ellis, 2022). In this section, I begin by reviewing theoretical frameworks and empirical findings regarding the influence of each factor on morphological acquisition. This is followed by an investigation into the learnability of morphology within a statistical learning paradigm, highlighting the existing gap in research on how these factors influence form-meaning mapping abilities, an essential component of language processing in naturalistic environments.

2.1 Morphology Processing Difficulty

2.1.1 The effect of L1 transfer

One of the most consistently reported influences on non-native morphological development is learners' L1. Research has shown that the morphological complexity of a learner's L1 can shape their perception and ultimately shape the non-native morphology acquisition. For example, in Experiment 2 of Ellis and Sagarra (2010a), it was found that Mandarin Chinese speakers, whose L1 lacks verb tense morphology, showed a strong preference for adverbial cues when processing the sentences with both tense morphemes and temporal adverbs. In contrast, English L1 speakers show less of a bias. The findings tentatively support that L1 morphology shapes attention on the perception of cue salience. In English, for example, tense and number are marked through inflectional morphology (e.g., -ed, -s), while Mandarin expresses these features lexically or through classifiers, which are more salient than the inflectional morphemes in English. This contrast explains the result in Experiment 2, where L1 Mandarin speakers heavily rely on the more salient temporal adverbs to mark tense. The results in Ellis & Sagarra (2010a) show that learners' attentional biases, formed through prior language experience, may lead to a learning bias where the acquisition of the more salient lexical cues overshadows redundant, less salient morphological cues. In this sense, L1 morphology complexity plays a critical role in non-native language development. This is further supported by a robust body of empirical evidence, demonstrating that non-native language learners from morphologically rich L1 backgrounds tend to acquire non-native morphology with greater ease and accuracy than learners from morphologically poor L1s (McManus, 2020; Sagarra & Ellis, 2013).

However, Ellis and Sagarra (2010b) found that as the complexity of verbal inflection increases, the impact of L1 appears to diminish, with cue salience emerging as the primary factor guiding non-native morphological learning. Nonetheless, the influence of a learner's L1 morphological richness on the non-native morphological acquisition has been substantiated through a significant study by van der Slik and colleagues (2019), where they analysed a dataset of over 8,700 adult non-native language learners of Dutch from 33 L1 backgrounds, and found that learners where the L1 was morphologically poorer consistently underperformed in measures of morphological accuracy (e.g., person marking, past tense, negation, inflectional synthesis) compared to those whose L1s were morphologically richer. Crucially, they also found that the influence of L1 morphology complexity persists regardless of exposure context, whether in formal classroom environments or naturalistic immersion settings. Moreover, interaction effects indicated that for learners with morphologically poorer

L1s, longer residence in the target language environment (i.e., the Netherlands) did not necessarily yield better outcomes. The result shows a sign of fossilisation, which means the language development does not progress despite continued exposure to language input. This suggests that learners with morphologically poor L1 may acquire less in non-native morphology over time if not adequately supported, reinforcing the enduring and cumulative impact of L1 morphology complexity on non-native morphological acquisition. Additionally, the study identified that learners with experience in morphologically rich non-native languages were better able to overcome age-related declines in learning capacity when acquiring Dutch morphology. These findings emphasise the enduring impact of L1 morphological complexity on non-native morphology development.

However, the exact mechanism of L1 transfer remains a subject of theoretical debate. While some studies support the full transfer hypothesis, whereby entire morphological systems from previously learned language are influencing non-native language learning (suggesting a wholesale effect) (Rothman, 2011; Schwartz & Sprouse, 2021), others advocate for a property-by-property account (Westergaard et al., 2017). According to this view, transfer is selective and based on structural similarity between specific features across languages, rather than holistic typological proximity. Empirical support for property-based transfer has come from studies showing that learners selectively transfer individual grammatical or morphological features (e.g., word order, agreement, adverb placement) depending on their structural alignment across the known and target languages.

Taken together, these findings show that L1 influence on non-native morphology is multifaceted. It likely includes both structural alignment (i.e., property-by-property similarities) and cognitive factors (i.e., attentional biases shaped by L1 salience). A nuanced understanding of these dynamics is essential for explaining the wide variability observed in non-native morphological acquisition. To understand L1 influence within a statistical learning paradigm, Study 1 investigated the effect of L1 crosslinguistic influence, whether it is a holistic transfer or influenced by property-by-property.

2.1.2 The Effect of Redundancy and Cue Competition

Beyond the L1 effect, distributional properties, such as redundancy, further complicate morphological acquisition (Ellis, 2022; DeKeyser, 2005). The challenge stems from two cues encoding the same meaning competing for attention (Ellis, 2007). For example, tense can be expressed through more salient lexical or phrasal cues, such as "yesterday" or "a few days ago", signalling past time. Similarly, number can be marked morphologically, as in the plural suffix “-s,” or lexically, using quantifiers like “many.” However, because of the limited capacity of cognitive processing, learners are generally more attuned to salient cues, particularly lexical ones, which can result in less attention being paid to the corresponding morphological cues and, consequently, being less effectively acquired (DeKeyser, 2005). This phenomenon relates to two learning mechanisms: blocking and overshadowing. Both involve a more salient cue inhibiting the learning of another co-occurring cue that encodes the same information. The key distinction lies in the source of salience. In blocking, the salience of a cue arises from prior learning—learners have already formed an association between cue A and outcome X, thereby reducing attention to a new, redundant cue. In overshadowing, the dominance of one cue over another is due to inherent perceptual features, without prior conditioning. Within language learning, blocking can be seen as a cumulative effect of overshadowing, developing over time through experience (Ellis, 2006).

A series of studies by Ellis and Sagarra (2010, 2011) empirically demonstrated how the blocking effect can be observed in a language learning context. In Experiment 1 of Ellis and Sagarra (2010a), native English speakers either received pretraining on temporal adverbs (e.g., hodie "today", heri "yesterday"), or on verbs with tense suffixes (e.g., cogito "I think", cogitavi "I thought"), and a control group received no pretraining. Participants read Latin phrases combining both cues (e.g., heri cogitavi “yesterday I thought”) and judged whether each referred to the past, present, or future. This is followed by a reception test where participants rated the temporal meaning of 48 phrases (some containing conflicting adverb and verb cues) on a 5-point scale, with 1 indicating extreme past and 5 for extreme future. Finally, a production test was included where participants were required to translate English phrases like “I thought” or “tomorrow I will think” into Latin. In contrast to participants in the control group, who distributed attention more equally, results in the pre-training group showed that participants rely heavily on the pretrained cues to predict the tense, indicating that the perceptually salient cue, due to the pre-training block the learning of the less salient one. Furthermore, participants showed more reliance on the pre-trained adverbs than the pre-trained verbs, demonstrating that the blocking effect is modulated by the inherent salience of the cues. In a series of experiments, it was also found that the perceived salient was modulated by learners’ L1 backgrounds, which, therefore, also influence the magnitude of blocking (Ellis & Sagarra, 2010a, Experiment 2; Ellis & Sagarra, 2010b). Overall, Ellis and Sagarra show that the magnitude of blocking was significantly modulated by cue salience, which was influenced by the prior-learned knowledge (e.g., pre-trained knowledge or L1 background) or the inherent cue salience (e.g., phonological salience).

Ellis and Sagarra (2011) increased the complexity of the language input by involving both tense and person in the inflections, and further confirmed the blocking effect. However, the paradigm in these studies, participants were only exposed to the auditory form of language input, testing only one aspect of natural language learning. More work is needed to explore whether the effect of redundancy can be generalised beyond Ellis and his colleagues’ paradigms into more ecologically valid, referential learning environments. Specifically, it remains unknown whether the learning mechanism of overshadowing are also present in more naturalistic situations where statistical learning meets referential ambiguity in terms of resolving sentence-referent mappings. This gap is addressed in Study 2, which will be discussed in greater detail later.

2.1.3 The effect of perceptual salience

Outside of the interaction with redundancy, perceptual salience alone has consistently been recognised as a critical factor in non-native morphological acquisition, particularly under implicit learning conditions (Dekeyser, 2005; Ellis, 2022). Many inflectional morphemes—such as the English past tense marker "-ed" or plural "-s", are realised as short, unstressed consonants in connected speech. Their low perceptual salience often renders them difficult to detect, especially for adult non-native language learners who rely more heavily on lexical content than on functional morphemes. This challenge has prompted increasing interest in how phonological properties shape perceptual difficulty.

A growing body of research has sought to explain how phonological features such as syllabicity, sonority, and stress interact to influence the detectability and learnability of these forms. In a key study, Bell et al. (2015) examined the perception of English past-tense morphology using a forced-choice auditory identification task. Participants listened to verb phrases and indicated whether they perceived a past-tense –ed morpheme. The study contrasted 'easy' contexts, where -ed was realized as a syllabic [ɪd] followed by a vowel (e.g., *waited in line*), with 'hard' contexts, where –ed was non-syllabic ([t]/[d]) and followed by a consonant (e.g., *walked the dog*). Results showed that learners were significantly more accurate in detecting -ed in syllabic contexts, suggesting that syllabicity enhances perceptual salience. The perceptual challenges of the English past-tense are further examined in a more naturalistic context in Strachan and Trofimovich (2019). In their paradigm, participants had an auditory identification task with video clips from sitcoms, which tested perception of -ed in phonologically salient ([ɪd]) versus non-salient ([t]/[d]) contexts. Their results revealed that all groups (intermediate, advanced non-native language learners, native speakers) were significantly more accurate in detecting -ed when it is pronounced saliently as [ɪd], though performance remained far from the ceiling even for native listeners.

These studies reveal that consonant-only form poses a great challenge for learners, indicating that perceptual salience plays a key role in learners' ability to notice and process morphological forms in real-time speech. However, prior research on the effect of perceptual salience has focused on detection rather than acquisition, and there is limited evidence on whether perceptual salience influences morphological learning outcomes in the early stage of non-native language learning. Moreover, previous studies have been focusing on treated perceptual salience as a categorical property—syllabic vs. non-syllabic— to test the effect of syllabicity, few study examined the perceptual salience as gradient properties, such as the combined effects of sonority and syllabicity or the impact of subtle phonetic contrasts (e.g., strong vs. weak vowels). These gaps are particularly notable in the context of statistical learning paradigms, where learners extract form-meaning mappings through repeated exposure to input without explicit instruction. Such environments simulate key aspects of naturalistic acquisition but allow precise manipulation of input features. However, very few studies have used this approach to directly test whether morphological acquisition is shaped by variation in salience, especially for morphemes differing in syllabicity and sonority.

Study 3 addresses this gap by manipulating the morphological cues in an artificial language in terms of syllabic structure (e.g., consonant-only vs. syllabic morphemes) and vowel sonority (e.g., /a/ vs. /ə/) between high salience and low salience conditions. Importantly, this design allows a direct test of whether the fine-grained contrasts in salience within vowels or contrast in syllabicity influence the early acquisition of morphology. This approach complements prior perception-based research by extending the inquiry into the learning phase of morphology acquisition.

In summary, non-native morphological acquisition is shaped by a complex interaction of bottom-up and top-down factors, including cross-linguistic transfer, perceptual salience, redundancy, contingency, and semantic transparency etc. In the next section, I will review factors that potentially explain the difference in ultimate attainment of morphology between L1 and non-native languages.

2.2 Why non-native morphology acquisition falls short of achieving native-like proficiency

One of the explanations for the persistent difficulty in mastering non-native morphology involves the role of redundancy, which may operate differently across L1 and non-native language contexts. Adult learners, shaped by prior linguistic experience, tend to prioritise salient lexical cues, leading to a 'blocking effect' that hinders the acquisition of redundant, low-salience morphological forms (Ellis & Sagarra, 2010a; 2010b). In contrast, children, who have not yet developed entrenched attentional strategies, are less susceptible to such effects. An alternative account suggests that children have less developed working memory and lexical retrieval skills; they may be more likely to acquire morphological cues before developing strong preferences for lexical ones (Clahsen & Felser, 2006). In contrast, adults, with more robust lexical retrieval capacity, tend to focus on overt lexical markers, often overlooking subtler morphological cues (Sagarra & Ellis, 2013).

Beyond cognitive and experiential explanations, both biological and environmental factors have been proposed. Newport (2019), for example, found age-related differences in grammatical morpheme learning, noting that while younger learners were more adept at abstracting underlying rules from statistical input, adults were more likely to mirror the surface-level distributional patterns without generalising rules effectively. Other than the potential biological reasons, differences in the learning sequence of cues might also account for the variant non-native morphology acquisition. In particular, adult learners are often exposed to lexical temporal markers before they encounter corresponding morphological forms, making the latter harder to acquire (Bardovi-Harlig, 1992; Meisel, 1987). In contrast, evidence from child language development suggests that inflectional morphology often precedes the emergence of adverbial time expressions (Dale & Fenson, 1996), facilitating earlier morphosyntactic mapping.

Together, these findings highlight the importance of investigating whether such difficulties can be overcome under conditions that resemble naturalistic L1 learning—namely, environments rich in consistent, patterned input. Examining the acquisition of morphology in a statistical learning paradigm offers a promising avenue for testing whether adult non-native language learners can learn morphological cues when provided with sufficient exposure. Although considerable research has examined the roles of L1 influence, redundancy, and perceptual salience in non-native morphological acquisition, relatively little is known about how these factors interact under naturalistic, input-rich conditions. This gap underscores the importance of exploring their effects within a statistical learning framework, where dense and patterned morphological input may shed light on whether longstanding challenges in adult non-native morphology acquisition can be overcome. The following section reviews non-native language acquisition studies situated in statistical learning paradigms, offering deeper insight into adult learners' capacity to acquire a novel language in environments that approximate natural language learning conditions.

2.3 Statistical Learning and Morphological Acquisition

A growing body of research highlights the role of statistical learning as a foundational mechanism in language acquisition (Isbilen & Christiansen, 2022). Broadly defined, statistical learning refers to the ability to track distributional regularities in sensory input, whether it is auditory, visual, or audio-visual, without explicit instruction (Frost et al., 2019).

One early challenge in language acquisition is the segmentation problem—that is, identifying word boundaries in continuous speech. Studies have shown that infants and adults can segment fluent speech by being sensitive to transitional probabilities between syllables: sequences that occur more frequently together (e.g., pretty baby) are interpreted as likely word units (Frost & Monaghan, 2016). These findings demonstrate that learners can detect local regularities to bootstrap word learning. However, segmentation alone is not sufficient for successful language acquisition. Learners must also solve the referential ambiguity problem—determining what linguistic forms actually refer to in sentential contexts.

CSL was proposed as a solution to this problem. In real-world communication, learners often encounter novel words alongside multiple possible referents, making it unclear which item the word denotes. For example, a learner might hear the word Pacho while viewing a scene with a panda, a ball, and a tree. A single trial provides no definitive mapping. However, by tracking co-occurrence patterns across multiple ambiguous trials, learners can gradually disambiguate word meanings (Yu & Smith, 2007). This method, known as CSL, capitalises on the human ability to accumulate statistical information over time.

In a typical CSL experiment, participants are exposed to a sequence of trials in which several words co-occur with several referents. Despite ambiguity within individual trials, consistent mappings can be inferred across trials. For example, Yu and Smith (2007) demonstrated that adult learners could acquire word-object mappings with high accuracy, even under high ambiguity (e.g., four words and four referents per trial). Such findings suggest that learners are capable of tracking cross-trial statistics to solve ambiguity and derive stable form-meaning associations.

While CSL research has primarily focused on lexical acquisition, recent studies have begun to explore whether similar mechanisms can support morphological learning for adult non-native language learners, particularly when morphemes convey meaning but lack clear, immediate referents in the environment. Finley (2023) extended CSL methods to investigate whether morphological patterns could facilitate word learning under referential uncertainty. In Finley's experiments, adult English speakers learned novel words composed of stems and suffixes. In the experimental condition, suffixes consistently signalled semantic categories (e.g., [-ke] for fruits, [-bu] for animals). In contrast, the control condition featured suffixes with no consistent semantic mapping. Results showed that participants in the experimental condition, who could rely on consistent morphological cues, learned novel words significantly better, especially when the initial learning phase provided sufficient exposure to the morphological system. This finding demonstrates that adult learners can extract and apply morphological regularities in CSL contexts, supporting the hypothesis that morphological bootstrapping can aid in disambiguating meaning.

Rebuschat et al. (2021) extended CSL research beyond lexical learning to investigate whether adult learners could acquire grammatical markers, specifically subject and object case marking, through exposure to sentence-scene pairings. In their first experiment, participants were presented with a single visual scene depicting two alien characters interacting (e.g., one chasing the other) while hearing a transitive sentence in an artificial language. These sentences contained nouns, verbs, adjectives, and case markers. Participants successfully learned nouns and verbs, but case markers were the least reliably acquired. To test the effect of referential complexity, the second experiment increased ambiguity by presenting two competing scenes per trial (target and foil). Under this condition, learners' accuracy in acquiring case markers dropped to chance levels, even though lexical learning remained robust. This finding highlights a key limitation of CSL for grammatical learning: while learners can track co-occurrences across scenes and sentences, successful morphological learning depends heavily on the referential clarity of the input. When ambiguity increases, learners appear to prioritise semantically transparent or visually anchored cues (e.g., nouns and verbs) over abstract grammatical forms that lack direct visual referents.

Notably, while research has begun to address morphology within CSL and investigate the effect of referential ambiguity, relatively little is known about how cross-linguistic transfer, redundancy, and salience affect morphology learning in CSL contexts. The present dissertation addresses these gaps.

2.4. Research Gaps and Rationale

2.4.1 Morphological Acquisition and the Limits of Prior SLA Studies

Despite increasing empirical attention to the challenges of non-native morphological acquisition, most existing studies have examined this difficulty under highly controlled conditions, such as written tasks, auditory-only input, or explicit training paradigms designed to emulate classroom instruction. While such methodologies allow for tight experimental control, they often fail to capture the audio-visual, referentially embedded nature of language acquisition in real-world settings. This disconnect raises important questions about how factors, such as cross-linguistic transfer, cue redundancy, and perceptual salience, operate in more ecologically valid, input-rich environments, where learners must integrate linguistic signals with complex visual and contextual information.

2.4.2 Gap 1: The Role of L1 Morphology in CSL

A longstanding finding in cross-linguistic transfer studies indicates that previously learned languages influence non-native language learning. Van der Slik et al. (2019), for instance, found that learners from morphologically rich L1s (e.g., Russian) performed better in Dutch morphology than those from morphologically poor L1s (e.g., Vietnamese). These effects have been interpreted as evidence of wholesale transfer: learners who speak a morphologically richer L1 would reach a higher end-state in non-native morphology learning. However, other accounts propose feature-based transfer, whereby only shared grammatical features (e.g., tense or number) are positively/negatively transferred across languages (Westergaard et al., 2017). Few studies have directly tested which of these mechanisms better explains morphological acquisition, particularly in implicit, statistically driven learning environments.

To address this gap, Study 1 in the present thesis investigates whether L1 transfer effects persist in a CSL paradigm, where morphological cues are embedded in a novel language and learned solely through auditory-visual co-occurrence. By comparing learners from three typologically distinct L1 backgrounds, Mandarin (morphologically poor), English (moderate), and German (rich), we examine whether learners with morphologically richer L1 have an advantage over acquiring tense, number, and agreement markers. If transfer operates wholesale, we predict a gradient pattern (Mandarin < English < German); if it is feature-specific, English and German learners should perform similarly on features shared with their L1s.

2.4.3 Gap 2: Redundancy and Cue Competition in Morphological Learning

Another persistent difficulty in non-native morphology acquisition lies in the redundancy of cues in the input. Morphological meanings are frequently encoded both morphologically (e.g., “-ed”) and lexically (e.g., “yesterday”), creating multiple overlapping cues for the same function. From a learning perspective, this introduces cue competition, whereby learners tend to rely on the most perceptually salient or previously learned cue. This dynamic is widely discussed in theoretical frameworks of associative learning (Rescorla & Wagner, 1972; Kamin, 1967) and has been adapted to SLA research to explain blocking and overshadowing learning mechanisms (Ellis, 2006, 2022).

Ellis and Sagarra (2010, 2011) provided experimental evidence that exposure to highly salient lexical cues (e.g., temporal adverbs) can inhibit the learning of co-occurring morphological cues (e.g., tense inflection). Their studies showed that learners who were first trained on adverbs struggled to acquire the corresponding inflectional forms, especially if those were less perceptually salient. The blocking effect was found to be asymmetrical: learning of morphology was blocked by prior attention to adverbs, but not vice versa.

Despite substantial evidence for blocking effects in non-native morphology acquisition, the precise boundary conditions under which these effects occur remain insufficiently understood. Many earlier studies have employed explicit training paradigms or artificial mini-grammars with metalinguistic explanations and conscious instruction, raising questions about the generalizability of their findings to more naturalistic learning contexts. It remains unclear whether blocking can arise in purely implicit learning environments, where learners must extract form-meaning mappings solely through exposure, as they would in real-world language learning. Moreover, although blocking has been robustly demonstrated in cases involving temporal adverbs and tense morphology, these designs do not separate the effects of cue redundancy from those of low perceptual salience, as the latter alone can hinder morphological processing and acquisition (Ellis, 2022).

To address these limitations, Study 2 of the current thesis investigates blocking effects within a CSL paradigm. Specifically, the study compares the learning of tense morphology, accompanied by redundant lexical adverbs, with number morphology, which shares similar acoustic properties but lacks a corresponding redundant lexical cue in our paradigm. By comparing the learning of tense and number cues, the study tests the effect of redundancy, teasing apart the effect of salience alone. Study 2 also manipulated whether lexical cues and their corresponding morphological forms co-occurred consistently or inconsistently, thereby testing whether redundant lexical cues block the acquisition of morphology either under conditions of inconsistent availability—mimicking the variability of natural language input—or under more regular, input-rich conditions.

2.4.4 Gap 3: The Role of Perceptual Salience in Morphological Acquisition

A large body of SLA research has highlighted the role of perceptual salience in shaping learners' ability to detect and acquire inflectional morphology. Morphological forms such as English past tense "-ed" or third person "-s" are often realised as short, unstressed, consonant-final segments, making them acoustically weak and prone to being missed in natural speech (e.g., Strachan & Trofimovich, 2019). These forms often lack syllabicity or prominent phonetic cues, contributing to their low perceptual accessibility. As a result, learners frequently fail to detect these morphemes during real-time processing, especially when they appear in reduced or non-salient contexts.

Perceptual studies (e.g., Bell et al., 2015) have shown that learners are more likely to detect syllabic morphemes (e.g., *hunted*) than their non-syllabic counterparts (*talked*), reinforcing the view that acoustic salience modulates morphological accessibility. However, most of this work has focused on detection or auditory perception tasks rather than on whether salience differences lead to actual differences in learning outcomes. Furthermore, in studies where salience is not experimentally manipulated, it is difficult to disentangle the effects of perceptual salience from those of other variables such as frequency, redundancy, or attention.

Although the theoretical role of salience is well acknowledged, relatively few studies have directly manipulated the acoustic features of morphological cues in controlled learning paradigms. Fewer still have tested whether enhancing salience through phonological features—such as syllabicity and sonority—can improve the acquisition of low-salience forms. This leaves a critical gap in our understanding of whether bottom-up acoustic properties, independent of metalinguistic instruction or task demands, are sufficient to improve learners' sensitivity to inflectional morphology under naturalistic, input-driven conditions.

To address this, Study 3 of the current thesis investigates the role of both perceptual salience in morphological acquisition using a CSL paradigm. The study manipulates syllabicity and vowel sonority across morphological cues while keeping input frequency and referential structure constant.

This design enables a more precise examination of whether learners benefit from the inclusion of default forms during early-stage morphology learning in input-driven environments.

2.5 Research Questions and Predictions

Building on the empirical and theoretical gaps identified above, the present thesis investigates whether and how adult non-native language learners can acquire morphological features under an input-rich, implicit learning paradigm — CSL. While past research has demonstrated adults' capacity to track co-occurrence patterns across modalities, little is known about whether this mechanism supports the acquisition of abstract grammatical morphology, and what factors modulate its effectiveness. Therefore, in this thesis, we first asked an overarching research question: *How do statistical learning mechanisms support non-native morphological acquisition, and what factors influence this process?*

RQ1: *Can adult learners acquire grammatical morphology (tense, number, subject-verb agreement) under a CSL paradigm?*

Prior studies have demonstrated successful CSL of nouns and verbs, but research on the acquisition of morphological cues remains limited and inconclusive (e.g., Finley, 2023; Rebuschat et al., 2021). To address this gap, we conducted three studies using a cross-situational sentence learning paradigm to investigate whether the morphological features can be learned by adult learners.

RQ2: *What are the factors that influence the statistical learning of non-native morphology?*

Study 1 investigated whether learners' L1 morphological richness affects their acquisition of non-native morphology. Previous studies have suggested that L1 background influences the detectability and interpretability of morphological cues (van der Slik et al., 2019; Wu & Juffs, 2022). We expect learners from morphologically rich L1s (e.g., German) to show enhanced sensitivity to non-native morphology compared to those from morphologically poor L1s (e.g., Chinese). Specifically, we predict that transfer effects will align more with a property-by-property pattern rather than wholesale transfer.

Study 2 explored the effect of redundancy. Drawing on the blocking literature (Ellis & Sagarra, 2010), we examine whether prior exposure to more salient, lexical cues (e.g., temporal adverbs) interferes with subsequent learning of morphological cues that encode the same meaning. We predict that redundancy will impede morphological learning, especially when lexical cues are highly salient and co-occur inconsistently with the target morphology.

Study 3 focused on examining whether the acoustic salience of morphological cues influence morphology acquisition. Research has highlighted that low salience poses serious barriers to morphological acquisition (e.g., Bell et al., 2015). However, limited studies have examined whether enhancing perceptual salience (e.g., through syllabicity or sonority) can improve morphological learning in naturalistic settings (e.g., Strachan & Trofimovich, 2019). We predict that learners will acquire high-salience cues more successfully than low-salience ones, and this advantage may be especially pronounced in the absence of explicit instruction.

3. Publishable paper 1: Learning morphology from cross-situational statistics

(second round of under review with *Studies in Second Language Acquisition*)

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Abstract

Non-native languages tend to be acquired through a combination of explicit and implicit learning, where implicit learning requires coordination of language information with referents in the environment. In this study, we examined how learners use both language input and environmental cues to acquire vocabulary and morphology in a novel language, and how their language background influences this process. We trained 117 adults with native languages varying in morphological richness (English, German, Mandarin) on an artificial language comprising nouns and verbs with morphological features (number, tense, and subject-verb agreement) appearing alongside referential visual scenes. Participants were able to learn both word stems and morphological features from cross-situational statistical correspondences between language and the environment, without any instruction. German-speakers learned subject-verb agreement worse than other morphological features, which were acquired equally effectively by English or Chinese speakers, indicating the subtle and varied influence of native language on implicit non-native language learning.

***Keywords*:** cross-situational learning, statistical learning, morphology, Bottleneck Hypothesis, cross-linguistic influence

Introduction

The acquisition of non-native languages tends to involve a combination of explicit instruction and implicit acquisition of the associations between sentences and referents in the environment around the speaker (Rebuschat, 2022; Williams & Rebuschat, 2023). In this study, we unpack the way in which learners combine information from the language with features of the environment to acquire both words and functional morphemes. Learning to map words onto co-occurring referents in the environment poses an impressive challenge. It is often difficult to figure out the meaning of a novel word based on one scene due to the potential ambiguity of possible mappings that can be made (Quine, 1960). However, recent research has suggested a way to solve the problem of referential ambiguity. After being exposed to multiple scenes, learners can determine the mapping between the sound and its referent, by keeping track of cross-situational statistics between words and referents that regularly appear together (Schroer & Yu, 2023; Smith & Yu, 2008; Yu et al., 2021). To date, cross-situational learning (CSL) is evidenced to be effective for learning referents that can be directly observed in the environment, such as nouns (e.g., Ge et al., 2025; Suanda & Namy, 2012; Vlach & DeBrock, 2019) and verbs (e.g., Monaghan et al., 2015; Scott & Fisher, 2012). However, the linguistic features that pose challenges to adult language learners often cannot be easily identified from the visual world, such as functional morphology (Slabakova, 2014). The question of whether adult language learners can learn morphology via CSL has to date only been addressed by very limited empirical studies.

Learning of morphemes via CSL

As one of the few studies that explore how morphological features may be learned via CSL, Finley (2023) tested the extent to which morphological cues relating to semantic categories of nouns could be acquired through CSL. When suffixes corresponded to semantic categories (e.g., animals, fruits, vehicles) the morphological cue could be rapidly acquired from CSL, and furthermore, the cue could then be used to improve the learning of the stems (see also Monaghan & Mattock, 2012). The beneficial effect of the morphological cues for learning, however, was only realised when referential ambiguity was initially low, enabling the role of the stem and the morpheme to be discerned. Finley's (2023) Experiment 1 demonstrated that morphological learning from presentations of single words is, in principle, a possibility. However, the complexity of natural language learning involves determining the role of word stems and affixes within longer and more complex sentences. Sentences in the natural language learning environment also have richer syntax or morphology, potentially without the initially low referential ambiguity that Finley (2023) showed was required to facilitate CSL of morphology.

Reflecting one aspect of the complexity of natural language learning in terms of multiple words and referents occurring simultaneously, Rebuschat et al. (2021) adopted a CSL paradigm where participants were exposed to presentations of sentences with visual scenes. Specifically, they investigated whether the marker words indicating the agent and patient of the sentences could be acquired from complex sentence-scene correspondences. In their Experiment 1, adult participants were presented with a single scene comprising two aliens interacting with one another in each learning trial, which co-occurred with hearing a transitive sentence in an artificial language that described the scene. After exposure, learning of nouns, verbs, adjectives, marker words, as well as sensitivity to word order, were then tested. Rebuschat and colleagues found that case markers can be learned but it was the least and latest learned linguistic features compared to nouns, verbs and adjectives. In a follow-up experiment (their Experiment 2), they found that the learning of the case markers was only at a chance level when referential ambiguity was increased by presenting two different scenes (one that matched the sentence they heard and one foil) in each learning trial. This finding was consistent with results from Walker et al. (2020) and Monaghan et al. (2021), which used the same artificial language paradigm, and found only low levels of case marker learning. Taken together, there is evidence that learning the mappings of a sound segment that express relations to more abstract, and harder-to-observe, properties of the environment to which the language relates, under certain circumstances, is possible, but only when the referential ambiguity stays low. However, the question remains why these markers are more challenging to acquire than other aspects of the language (e.g., Monaghan et al., 2021; Rebuschat et al., 2021; Walker et al., 2020).

Explanations for why morphology poses learning difficulties

There are several explanations for why morphology is more difficult to learn, which could operate individually or cumulatively to explain learning (DeKeyser, 2005; Ellis, 2022; Slabakova, 2014), and that could limit the effectiveness of CSL to support the acquisition of morphology. First, the immediacy, or transparency, of a cue's referent may influence natural language learning (Hofweber et al., 2023; Sehyr & Emmorey, 2019). In Rebuschat et al.'s (2021) study, the function of the case markers was not immediately available within a single scene but instead had to be interpreted from the interoperation among words within the sentence, and between potential agent and patient actors in the environment. This meant that the case markers were opaquer as a referent to the markers than were the nouns, verbs, or adjectives, because of their lower salience (van Zoest & Donk, 2005). If opacity of referents and mappings are contributors to CSL of morphology, then this is unlikely to be to the same degree across all targets for morphological features. For instance, tense morphology may be difficult to acquire because of difficulties in isolating temporal order in events (Tünnermann & Scharlau, 2018), whereas number (e.g., singular or plural) may be easier to acquire because of its more immediate appearance in environmental stimuli – if there is one or more than one panda in the environment then that is easily observed, but whether the panda walked yesterday or will walk tomorrow cannot be determined from observation of the (current) environment. In contrast, subject-verb (SV) agreement may be hard to acquire both because it is not visually or contextually apparent in the environment, and also because of the integration of syntactic and morphological constraints that are required, potentially explaining why SV agreement is widely observed to be difficult to learn in non-native language acquisition studies (Slabakova, 2014).

A second potential explanation for why morphology might be more difficult to acquire is that morphological cues are usually not acoustically salient in a speech stream (e.g., syllabically shorter with more reduced vowels than word stems) (Gass et al., 2018). Due to the limited capacity of working memory, learners tend to rely on the more salient cues (Cintrón-Valentín & Ellis, 2016). In Rebuschat et al. (2021), for instance, the case markers were shorter than the nouns and verbs (monosyllabic versus bisyllabic). Participants might have focused more on the learning of nouns and verbs as they are perceptually easier to process. However, the low level of learning of case markers in Rebuschat et al. (2021) could have been due to many possibilities, including cue salience, but also potentially the opacity or transparency of the morphological cues. Our study is designed to tease apart some of these contributors to difficulties and differences in learning morphology.

A third possible contributor to morphology learning difficulty is the influence of learners' native languages (L1s). Learning an additional language can be influenced by previously learned languages, a phenomenon referred to as cross-linguistic influence (Suethanapornkul, 2020) and may involve competition among cues available in known and additional languages (Nixon, 2020). A multitude of empirical evidence shows that L1 plays a dominant role in influencing additional language learning, both in classroom (Choi & Ionin, 2021; Finn & Hudson Kam, 2015) and immersion (Diaubalick & Guijarro-Fuentes, 2019) settings. For instance, in an implicit language learning task, Ellis (2007) found that adult native speakers of an L1 that has little inflectional morphology tend to pay more attention to lexical cues rather than morphological cues that encode the same meaning. The information that morphological features carry is thus, at least in some cases, redundant and this could result in the learning of the morphological cues being blocked by cues that are more learnable to the participants, which also varies based on L1 (see Nixon, 2020, for a discussion of blocking in speech learning). Similarly, a large dataset of non-native Dutch learners revealed that those adults with morphologically less complex L1s performed worse in acquiring Dutch than those with morphologically richer L1s (van der Slik et al., 2019). Hence, the speaker's L1 may influence the degree to which different morphological features are detected by the speaker.

Taken together, existing evidence points toward a wholesale transfer effect driven by the morphological richness of the L1. Nevertheless, this effect has yet to be systematically examined in the context of adult immersive novel language learning. Our study aimed to address this gap by examining the effect of L1 morphological richness on morphology learning in a CSL paradigm, comparing the learning between L1 speakers of Mandarin, English and German. Mandarin indicates tense with adverbs or prepositions instead of inflectional cues (e.g., 他一般周一游泳 *tā yībān zhōuyī yóuyǒng*, "He usually Monday swim";我明天学习 *wǒ míngtiān xuéxí*, "I tomorrow study"), whereas English and German tend to indicate tense using morphology or short auxiliary verbs (e.g., *Ich gehe*, "I walk"; *Ich werde gehen*, "I will walk"), sometimes in addition to prepositions. English and German also indicate number (singular or plural) using a suffix morpheme. Mandarin, in contrast, only indicates number using one of several noun-specific classifiers preceding the noun (e.g., plum, Pflaume, 李子 "lǐzǐ"; plums, Pflaumen, 一袋李子 "Yī dài lǐzǐ" "a bag of plums"). When learning non-native morphological cues for tense and number, if transfer is wholesale, then we might expect L1 German speakers to outperform L1 English speakers, because of the greater profusion of morphological cues, who in turn would outperform L1 Mandarin speakers.

Current study

In this study, we examined the extent to which adults can learn the meaning of morphological cues with implicit exposure to the language in a CSL paradigm, determining whether learning varies for morphological cues with different functional targets (that vary in opacity), and assessing the extent to which implicit acquisition of morphological cues depends on the speakers' affinity with morphological cues present within their L1. We tested the effect of transparency of different morphological cues within the novel language, in terms of the extent to which each of the morphemes is dependent or independent of syntactic constraints. Selecting tense, number, and SV agreement thus varied the transparency of the cues, i.e., whether there are immediately observable referents to the morphemes within the environment. We thus determined the limits of CSL in supporting participants' acquisition of different morphological targets – tense, number, and SV agreement – at the same time as learning nouns and verbs.

Our CSL paradigm was inspired by Rebuschat et al. (2021), following a similar design in which participants were asked to make decisions on sentence-scene mapping after hearing one sentence in an artificial language and being presented with two scenes per trial. While the learning conditions do not reflect the full complexities of natural language learning, this design enables us to focus on two aspects of natural language immersive learning and determine their impact on language learning. First, our paradigm reflects the need for language and (visual) environmental information to be coordinated for learning. Second, our design enables us to determine how referential ambiguity among multiple morphemes occurring in each utterance and multiple potential referents in the scene around the learner affects processing.

In our study, we controlled cue salience and transparency of the grammatical morphemes of tense and number – these affixes were in CV (Consonant + Vowel) form and their referents were visually available in every scene. This allowed us to identify the effect of transparency by comparing the learning between these visually available cues (tense and number) and a visually unavailable cue, which was SV agreement. This experimental design enables us to hone in on exactly what aspect of the language has been learned by manipulating the presence of information in the visual scene, allowing us to target acquisition of word stems or morphemes. An accompanying grammatical judgment task (GJT) enabled us to determine whether the SV agreement was acquired. Although morphological cues in natural language can be more abstract and are not always available in the environment, such as whether an event occurred in the past, present, or future, the design of our study tests for the first time whether participants can isolate the morphological segments from continuous speech and keep track of visual referents that consistently co-occur with them. Having two scenes per learning trial also means that we increase the ambiguity of the possible word-referent mappings available in the environment, mimicking that of naturalistic language learning situations (e.g., Yu & Ballard, 2007), and enables us to test learning online, as it proceeds with exposure.

Furthermore, in an exploratory analysis we also investigated whether explicit knowledge of morphology emerges from the implicit CSL learning environment without any instruction or feedback. Learners may become aware of the meanings of number and tense affixes in our studies, as explicit knowledge has consistently been demonstrated to arise from implicit CSL learning (Ge et al., 2025; Monaghan et al., 2019). Conversely, participants might not recognise the SV agreement since it has been shown that incidental exposure cannot support awareness of functional morphology, such as SV agreement (Kachinske & DeKeyser, 2024). We also expect to see that L1 German speakers exhibit greater awareness of SV agreement than L1 English and Mandarin speakers, given that L1 morphological richness has been evidenced to correlate with non-native language awareness (Wu & Juffs, 2022). However, it remains unclear whether CSL learning can facilitate explicit morphological knowledge and whether this awareness interacts with L1 morphological richness, the result of which gives implications for the types of morphology that require explicit language instruction.

Research questions and predictions

Our first research question asked whether grammatical morphemes could be learned from CSL alongside word stem learning. Accurate predictions are currently difficult to ascertain for this research question, as adults were evidenced to be able to learn the abstract grammatical morphemes from cross-situational statistics (Finley, 2023) but learning morphology from sentence-based language input was challenging (Rebuschat et al., 2021).

Our second research question asked whether there are differences in learning morphological features according to their transparency. Learning of tense, number, and SV agreement varied in terms of transparency of the target. We predicted that tense and number would be easier to acquire than SV agreement, as previous research indicated that transparency affects learning (Hofweber et al., 2023; Sehyr & Emmorey, 2019). However, it is difficult to predict whether tense and number would differ from one another, as both of the visual referents to tense and number were made transparent in our experiment.

The third research question investigated the extent to which morphological learning difficulty is affected by L1 background (English, German, Mandarin). We tested whether differences in morphological expressiveness in learners' L1(s) affected the acquisition of different morphological features from cross-situational statistics. We test two theories of transfer by comparing the learning of tense and number affixes between L1 English, German and Mandarin speakers. If there is a wholesale transfer effect from L1 to additional language learning of morphology, then L1 morphological richness would affect learners' sensitivity towards (all of) the morphological features in the novel language, such that the German group should outperform both the English and Mandarin L1 groups. However, if transfer is feature-by-feature according to structural similarity (e.g., Westergaard et al., 2017) then the English and German groups should be similar to one another, and outperform the Mandarin L1 group. However, the crosslinguistic transfer effect may be limited to semantically transparent, interpretable features, like number and tense in our paradigm. In contrast, participants from different L1s may demonstrate similar accuracy in SV agreement tasks, as its difficulty is likely to be driven by real-time processing issues rather than interference from L1 (Lago et al., 2025).

Finally, as an explorative research question, we also assessed participants for their explicit awareness of the different morphological features and determined whether this explicit knowledge related to language acquisition of different aspects of the language. Based on previous studies (e.g., Ge et al., 2025; Monaghan et al., 2019), we predicted that the awareness of the knowledge would predict the learning of different linguistic features.

The design and analysis were preregistered before data collection (https://osf.io/x6svp).

Methods

Participants

Sample size was estimated using Monte Carlo simulations of data, which predicted that 35 participants per language group would be sufficient for power of 0.8 in order to find medium size effects (Cohen's d = 0.5) of main effects of morphological feature type and language background affecting learning overall. The detailed description of our power analysis can be found with our materials, data, and analysis scripts (https://osf.io/dvpgq/?view_only=5ce6d476492e42ccae7e906f178fdfcc).

One hundred and seventeen L1 English, German and Mandarin native speakers voluntarily participated in this study. However, ten participants had to be excluded either because they took written notes during the experiment or because their language background did not meet the inclusion criteria of being either an L1 English, German or Mandarin speaker. Due to technical issues, two participants had to be excluded due to their missing data in the CSL task and debriefing questionnaires. Our final sample thus consisted of 105 participants (74 women, 31 men), which were distributed into three groups, based on their L1(s).

Thirty-five participants each spoke Mandarin, English, and German as their L1(s). None of the participants reported having learned Portuguese, on which the phonetics of the artificial language were based. However, all participants in L1 Mandarin and L1 German groups reported having learned a non-native language that marked number, tense, and SV agreement, mostly English, whereas 66% (23/35) of participants in L1 English group reported being monolingual. The mean age in our sample was 23.27 (SD = 4.72, range 18 to 36 years), and there were no significant differences between the groups in terms of age. Participants were recruited via social media (L1 Mandarin), word of mouth (L1 German) or via their institution's participant panel (L1 English).

The study was approved by the ethics review panel of the Faculty of Arts and Social Sciences at Lancaster University and conducted in accordance with the provisions of the World Medical Association Declaration of Helsinki. None of the participants were remunerated in this study. However, the L1 English group received course credits at their home institution for taking part.

Materials

Artificial language.

Vocabulary. The artificial language consisted of 16 disyllabic pseudowords: half functioned as nouns and half as verbs. Nouns referred to eight distinct cartoon animals (e.g., panda, pig), while verbs denoted common actions (e.g., working, walking, sleeping). An additional five monosyllabic pseudowords served as grammatical morphemes marking number (singular/plural) and tense (past, present, future). All vocabulary items were recorded in a monotone by a female native speaker of Portuguese.

The eight cartoon animals served as visual referents for the noun vocabulary. Each was shown performing the eight actions, either alone or two of the same animals, depending on the number. Tense was indicated by visual time cues presented above the action: a written word in the participant's native language, paired with an icon (left arrow = past, circle = present, right arrow = future), as illustrated in Figures 1 and 2[1].

We randomized four lists of word-referent mappings to reduce the impact of a particular mapping being easier to learn. The sixteen disyllabic pseudowords were randomly mapped to the characters and the actions, and the five monosyllabic pseudowords to the different grammatical morphemes. Table 1 presents the artificial language vocabulary and their respective meanings, for one of the four random mappings. The complete set of random mappings can be found in Table S-1. The animal cartoon characters can be found in Appendix ***A***. The entire set of images can be found on our OSF site.

Table 1

The artificial language vocabulary used in this study. There were 8 nouns, 8 verbs, and 5 grammatical morphemes (tense and number marking). There were four random pseudoword-referent mappings to avoid pre-existing biases. Here, we report one of the randomizations.

Category	Pseudowords	Meaning

Nouns		/faʊlu/	panda
		/fima/	pig
		/fuki/	lion
		/jitu/	mouse
		/kitə/	sheep
		/lipə/	rabbit
		/luʧi/	dog
		/ʃaji/	cow
Verbs		/naɪpə/	cook
		/paʧu/	work
		/paʃə/	swim
		/siʃə/	run
		/pulə/	sleep
		/suli/	walk
		/masə/	sing
		/tusi/	paint
Morphemes	Number	/saɪ/	singular
		/ti/	plural
	Tense	/nɑ/	past
		/kə/	present
		/paʊ/	future

Grammar. The artificial language sentences were intransitive and followed SV order. The number morphemes were attached to both the nouns and the verbs, and the tense morphemes were only to the verbs. That is, each noun consisted of the stem plus the number suffix (singular or plural), and each verb consisted of the stem, followed by a tense suffix (past, present, future) and a number suffix (singular or plural). The double marking of number suffixes was employed, which is used to indicate SV agreement in some natural languages such as Spanish. In Spanish, both the subject noun and the verb are morphologically marked for number — for instance, los niños cantan ("the children sing"), where plural suffixes appear on both the noun (-s) and the verb (-an). It is worth noting that in our artificial language, the number was marked using identical suffixes on both subjects and verbs. While this reinforces form-meaning mappings, it may have unintentionally reduced the overall complexity of the language by increasing the transparency and predictability of the morphological system. In natural languages such as English, subject-verb (SV) agreement often exhibits lower contingency than in our artificial language. For instance, the morpheme -s marks plural nouns (e.g., dogs) but singular verbs (e.g., walks), creating inconsistencies in form-meaning mappings. Such low contingency between form and meaning has been shown to impede learnability (Ellis, 2022). In contrast, the double marking system in our artificial language featured highly contingent, one-to-one mappings between form and meaning—for example, [ti] unambiguously marked plurality, and [sai] consistently marked singular. This increased transparency represents a limitation of the current study, as it may have made the morphological system easier to acquire than what learners would encounter in some natural languages.

For example, following the first randomization in Table 1, the sentence /faʊluti paʧunɑti/ would mean "The pandas worked" and would be constructed as follows:

(1) /faʊluti paʧunɑti/

Faulu	ti	pachu	na	ti
Panda	pl	work	past	pl

“The pandas worked.”

We constructed 504 artificial language sentences, comprising 480 sentences in the CSL task (384 in training trials and 96 in test trials), and 24 sentences in the GJT.

Retrospective verbal reports

We used a questionnaire to gather retrospective verbal reports (Rebuschat, 2013). These allowed us to determine if participants became aware of (aspects of) the artificial language, and if so, which ones (Rebuschat, 2013). The questionnaire was adapted from Rebuschat et al. (2015). We started by asking participants to report any strategies they might have used during the CSL task. Specifically, we asked how they decided which scene was the correct referent of the sentence, whether they were just guessing or whether strategies had been applied. A follow-up question regarding the strategies was asked that if their strategies had changed throughout the CSL task. In the second section, we investigated the degree of awareness regarding the meaning of the grammatical morphemes. The questions gradually prompted them with more and more explicit information. We started with a general question by asking whether they noticed any patterns or rules about the grammatical structure. This is followed by more specific questions asking whether they had noticed and realized the meaning of the sound segments *na, ke, pau, sai* or *ti*. Finally, we asked them what they thought the aim of the study was. The questionnaire can be found in Appendix B.

Procedure

After providing informed consent, participants completed the language background questionnaire, followed by two tasks: CSL and grammaticality judgments, as described below. Finally, they completed the debriefing questionnaire (retrospective verbal reports). The entire procedure took around 60 minutes.

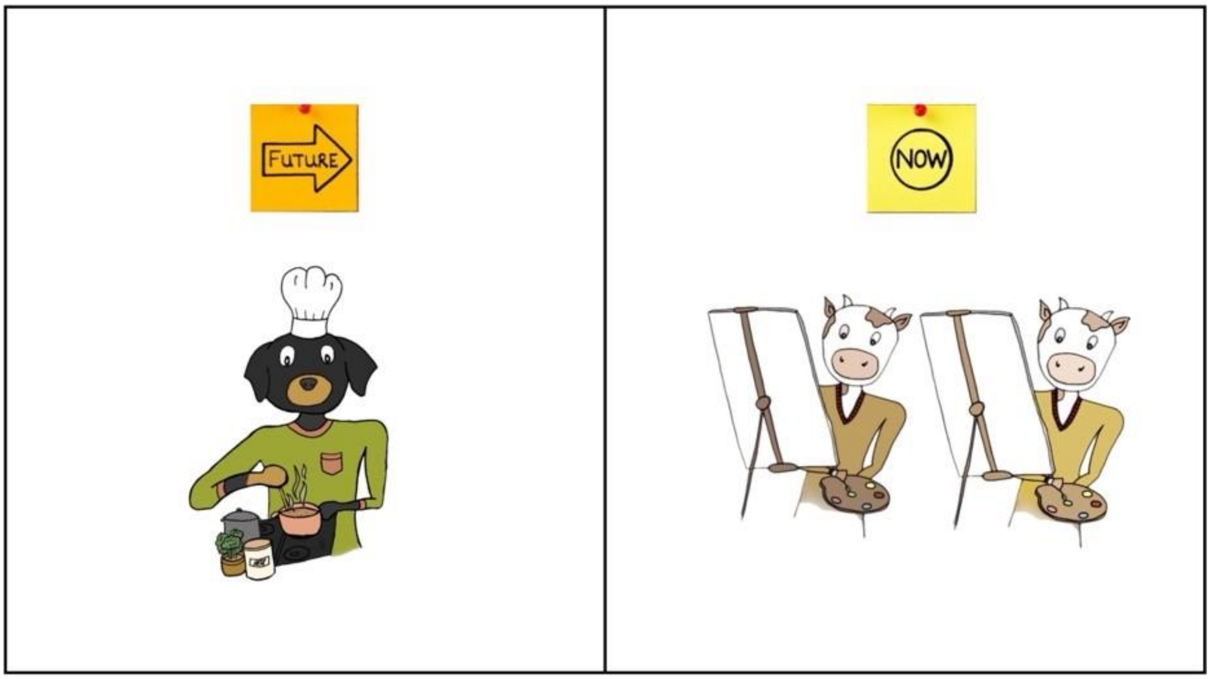
Cross-situational learning task

The CSL task was used to train and test participants on the acquisition of novel nouns, verbs and morphemes. Participants were informed that they would hear an artificial language sentence and see two scenes on the screen. Their task was to decide, as quickly and accurately as possible, which scene the sentence referred to. No feedback was provided.

During each trial, participants were first presented with a fixation cross for 500 milliseconds, followed immediately by the presentation of two static scenes, one on the left and one on the right side of the screen. One thousand milliseconds later, participants were then played an artificial language sentence describing one of the two scenes. Immediately after the sentence finished playing, participants had to indicate, as quickly and as accurately as possible, which scene the sentence referred to. They were instructed to press Q on the keyboard for the left scene or P for the right scene. No time limits were set for each trial; the next trial was only played after participants entered a response. Figure 1 provides an example of a training trial of the CSL task.

Figure 1

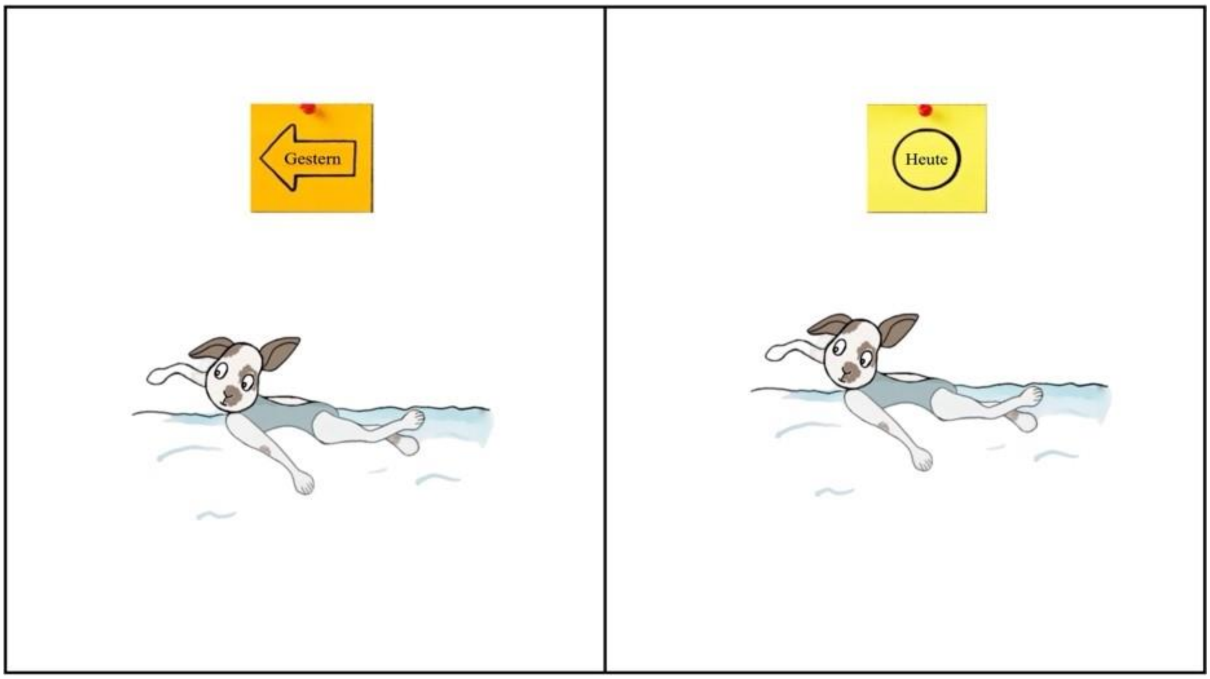
An example of a training trial in the (English) CSL task. Participants were presented with two scenes depicting animal(s) performing an action and played a single artificial language sentence (e.g., /lut̠ʃisaɪ naɪpəpaʊsaɪ/). Their task was to decide, as quickly and accurately as possible, which scene the sentence referred to. The trial was used with the L1 English group, so the time indicators are presented in English.



There were two types of CSL trials, training trials and test trials, which differed in terms of the number of elements that varied between the correct and foil scenes. In the training trials, to reflect ambiguity of potential referents in the environment, the target and the foil scenes differed in terms of two to four elements (different agents, actions, number, and/or time cues), for example in Figure 1, the scenes differed in agent, action, number, and time. However, in the test trials, the two scenes only differed in one aspect. This manipulation allowed us to test what nouns, verbs and grammatical morphemes participants had learned as they completed the CSL task. To test noun learning, the two scenes were identical except for the agents (same actions, same time cues, different agents). To test verb learning, the two scenes were identical except for the actions (same agents, same time cues, different actions). To test morpheme learning, the two scenes were identical except for the time cues (same agents, same actions, different time cues) or they were identical except for the number of agents (same actions, same time cues, but different number of agents). Figure 2 provides an example of a test trial for tense – the correct scene can be selected only if the tense morpheme is known.

Figure 2

An example of a tense test trial in the (German) CSL task. In test trials, the two scenes were identical with a single difference. In the example trial, only the time of the event is different between the two scenes, as seen in the time indicators "gestern" (German, yesterday) and "heute" (today). The trial in this example tests if participants have learned the past tense morphemes as the agent and the action. The trial was used with the L1 German group, so the time indicators are presented in German.



The CSL task consisted of eight blocks, each of which contained 48 training trials. We carefully balanced the presentation frequency of nouns, verbs and morphemes across blocks, the frequency of target and foil scenes, and their respective locations on the screen (left or right). Importantly, blocks 4, 6 and 8 of the CSL task also contained 32 test trials, in addition to the 48 training trials. That is, in these blocks, both training and test trials occurred in random sequence. Of the 32 test trials, eight were designed to test noun learning, eight to test verb learning, eight to test the acquisition of the number morphemes and a further eight to test the acquisition of the tense morphemes. The advantage of mixing training and test trials in specific blocks was that it enabled us to test what aspects of the language participants were acquired first (see Rebuschat et al., 2021).

Nouns, verbs, and morphemes occurred an equal number of times within each block except for one morpheme for tense (past/now/future) being unavoidably occurred one time less than the others but the differences were even over three blocks. Animal, action, tense, and number features in the pictures occurred an equal number of times in both target and foil scenes, except for time indicators for the same reason. Since no feedback was given, if participants were able to use the cross-situational statistics, then they should be able to learn to distinguish the target from foil scenes by tracking the co-occurrences between particular morphemes and particular features of the scene that always co-occurred. Note that tense and number morphemes occurred in different frequencies over trials – as tense related to three targets (past, present, future) and number related to two (singular, plural). Thus, there was a difference in frequency, which can affect non-native language learning (Ellis, 2012). We return to consider this point in the Discussion.

Grammaticality judgment task

The GJT was used to test SV agreement. In each trial, participants were first played an artificial language sentence (without any scenes on the screen). After the sentence finished playing, they saw a question mark. Participants were instructed to decide, as quickly and accurately as possible, if the sentence sounded "good" or "bad" to them (in relation to the previously heard artificial language stimuli). They pressed Q if the sentence sounded good to them and P if it sounded bad. There were 24 trials. Half the sentences were grammatical, i.e. they had correct SV agreement, and the other half was ungrammatical. The ungrammatical sentences contain mismatching of numerals between subject and verb (e.g., subject singular, verb plural, or subject plural and verb singular). The GJTs occurred three times, always after a mixed CSL block, i.e. after blocks 4, 6 and 8. In each GJT, we presented 8 SV agreement test trials (four grammatical, four ungrammatical). The artificial language sentences can be found on our OSF site in the spreadsheets showing the data.

Statistical analysis

One sample t-tests were conducted to identify when accuracies were above chance, allowing us to compare our data to previous studies. We applied the Holm-Bonferroni method to correct for multiple comparisons, which takes into account the ordering of tests to minimise Type I and Type II errors. We predicted that learning would be most likely to exceed chance later in the training, and so we ranked the final block first and initial block last for the correction of p-values. We then used logistic mixed-effects models (Jaeger, 2008) to test our four research questions. The first model investigated predictors that might influence the training trial accuracies, where accuracy was coded as a binary dependent variable. We started from the null model, which included intercepts for random effects of subjects and items (where item was the sentence participants heard) as well as by-subject random slope for Block and by-item random slopes for Block, L1 and their interaction[2]. To find the best fitting model, we added fixed effects of Block (1 to 8), L1 (Mandarin, English and German), and Block:L1, and tested the improvement in model fit using log-likelihood tests. We also tested the quadratic effect for Block after other fixed effects were entered, to determine whether learning was linear or varied over time.

The next two models investigated factors that might influence the accuracies in the morphology test trials and the nouns and verbs tests trials. For the analysis of the morphological features, the random intercepts in the null model were subjects and items as well as by-subject slopes for Block, morphology test types and by-item random slopes for Block and L1[3]. For the noun and verbs tests, the model was exploratory because we did not preregister this analysis. We started with a null model, which included the random intercept of subjects and items as well as by-subject slopes for Block, noun versus verb and by-item random slopes for Block, L1. The final exploratory mixed effects model investigated whether adding awareness (aware vs. unaware), Awareness:Block, and Awareness:L1, improved model fit for the second mixed effects model.

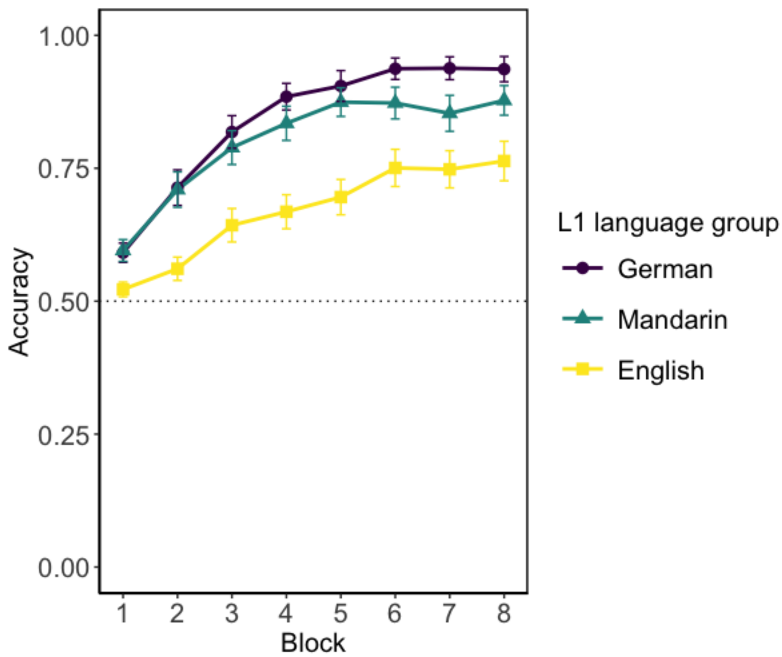
Results

Performance on the cross-situational learning task

The performance on the training trials of the CSL task is displayed in Figure 3, and Table S-2 provides a detailed summary of the performance on the training trials by block and by language group.

Figure 3

Mean accuracy on the training trials of the CSL task. Error bars represent 95% Confidence Intervals. The dotted line (0.5) shows chance performance.



The first mixed-effects model investigated the predictors that have effects on training trials' accuracy, in order to address the first research question about whether CSL is sufficiently powerful to drive grammatical morpheme learning alongside word stem learning. An effect of overall learning, with improvement with exposure, would provide preliminary evidence that learning the language was possible. An effect of language group would also begin to address the third research question determining whether language background influenced acquisition of the novel language.

Beginning with the baseline model containing only random effects, we found that adding the fixed effect of Block significantly improved model fit ($\chi2(1) = 104.19$, $p < .001$), supporting the first research question showing that learning was possible overall (see Figure 3). There was also a significant effect of adding L1 group ($\chi2(2) = 6.7795$, $p = .034$), indicating that language background did affect acquisition. This was nuanced by the interaction between Block and L1 group ($\chi2(2) = 19.704$, $p < .001$). For the interaction between Block and L1, compared to the L1 English group, the L1 Mandarin (logit estimate = .254, SE = .091, $p = .005$) and L1 German (logit estimate = .422, SE = .092, $p < .001$) groups interacted positively significantly with Block. However, L1 German compared to the L1 Mandarin group did not interact significantly with Block (estimate = .168, SE = .093, $p = .072$). The rate of learning over time was thus slower for the L1 English than the L1 German or Mandarin group, showing that language background affected the overall pace of learning, as illustrated in Figure 3. The quadratic effect for Block showed no significant difference ($\chi2(1) = 2.052$, $p = .152$). To ensure there was no bias in word-meaning mappings, we also tested whether different versions of these mappings affected overall learning. The analysis showed that including language version as a predictor did not significantly improve the model fit ($\chi^2(3) = 0$, $p = 1$), indicating no performance differences across word-meaning mappings. The final best-fitting model is reported in Table S-8.

Distinguishing test types in the cross-situational learning task

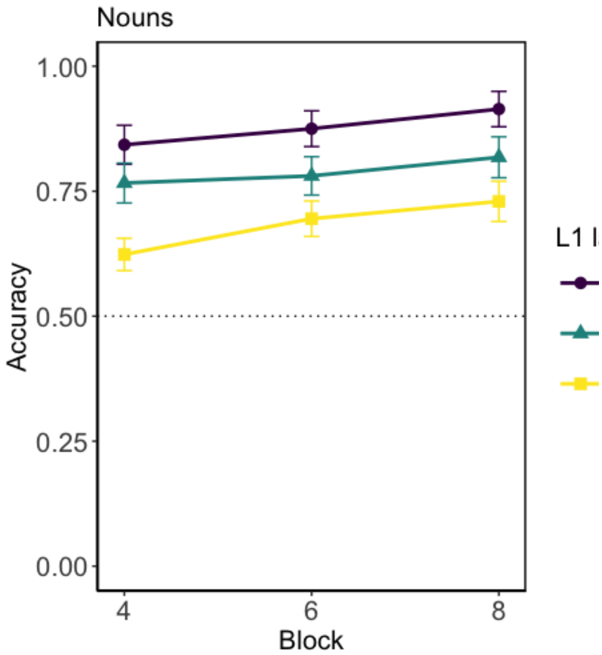
The training trials do not tell us what participants' decisions are based on; they could correctly select a scene due to any of the distinctive features it contains. To determine precisely what lexical or morphological features participants have acquired, we analysed their performance on the test trials of the CSL task. This enables us to test the second research question to uncover the effect of transparency on learning morphemes, and to provide further information regarding whether the influence of language background affects learning generally or for particular language features, addressing research question 3.

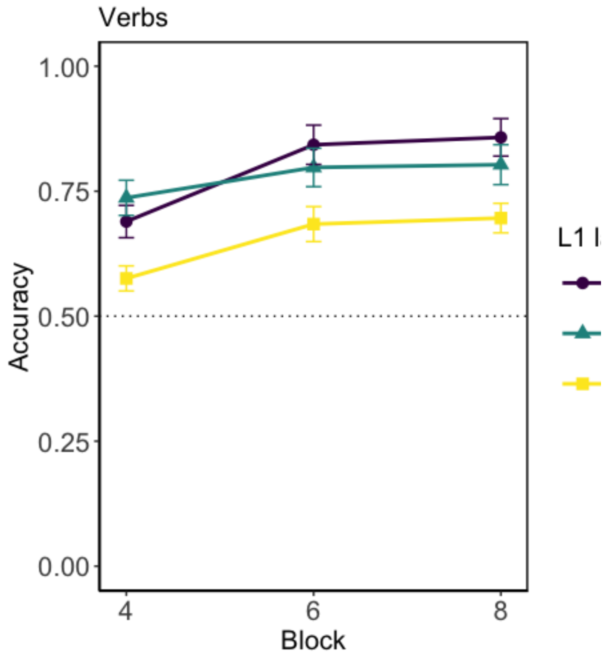
Figures 4a to 4d visualize the accuracy of the test trials that occurred in blocks 4, 6, 8 of the CSL task. Figure 4e visualizes performance across the three groups for the grammaticality judgment task, to investigate SV agreement. Table S-3 and S-4 presents detailed analyses of performance by block and language group on each type of test trial.

Figure 4

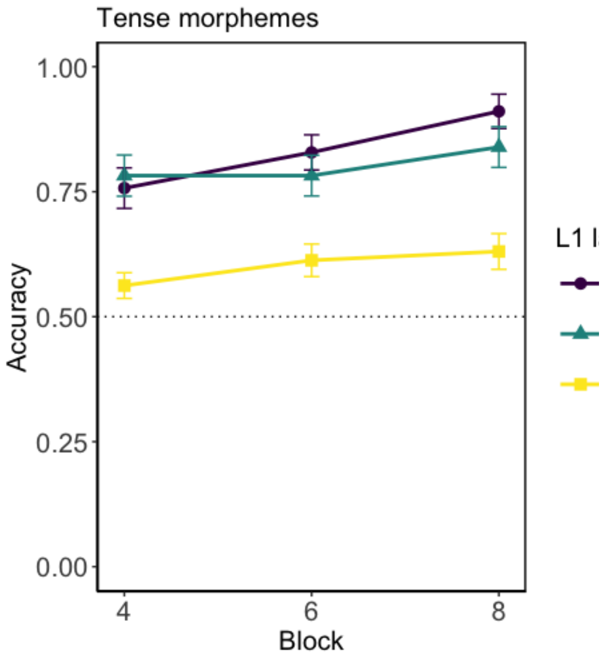
Performance on test trials for lexical categories (nouns, verbs, tense and number morphemes, Figures 4a to 4d) and syntax (SV agreement, Figure 4e). Error bars represent 95% Confidence Intervals. The dotted line (0.5) shows chance performance.

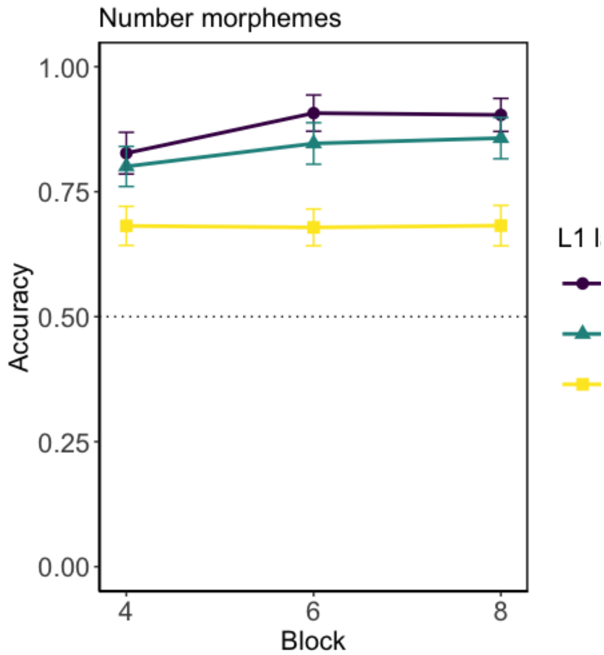
A **B**


Nouns
1.00
0.75
0.50
0.25
0.00
Accuracy
4
6
8
Block
L1 l

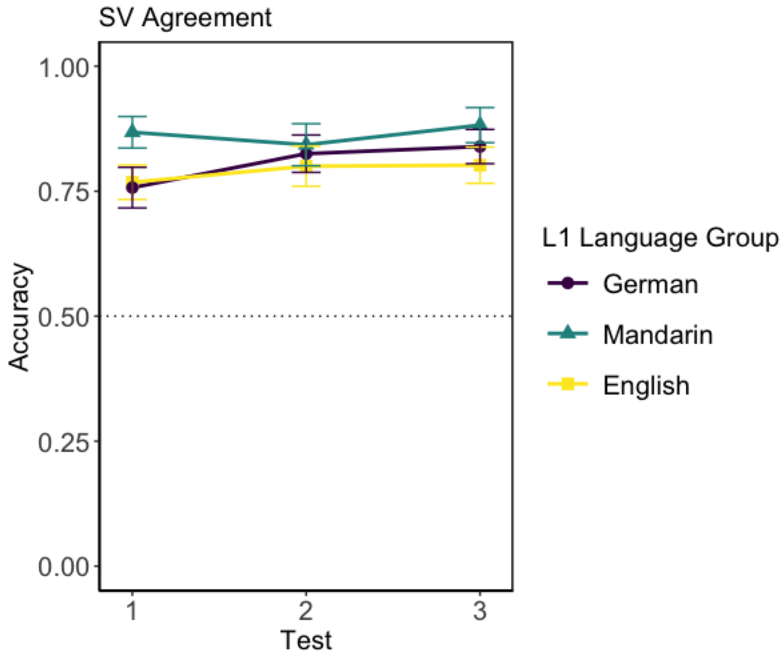

Verbs
1.00
0.75
0.50
0.25
0.00
Accuracy
4
6
8
Block
L1 l

C **D**


Tense morphemes
1.00
0.75
0.50
0.25
0.00
Accuracy
4
6
8
Block
L1 l


Number morphemes
1.00
0.75
0.50
0.25
0.00
Accuracy
4
6
8
Block
L1 l

E



To provide descriptive statistics as to whether and when adult learners had acquired each specific feature (nouns, verbs, number morphemes, tense morphemes, SV agreement) via CSL, we ran one-sample t-tests for the test trials in the three test blocks to determine the time when the performance was greater than chance (with p-values required to be lower than .05/3 for block 4, lower than .05/2 for block 6, and lower than .05 for block 8, in accordance with Holm-Bonferroni correction). Results for L1 Mandarin, L1 English and L1 German groups are shown in Tables S-5, S-6, and S-7. Performance was significantly above chance for all test types in L1 Mandarin and L1 German groups. The L1 English group showed slower learning in tense and verb tests. In L1 English group, the accuracy for tense tests in block 4 ($t(34) = 1.57$, $p = .126$, $d = 0.27$) was not significantly above chance yet but it increased to above chance level in block 6 ($t(34) = 2.50$, $p = .017$, $d = 0.42$) and block 8 ($t(34) = 2.76$, $p = .009$, $d = 0.47$). The accuracy for verb tests in block 4 ($t(34) = 2.08$, $p = .046$, $d = 0.35$) was also not significantly above chance until block 6 ($t(34) = 5.35$, $p < .001$, $d = 0.91$). This indicates that by block 4, participants in all groups were likely to have acquired all linguistic features in the artificial language, except for the acquisition of tense markers and verbs in L1 English group, the learning of which shows later in block 6 and block 8.

We next tested whether learning varied according to the morpheme type being tested (research question 2), as well as whether the L1 background had a distinct effect on different aspects of the language (research question 3). For this, we conducted a mixed-effects model just on the morphology tests.

For the baseline model, we found that adding Block ($\chi2(1) = 38.829$, $p < .001$), L1 ($\chi2(2) = 9.437$, $p = .009$) was significant, showing that learning was possible and progressed with exposure over all test types. There was also a significant effect of morphology test type ($\chi2(2) = 16.498$, $p < .001$), indicating that accuracies were significantly different among morphology tests. The interaction between morphology test type and L1 group ($\chi2(4) = 10.269$, $p = .036$) also significantly improved model fit. There was no significant effect of the interaction between morphology test type and block ($\chi2(2) = 1.056$, $p = .59$).

In order to interpret the morphology test type by L1 group effect, we conducted post hoc tests comparing language group for each test type, and then comparing test types within each language group. For the tense test, L1 Mandarin and L1 German were similar in accuracy (logit estimate = .002, SE = .410, p = .996), and significantly more accurate than L1 English (logit estimate = -1.275, SE = .388, p = .001), as shown in Figure 4C. A similar pattern was observed for the number test (Figure 4D). In the SV agreement test, L1 Mandarin was significantly more accurate than L1 German (logit estimate = -1.080, SE = .418, p = .010). The accuracies in the L1 English group were not significantly different than either the L1 Mandarin (p =.118) nor German (p =.274) groups. For the within group comparison, in the L1 Mandarin group, we found that number was learned significantly better than tense (logit estimate = .942, SE = .344, p = .006), but no significant difference between SV agreement and tense (logit estimate = .606, SE = .389, p = .120), nor between SV agreement and number (logit estimate = -.163, SE = .466, p = .727). In the L1 English group, SV agreement accuracy was significantly higher than tense (logit estimate = - 1.302, SE = .353, p < .001), but not significantly higher than number (logit estimate = -.497, SE = .421, p = .238) . Number was also significantly higher than tense (logit estimate = .836, SE = .288, p = .004). In the L1 German group, number was learned significantly better than tense (logit estimate = -.894, SE = .359, p = .013) and SV agreement (logit estimate = -1.319, SE = .464, p = .005), while tense was not significantly different from SV agreement tests (logit estimate = -.324, SE = .392, p = .408). The effect of interaction between L1 and morphology test types suggests that there are distinctions in terms of accuracies on different morphology tests varying between different L1s. The final best-fitting mixed effects model is shown in Table S-9.

The third mixed-effects model explored whether nouns and verbs were learned differently in the CSL paradigm. We found that adding Block ($\chi 2(1) = 43.628$, $p < .001$), L1 ($\chi 2(2) = 13.153$, $p = .001$), and noun versus verb ($\chi 2(1) = 7.557$, $p = .006$) significantly improved model fit over the baseline model containing only random effects. For L1, accuracy in L1 Mandarin (logit estimate = .857, SE = .283, p = .002) and L1 German (logit estimate = .953, SE = .285, p < .001) groups were significantly higher than the L1 English group but did not differ from one another (logit estimate = .093, SE = .297, p = .754). Nouns were learned more readily than verbs, consistent with previous studies (Monaghan et al., 2015), see Figure 4. There were no significant interactions (noun versus verb: L1, $\chi 2(2) = 3.508$, $p = .173$; noun versus verb: Block, $\chi 2(1) = .014$, $p = .905$). Hence, L1 background again had an influence on the extent of learning, however, unlike for the grammatical feature morpheme types, this was an overall effect, rather than specific to morpheme type. The best-fitting mixed effects model is shown in Table S-10.

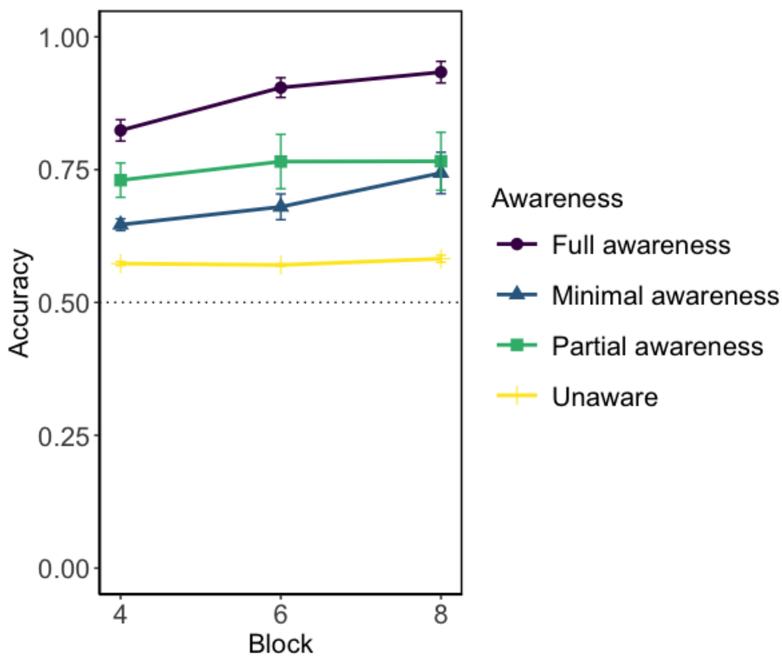
Retrospective verbal reports

Participants' answers to the debriefing questions were coded following according to Rebuschat et al.'s (2015) coding scheme of awareness, ranking from full awareness to complete unawareness (see Appendix B). Participants who reported using morphological rules to distinguish words strategically were considered to have "full awareness" (Q1~2), those who mentioned past, present, future (Q3), singular, plural (Q4) or specified the SV agreement when asking about the patterns of the language or the morphology system were considered "partial awareness", and those who only mentioned tense, number or pattern of sounds were coded as having "minimal awareness". Participants who did not report tense, number or SV agreement were coded as "unaware". All participants who reported minimal, partial, or full awareness were coded as "aware" and others "unaware".

Following the criteria outlined above, we found that 60 out of 105 participants were fully aware of the morphological rules. Overall, seventeen participants in the L1 English group, thirty participants in the Mandarin group and thirty-one participants in the German group were at some level aware of the morphological cues. All participants reported guessing at the beginning, but some later used strategies of calculating the number of categories in the pictures (animals, actions, time, number of animals) to figure out their meaning by comparing similar pictures. And some others reported that they learned from the errors when testing and renewing different assumptions. Seventeen participants at some level noticed the morphological cues. When asked about the meaning of inflectional cues, they either gave a generic answer like number or tense, SV agreement or were more specific about the meaning of each sound (e.g., "Yes, I believe 'sai' is highlighting a single character, while 'ti' stands for many."; "The structure of the sentence is (subject + number morphemes + verb + tense + number morphemes)"). According to the criteria, nine participants were categorised as partially aware of the morphological rule and eight were minimally aware. The rest of the twenty-seven participants reported no awareness of the morphological cues.

Figure 5

Participants' accuracy on all the CSL tasks, including training and test trials: comparisons between awareness groups (Full Awareness, Partial Awareness, Minimal Awareness, Unaware). Note. Error bars represent 95% Confidence Intervals.



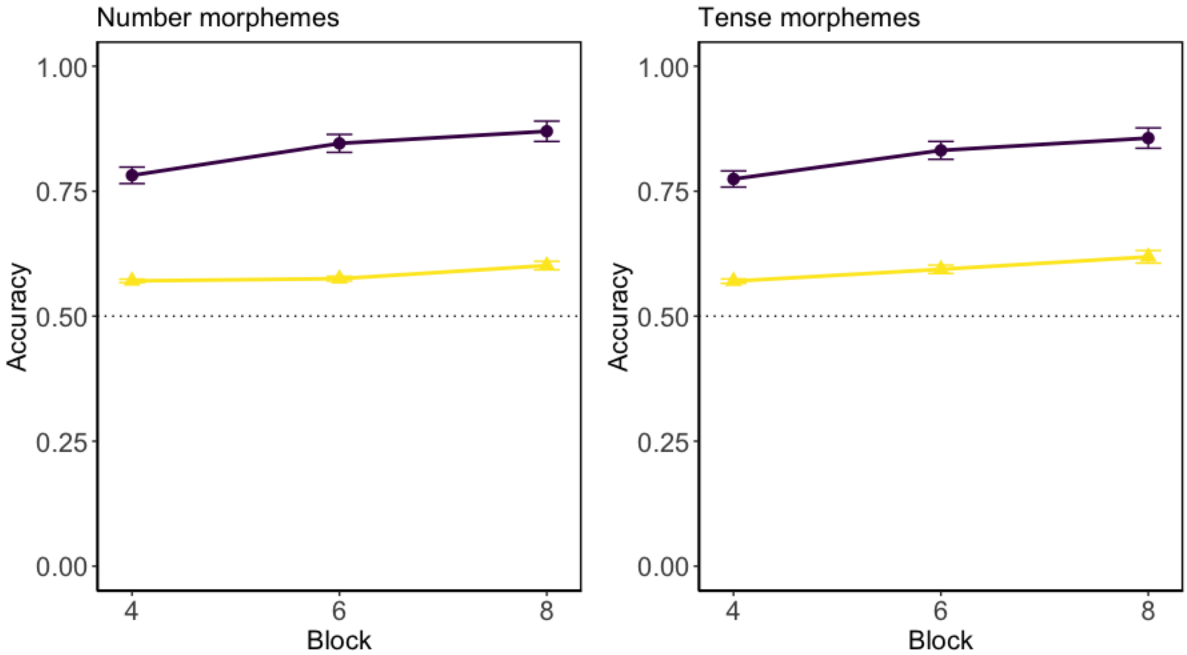
Accuracies of CSL tasks between participants who showed different levels of awareness in their debriefing questionnaires are shown in Figure 5. In order to test the fourth research question – determining the role of awareness in learning morphological features in the language – we first of all conducted descriptive tests using t-tests on overall performance for each awareness level, and then compared aware and unaware for each morphological feature. We then conducted mixed effects models to determine how awareness interacted with different language groups and morphological test types.

Participants who showed full awareness performed significantly better than those with partial awareness ($t(67)= 3.73$, $p < .001$) and minimal awareness groups ($t(66)= 5.420$, $p < .001$). We did not find significant differences between partial-aware and minimal-aware groups ($t(15)= -1.116$, $p =.282$). The partial-aware ($t(34)=5.197$, $p < .001$) and minimal-aware ($t(34)=3.511$, $p = .001$) groups showed significantly higher accuracy in CSL tasks than the unaware group. As there was a large and clear discrepancy in CSL performance between people who were aware and unaware of the morphological features, we further explored the performance differences between adults who generate awareness during the immersive learning environment and those who do not. For the following analysis, we included full awareness, partial awareness and minimal awareness groups in the awareness group, in comparison with the unawareness group, because there was the largest difference in performance between the unaware and minimal awareness groups, and this meant that the results would be consistent with previous studies of awareness and language learning (e.g., Rebuschat et al., 2015).

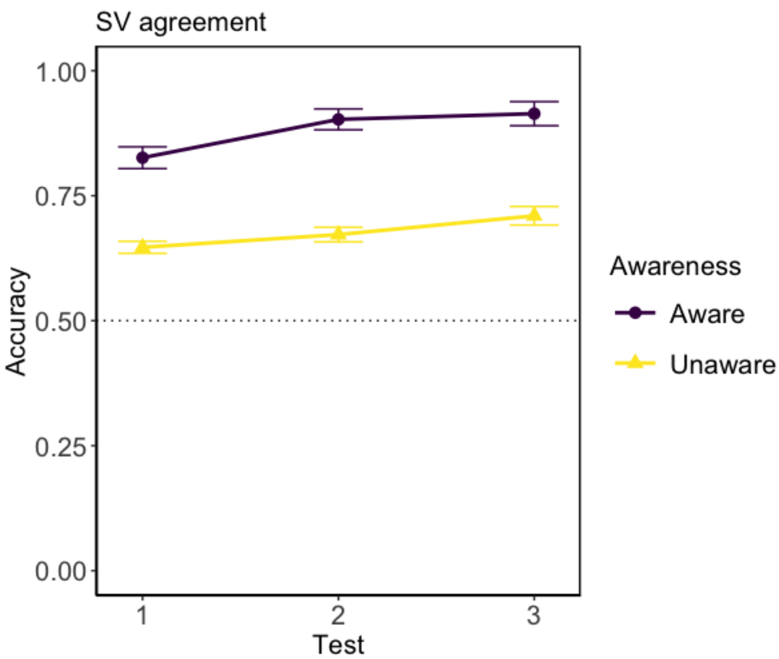
Figure 6

Participants' accuracy on CSL tasks: comparisons between participants who reported being aware and unaware of specific morphological features. Note. Error bars represent 95% Confidence Intervals.

A **B**



C



As shown in Figure 6, participants who showed awareness of tense, number and SV agreement performed significantly differently from participants who showed unawareness of the related morphological features. Figure 6A shows that participants being aware of the morphological number performed significantly better than participants who were unaware ($t(103)= 8.232, p < .001$). In Figure 6B, participants aware of tense are significantly more accurate than the unaware ($t(103)= 6.542, p < .001$). Similarly, in Figure 6C, participants being aware of SV agreement performed significantly better than the unaware ($t(103)= 8.085, p < .001$).

For the mixed-effects model, testing the predictors of learning, we found that, as in our second model, above, there were significant effects of Block ($\chi^2(1) = 38.853, p < .001$), and L1 group ($\chi^2(2) = 7.668, p = .020$), as well as Awareness ($\chi^2(1) = 42.738, p < .001$) and Awareness: Block ($\chi^2(1) = 30.159, p < .001$). The inclusion of Awareness: L1 did not significantly improve the model fit ($\chi^2(2) = 1.798, p = .407$), which is excluded from the final model. The best-fitting model is detailed in Table S-11. Taken together, these results showed that awareness predicted the accuracy of the CSL tasks - participants could develop explicit knowledge of the morphological properties of the language and those that did performed more accurately in learning the language. Furthermore, this effect appeared to be consistent across participants from different language backgrounds. The analysis of the debriefing questionnaire demonstrates the importance of awareness of the morphological features in the early acquisition of non-native language learning, specifically in an immersive learning setting.

Discussion

In this study, we investigated the extent to which adults can learn the meaning of morphological cues in an implicit learning environment without any explicit instruction of the language. The CSL paradigm was adopted, which mirrors a key aspect of the natural language environment where language and environmental cues co-occur and require coordination, but presented in a controlled laboratory setting. While being exposed to the audio-visual co-occurring events, participants were asked to identify which of two scenes a spoken sentence was referring to. This reflected the ambiguity of reference in a naturalistic language learning environment, and enabled us to test how this information can be combined during learning. Importantly, no instruction about the language structure was given, and no feedback was provided throughout the experiment. To investigate whether low transparency makes morphology difficult to learn, we compared the learning of number and tense with subject-verb agreement of an artificial language. This study also explores the influence of L1 morphological background on learning of non-native morphology. We recruited L1 Mandarin, English and German speakers, ranging from morphologically poor to rich languages.

Our first research question investigated whether grammatical morphemes can be learned from the CSL paradigm alongside word stem. Whereas learning of words is well-established (Dal Ben et al., 2023; Monaghan et al., 2015), acquisition of morphology from implicit learning situations, such as CSL, is less often assessed (Finley, 2023; Rebuschat et al., 2021), and never directly compared to word stem learning. In our study, overall robust learning was found even by the first five minutes of exposure for all three L1 groups (L1 English, L1 German, L1 Mandarin), and, furthermore, participants' performance on both training and test trials significantly improved over time. Our findings from the training trials performance suggest that it is likely adults possess the cognitive ability to rapidly learn both the word stems and affixes at the same time, without any feedback or explicit instruction of their meanings. In the test trials, we found that both word stems and grammatical morphemes, when assessed separately, were acquired from cross-situational statistics. However, word stems were also acquired more accurately than grammatical morphemes, consistent with previous studies of morphological acquisition (Rebuschat et al., 2021). While the results did not reveal a clear pattern indicating that word stems and grammatical morphemes were acquired at different rates in this study, the measures of learning against chance (Table S-5 to Table S-7) did show that learning of word stems may have preceded learning of tense morphemes for the L1 English group. Whereas, by block 4, learning of nouns, verbs, number morphemes, and SV agreement was significantly better than chance, this was not yet the case for tense, which was significantly acquired by block 6. There was no evidence of a difference in precedence for learning word stems over grammatical morphemes for L1 German or L1 Mandarin groups. Thus, for L1 English, the acquisition of tense morphemes may have depended upon prior acquisition of the word stems. For the other language groups, perhaps because learning was overall more accurate, different rates of learning were not apparent.

Our study shows much higher learning of functional markers than previous studies of morphological acquisition (e.g., Finley, 2023; Rebuschat et al., 2021). In Rebuschat (2021), for instance, case markers for subject and object roles were found to be difficult to learn (Monaghan et al., 2021; Rebuschat et al., 2021; Walker et al., 2020). According to Ellis (2022), three key characteristics of morphology that pose learning challenges are salience, contingency, and redundancy. However, compared with previous studies of case marker learning from CSL (Monaghan et al., 2021; Rebuschat et al., 2021; Walker et al., 2020), our morphological cues were similarly salient (in CV form), and yet even with this relatively low salience, learning was still very effective in our study. Therefore, one of the possible reasons for different learning outcomes in our study compared to previous studies of morphological acquisition might result from the transparency of the cue indication in the visual scene (DeKeyser, 2005). Compared to the case marker, the meaning of which needs to be deducted from understanding the relationship between the subject and object in the visual scene, the indication of number and tense in our study is more straightforward. However, learners can rapidly and successfully learn form-meaning mapping even when the cues are more abstract (e.g., Finley, 2023).

In our second research question, we investigated whether we would see differences in learning morphological features according to their transparency. According to the Bottleneck Hypothesis (Slabakova, 2014), functional morphology, such as SV agreement, is predicted to be the most difficult part to learn in non-native language acquisition, due to the requirement to align the syntactic relations among words in the sentence with properties of the environment. In contrast, other morphological features, such as tense and number, can relate to more transparent features of the environment that do not require inter-relations within the syntax to be simultaneously processed with the environment to which the sentence refers. The results in our study show otherwise. Robust learning was also found in the SV agreement tests in all three L1 groups, which indicates that learners are able to resolve both morphology and syntax. Furthermore, when considering all the language groups together, number was found to be learned significantly more accurately than tense. Frequency might be one of the explanations for the better performance in learning number cues, as each of the number cues had a higher input frequency than either of the tense cues. However, participants in L1 Mandarin and English groups performed significantly better in SV agreement than other linguistic features, even when it appeared less frequent than number cues. Our results did not align with the bottleneck hypothesis, which suggested the learning difficulty of functional morphology comes from the intertwining of different linguistic features (e.g., morphology and syntax). Note that the feature of SV agreement in our artificial language was expressed in the way that the subject and verb have the same ending of number cue, while in English, for example, have the same ending of subject and verb but the number of subjects could vary. For instance, when "-s" appears at the end of the subject, the number of the subject is more than one in the visual scene, but when "-s" appears at the end of the verb, it indicates the singular number of subjects instead. Therefore, our results suggest that the inconsistency of form-meaning mapping, or "low contingency" in Ellis (2022), accompanied by the SV agreement might be the reason for the bottleneck of learning rather than the intertwining of linguistic features. Our results also found that tense and SV agreement, however, were not significantly different. There are several possible reasons for this pattern. First, it may be that the differences in the transparency of the target varied. Number may have been more apparent in the visual scenes than tense or SV agreement. However, tense was more apparent than SV agreement, which had to be deduced from the relations among stimuli in the language, and with the exception of the L1 German group, SV agreement was learned more easily overall. Alternatively, tense may have been more difficult to acquire, not because of transparency, but because it is less frequent than SV agreement as well. As tense varied over three targets rather than two (for number and SV agreement). This could have affected learning – with lower performance on tense due not to relative difficulties in the acquisition of tense but rather due to difficulties in learning a three-way rather than a two-way morphological system. Varying tense across just two temporal states – e.g., past and present – will enable us to distinguish learning effects associated with frequency and variability from those relating to transparency.

Our third research question addressed whether L1 background influences ease of learning of different aspects of morphology from CSL, and also whether there were knock-on effects for word stem learning. In our results, we found that for the training trials, German and Mandarin speakers learned more quickly than did the English participants. When this was investigated in terms of the individual morphological features, we found that having a morphologically rich L1 (German) did not have an overall benefit over a more morphologically impoverished L1 (Mandarin). However, the L1 German group performed significantly better in number and tense tests compared with L1 English group, suggesting a wholesale transfer effect, rather than a feature-by-feature transfer effect, which is consistent with previous findings (e.g., van der Slik et al., 2019). Results in the SV agreement tests also seem to support the claim that L1 transfer only applies to the interpretable linguistic features such as tense and number in our studies, but not SV agreement (Lago et al., 2025).

What can explain the overall higher performance in the L1 Mandarin group compared to the L1 English participants? The lower performance in the L1 English group could be because the majority of L1 English speakers in our study were monolingual, potentially a disadvantage compared to the other two groups where multilingualism was prevalent (Nation & McLaughlin, 1986). The effective and accurate learning of the morphological markers in our study, particularly for the L1 Mandarin and German groups, might be due to the fact that most L1 Mandarin speakers and L1 German speakers reported having a high proficiency in at least another language, which might improve their learning of morphology because of prior experience of explicit learning of numbers and tense markers in the non-native language learning classroom (Bono, 2011). Although L1 Mandarin speakers do not have number and tense markers in their L1, the experience of explicitly learning another language might have turned their attention to those markers during the CSL (Thomas, 1988).

Another possible explanation for good performance on tense markers of the L1 Mandarin group is that they were able to link the morphological features in the current study with time adverbs present in Mandarin. While inflectional morphological cues do not exist in Mandarin, time indications like *了(le)* and *过（guo）* are often in CV form. From our study, it is not possible to distinguish categorically whether participants were learning morphological inflections or treating the linguistic indicators of past, present, and future as adverbs. Ellis and Sagarra's (2011) study of tense learning, for instance, implemented time with a similar referent in the visual scene to which the language related, but tested also the role of both an adverb and an inflection indicating tense. In that study, again it is not possible to ensure that the inflection was processed as a suffix inflection, rather than as another adverb, but the fact that L1 Mandarin participants were poorer at acquiring the inflection, but not the adverb (due to the inflection being at odds with the structure of the learners' first language), suggested that such a suffix operated in a similar way to an inflection for the learners. Thus, a limitation of the current study lies in the potential language background and demographic differences other than morphological richness between L1 groups that could account for the learning difference.

For all L1 groups, tense was learned with less accuracy than number, however, relative ease of learning of SV agreement varied by L1 group. This was easiest to acquire for L1 Mandarin and English groups, but more difficult for the L1 German group. This could be due to a negative transfer from German L1, as similar grammatical agreements largely exist in the German language – for example, between adjective and object depending on the gender, number as well as the case. For English, SV agreement only exists in the simple present tense, possibly resulting in no L1 transfer effects being observed.

There may be additional demographic or motivational differences between the groups that also resulted in different performance. For example, groups differed in how they were recruited (word of mouth, social media, or participant pools), as outlined above. Measuring additional demographic or motivation characteristics of learners may well help us pinpoint where overall effects in learning come from. Nevertheless, these overall effects of L1 group on learning cannot readily explain the more subtle interaction between L1 group and morphological feature – general background properties of participants are very unlikely to result in better performance only for certain morphemes. These interactions are more likely to be a consequence of language background exerting its effect on learning. Note that the effect of L1 background on learning provides support for the validity of use of a laboratory-based CSL study of language learning – if participants were merely approaching the task as a problem solving exercise, then we would be unlikely to find effects of different language background on combining the language and environmental information in the task.

Finally, in exploratory analyses, we determined whether participants might be able to acquire explicit knowledge of the language structure and if that was related to their learning. We found that a considerable number of participants were able to report the linguistic structure relevant to morphology as a consequence of implicit statistical exposure to the language from CSL, suggesting is align with findings in previous studies that explicit knowledge can arise from implicit exposure (e.g., Ge et al., 2025; Monaghan et al., 2019). However, we did not find significant differences in awareness between groups, which did not confirm the previous finding that L1 morphological richness correlates with awareness (Wu & Juffs, 2022). Moreover, our findings align with theoretical perspectives that conceptualise implicit and explicit learning as interrelated and dynamic processes (e.g., Rebuschat, 2013; Ellis, 2005). Specifically, the results suggest that awareness can emerge from implicit learning, particularly under conditions where the input is statistically rich, well-structured, and consistent (Rebuschat, 2013). In the context of non-native language acquisition, this implies that explicit instruction aimed at drawing learners' attention to morphological features may enhance subsequent implicit learning of the language.

Conclusion

Our study provides the first evidence that learners can acquire multiple morphological features of a language simultaneously, accurately, and in tandem with learning word stems from a language via CSL, challenging the notion that adults struggle with morphology acquisition primarily due to biological constraints.

The current study also provides insight into which aspects of morphology might influence its acquisition. We showed that the morphological features of a learners' L1 affected acquisition, sometimes in surprising ways, with greater learning of morphological properties that were less fully expressed in L1.

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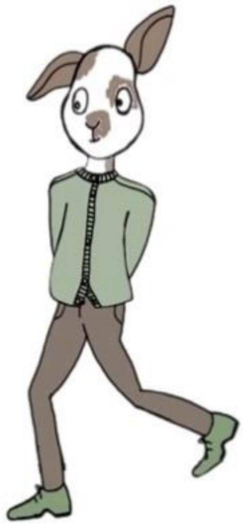
Appendix A

The animal cartoon characters used in the CSL task. The entire set of images can be found on our OSF site (https://osf.io/dvpgq/?view_only=5ce6d476492e42ccae7e906f178fdfcc).



Appendix B

The debriefing questionnaire used in the study to elicit retrospective verbal reports. The questionnaire was adapted from Rebuschat et al. (2015).

Q1: How did you decide which picture was the correct referent? Did you just guess throughout the experiment, or did you follow any particular strategies? If so, what strategies did you follow?

Q2：Did you notice any particular patterns or rules about the grammatical structure of this new language?

Q3： Did you notice the sounds “na”, “ke” or “pau”? If so, what do you think they mean? (The tense morphemes asked in Q3 variants between different versions of mappings.)

Q4： Did you notice the sounds “sai” or “ti”? If so, what do you think they mean? (The number morphemes asked in Q4 variants between different versions of mappings.)

Q5： Do you think the way you made decisions on the pictures changed throughout the experiment?

Q6：What do you think was the aim of this study?

Supplementary Materials

Table S-1

Artificial language-four random sound-meaning mappings

Noun	Version 1	Version 2	Version 3	Version 4
panda	/faʊlu/	/pulə/	/kitə/	/kitə/
pig	/fima/	/faʊlu/	/paʧu/	/lipə/
lion	/fuki/	/fuki/	/suli/	/fima/
mouse	/jitu/	/fima/	/pulə/	/tusi/
sheep	/kitə/	/siʃə/	/faʊlu/	/paʧu/
rabbit	/lipə/	/ʃaji/	/fuki/	/faʊlu/
dog	/luʧi/	/tusi/	/jitu/	/jitu/
cow	/ʃaji/	/masə/	/ʃaji/	/paʃə/
Verb	Version 1	Version 2	Version 3	Version 4
cook	/naɪpə/	/jitu/	/paʃə/	/ʃaji/
work	/paʧu/	/naɪpə/	/luʧi/	/fuki/
swim	/paʃə/	/lipə/	/masə/	/masə/
run	/siʃə/	/paʧu/	/fima/	/suli/
sleep	/pulə/	/paʃə/	/tusi/	/siʃə/
walk	/suli/	/luʧi/	/lipə/	/luʧi/
sing	/masə/	/suli/	/naɪpə/	/naɪpə/
paint	/tusi/	/kitə/	/siʃə/	/pulə/
Tense cue	Version 1	Version 2	Version 3	Version 4
past	/nɑ/	/kə/	/saɪ/	/ti/
now	/kə/	/paʊ/	/nɑ/	/paʊ/

future	/paʊ/	/nɑ/	/ti/	/kə/
Number cue	Version 1	Version 2	Version 3	Version 4
one	/saɪ/	/ti/	/kə/	/saɪ/
two	/ti/	/saɪ/	/paʊ/	/nɑ/

Table S-2

Performance in each L1 groups across 8 blocks – training trials only

Group		Blocks							
		1	2	3	4	5	6	7	8
L1 English	M	.52	.56	.64*	.67*	.70*	.75*	.75*	.76*
	SD	.08	.13	.19	.19	.20	.21	.21	.22
L1 German	M	.59*	.71*	.82*	.89*	.90*	.94*	.94*	.94*
	SD	.11	.20	.18	.15	.17	.12	.13	.14
L1 Mandarin	M	.60*	.71*	.79*	.83*	.87*	.87*	.85*	.88*
	SD	.12	.20	.19	.19	.16	.18	.20	.16

Note. Asterisks indicate performance above chance level with Holm-Bonferroni correction (where block 8 is ranked first as most likely to result in learning above chance, and block 1 is ranked last).

Table S-3

These are the results of CSL test trials

Group	Test types		Blocks		
			4	6	8
L1 English	Nouns	M	.62*	.70*	.73*
		SD	.19	.21	.24
	Verbs	M	.58	.68*	.70*
		SD	.15	.21	.17
	Number morphemes	M	.68*	.68*	.68*
		SD	.23	.22	.24
	Tense morphemes	M	.56	.61*	.63*
		SD	.15	.19	.21
L1 German	Nouns	M	.84*	.88*	.91*
		SD	.23	.21	.21
	Verbs	M	.69*	.84*	.86*
		SD	.19	.23	.22
	Number morphemes	M	.83*	.91*	.90*
		SD	.25	.21	.20
	Tense morphemes	M	.76*	.83*	.91*
		SD	.24	.21	.20
L1 Mandarin	Nouns	M	.77*	.78*	.82*
		SD	.24	.23	.24
	Verbs	M	.74*	.80*	.80*
		SD	.21	.23	.24

Number morphemes	M	.80*	.85*	.86*
	SD	.24	.25	.24
Tense morphemes	M	.78*	.78*	.84*
	SD	.24	.24	.24

Note. Asterisks indicate performance above chance level with Holm-Bonferroni correction (where block 8 is ranked first as most likely to result in learning above chance, and block 4 is ranked last).

Table S-4

These are the results of the GJT

		Test		
		1	2	3
L1 English	M	.77*	.80*	.80*
	SD	.23	.23	.24
L1 German	M	.76*	.83*	.84*
	SD	.22	.24	.24
L1 Mandarin	M	.87*	.85*	.88*
	SD	.22	.23	.23

Note. Asterisks indicate performance above chance level with Holm-Bonferroni correction (where test 3 is ranked first as most likely to result in learning above chance, and test 1 is ranked last).

Table S-5

One-sample t-tests and Cohen's d for performance against chance level (0.5) for each test type, at each test block in L1 Mandarin group.

Block	Test Type	t(34)	Cohen's d	p-value
Block 4	Nouns	6.58	1.11	< .001
	Verbs	6.61	1.12	< .001
	Number Morphemes	6.93	1.17	< .001
	Tense Morphemes	6.97	1.18	< .001
	SV Agreement	11.65	1.97	< .001
Block 6	Nouns	7.32	1.24	< .001
	Verbs	7.32	1.24	< .001
	Number Morphemes	9.11	1.54	< .001
	Tense Morphemes	6.18	1.05	< .001
	SV Agreement	8.15	1.38	< .001
Block 8	Nouns	7.40	1.25	< .001
	Verbs	7.38	1.25	< .001
	Number Morphemes	9.75	1.65	< .001
	Tense Morphemes	9.70	1.64	< .001
	SV Agreement	10.88	1.84	< .001

Table S-6

One-sample t-tests and Cohen's d for performance against chance level (0.5) for each test type, at each test block in L1 English group.

Block	Test Type	t(34)	Cohen's d	p-value
Block 4	Nouns	2.71	0.46	.010
	Verbs	2.08	0.35	.046
	Number Morphemes	4.26	0.72	< .001
	Tense Morphemes	1.57	0.27	.126
	SV Agreement	7.78	1.32	< .001
Block 6	Nouns	4.66	0.79	< .001
	Verbs	5.36	0.91	< .001
	Number Morphemes	3.91	0.66	< .001
	Tense Morphemes	2.50	0.42	.017
	SV Agreement	7.48	1.27	< .001
Block 8	Nouns	5.42	0.92	< .001
	Verbs	4.83	0.82	< .001
	Number Morphemes	3.78	0.64	< .001
	Tense Morphemes	2.76	0.47	.009
	SV Agreement	8.34	1.41	< .001

Table S-7

One-sample t-tests and Cohen's d for performance against chance level (0.5) for each test type, at each test block in L1 German group.

Block	Test Type	t(34)	Cohen's d	p-value
Block 4	Nouns	9.25	1.56	< .001
	Verbs	4.02	0.68	< .001
	Number Morphemes	9.75	1.65	< .001
	Tense Morphemes	5.96	1.01	< .001
	SV Agreement	6.33	1.07	< .001
Block 6	Nouns	12.03	2.03	< .001
	Verbs	9.43	1.59	< .001
	Number Morphemes	14.19	2.40	< .001
	Tense Morphemes	6.51	1.10	< .001
	SV Agreement	8.70	1.47	< .001
Block 8	Nouns	18.18	3.07	< .001
	Verbs	8.57	1.45	< .001
	Number Morphemes	11.24	1.90	< .001
	Tense Morphemes	12.91	2.18	< .001
	SV Agreement	9.92	1.68	< .001

Table S-8

Best fitting model for testing the effect of time and L1 on participants' accuracy in the training trials of the CSL task. (L1 Mandarin was on the intercept.)

	training_trial_accuracy				
Predictors	*Odds Ratios*	*std. Error*	*CI*	*Statistic*	*p*
(Intercept)	0.95	0.11	0.76 – 1.19	-0.42	0.675
block	1.77	0.12	1.56 – 2.02	8.68	**<0.001**
L1 [English]	0.80	0.12	0.59 – 1.08	-1.47	0.141
L1 [German]	0.76	0.12	0.55 – 1.04	-1.69	0.090
block × L1 [English]	0.78	0.07	0.65 – 0.93	-2.79	**0.005**
block × L1 [German]	1.18	0.11	0.99 – 1.42	1.80	0.071

Number of observations: 42111, Participants: 105, Item: 1026, AIC = 34454.1, BIC = 34713.5, log-likelihood = -17197.1.

R syntax: glmer (training_trial_accuracy ~ block + L1 + block:L1 + (1 + block + L1 + block:L1 | item) + (1 + block | ppt), data=overall_training_dataset_renamed, family = binomial, control=glmerControl (optCtrl = list(maxfun = 100000), optimizer = "nloptwrap", calc.derivs = FALSE))

Table S-9

Best fitting model for testing the effect of morphology test types (tense, number, SV agreement tests) on test trials' accuracy (L1 Mandarin and tense tests were on the intercept).

	test_trial_accuracy				
Predictors	*Odds Ratios*	*std. Error*	*CI*	*Statistic*	*p*

(Intercept)	4.97	2.16	2.12 – 11.66	3.68	<0.001
block	1.33	0.06	1.22 – 1.44	6.48	<0.001
L1 [English]	0.25	0.13	0.09 – 0.72	-2.58	0.010
L1 [German]	0.92	0.52	0.30 – 2.78	-0.15	0.879
morphotesttype [Tense morphemes]	0.41	0.14	0.21 – 0.80	-2.62	0.009
morphotesttype [SV agreement]	0.86	0.40	0.34 – 2.13	-0.34	0.737
L1 [English] × morphotesttype [Tense morphemes]	1.06	0.46	0.45 – 2.48	0.13	0.896
L1 [German] × morphotesttype [Tense morphemes]	1.05	0.50	0.41 – 2.68	0.10	0.923
L1 [English] × morphotesttype [SV agreement]	1.98	1.22	0.59 – 6.64	1.10	0.270
L1 [German] × morphotesttype [SV agreement]	0.34	0.22	0.09 – 1.20	-1.68	0.093

Number of observations: 7826, Participants: 105, Item: 302, AIC = 6288.4, BIC = 6497.4, log-likelihood = -3114.2.

R syntax: glmer(test_trial_accuracy ~ block + L1 + morphotesttype + morphotesttype:L1 + (1 + block + morphotesttype | ppt) + (1 + block + L1 | item), data=overall_testing_add3, family="binomial", control=glmerControl (optCtrl = list(maxfun = 100000), optimizer = "nloptwrap", calc.derivs = FALSE))

Table S-10

Best fitting model for testing the effect of noun versus verb on test trials' accuracy (L1 Mandarin and noun tests were on the intercept).

	test_trial_accuracy				
Predictors	*Odds Ratios*	*std. Error*	*CI*	*Statistic*	*p*
(Intercept)	1.59	0.43	0.94 – 2.70	1.72	0.085
block	1.36	0.06	1.25 – 1.48	7.25	<0.001
L1 [English]	0.42	0.12	0.24 – 0.74	-3.03	0.002
L1 [German]	1.10	0.33	0.61 – 1.97	0.32	0.747
noun or verb [verb test]	0.67	0.09	0.51 – 0.86	-3.09	0.002

Number of observations: 5111, Participants: 105, Item: 188, AIC = 4679.2, BIC = 4816.6, log-likelihood = -2318.6.

R syntax: glmer(test_trial_accuracy ~ block + L1 + noun_or_verb + (1 + block + noun_or_verb | ppt) + (1 + block + L1 | item), data=overall_testing_add3, family="binomial", control=glmerControl (optCtrl = list(maxfun = 100000), optimizer = "nloptwrap", calc.derivs = FALSE))

Table S-11

Best fitting model for accuracy for the overall CSL tasks (including both training and test trials), testing the awareness effect

	Correct				
Predictors	*Odds Ratios*	*std. Error*	*CI*	*Statistic*	*p*
(Intercept)	1.62	0.34	1.07 – 2.46	2.27	**0.023**
block	1.39	0.05	1.29 – 1.49	9.04	**<0.001**
language [English]	0.79	0.11	0.60 – 1.05	-1.65	0.100
language [German]	1.08	0.19	0.77 – 1.52	0.47	0.641
two-way coded awareness [Unaware]	0.97	0.32	0.51 – 1.85	-0.08	0.935
block × two-way coded awareness [Unaware]	0.72	0.04	0.65 – 0.81	-5.84	**<0.001**

Number of observations: 12937, Participants: 105, Item: 455, AIC = 11378.5, BIC = 11542.8, log-likelihood = -5667.3.

R syntax: glmer(Correct ~ block + L1 + `two-way coded awareness` + `two-way coded awareness`:block + (1 +block + general.awareness | ppt) + (1 +block +L1 | item), data = Overall_testtrial_awareness, family="binomial", control=glmerControl (optCtrl = list(maxfun = 100000), optimizer = "nloptwrap", calc.derivs = FALSE))

4. Publishable paper 2: Blocking or highlighting in statistical learning: How distributional properties shape non-native morphology acquisition in adult learners (awaiting to be submitted)

Page number: 96-143

Abstract

Previous studies have shown that earlier learned cues (e.g., "yesterday") can block the learning of co-occurring cues that convey the same meaning (e.g., past tense “-ed”), and that this blocking effect is modulated by salience of the cue (“yesterday” is more salient than “-ed” as it is more pronounced), suggesting that prior knowledge can interfere with the acquisition of an alternative cue expressing the same concept (Ellis & Sagarra, 2010). However, it remains unknown whether, in the absence of prior learning, learners would naturally attend to and acquire the more salient cue first, thereby blocking the learning of the less salient one. Additionally, in natural language, cues do not consistently appear together, they often occur with variability.

The present study addresses this gap by examining whether the presence of lexical cues overshadows or blocks the learning of morphological cues in a statistical learning context, and whether this effect interacts with cue distribution. We employed a cross-situational learning (CSL) paradigm with two between-subjects conditions: consistent and variable. In the consistent condition, both cues were always present and equally predictive of time reference. In the variable condition, each cue appeared in only two-thirds of the sentences.

An overshadowing effect was observed in both conditions, with the more salient temporal adverbs being learned more successfully than the morphological tense markers. Overall performance was significantly higher in the consistent condition, indicating that consistent cue availability supports learning. However, this benefit did not interact with the overshadowing effect, suggesting that the blocking of less salient cues was not alleviated by the consistent co-occurrence of both cues.

***Keywords*:** cross-situational learning; morphology learning; blocking; overshadowing; redundancy

Introduction

A key part of language acquisition requires internalising associations between linguistic forms and their meanings (e.g., Ellis, 2006; Saffran, 2020). However, some mappings are easier to acquire than others. For example, in languages with verbal morphology, temporal reference can be expressed either through more perceptually salient lexical cues (e.g., "yesterday") or through less salient morphological cues (e.g., the past tense "-ed") (Schmidt, 2001; Terrell, 1991; Van Patten, 1996). However, there is a consistent learning differential between these two types of cues. While lexical cues such as "yesterday" are generally acquired with relative ease, the mapping of morphological markers like "-ed" onto past tense meanings tend to present persistent challenges for non-native language learners. Indeed, difficulties in the acquisition of morphological cues have been far more extensively documented than challenges in lexical learning (Grüter et al., 2012; Jiang, 2007; Pica, 1983; Rebuschat et al., 2021).

Learned-attention provides a plausible explanation for this difficulty in that the learning of lexical cues affects the acquisition of corresponding morphological cues due to differences in cue salience (Ellis, 2006). This hypothesis is grounded in two general-purpose associative learning mechanisms: *Overshadowing* and *Blocking* (Jones & Haselgrove, 2013; Kamin, 1967; Kruschke, 2006; Rescorla & Wagner, 1972). *Overshadowing* describes a salience-driven learning bias, whereby when two cues are simultaneously presented that predict the same outcome, the more salient cue dominates learning. In contrast, *Blocking* typically presupposes prior learning of one cue, which inhibits subsequent learning of another. These mechanisms have been extensively investigated in associative learning research and have been shown to operate across cognitive tasks (Mackintosh, 1971; Redhead & Chan, 2017; Rodríguez et al., 2011; Schmidt & De Houwer, 2019). Extending this line of research, Ellis and colleagues demonstrated that blocking effects also manifest in the non-native language acquisition context (Ellis, 2007; Ellis, 2008; Ellis & Sagarra, 2010; Ellis &

Sagarra, 2011; Ellis & Sagarra, 2014). They found that prior learning, (e.g., lexical cues "yesterday"), could block the learning of latter-introduced cue encoding the same meaning (e.g., morphological cues "-ed") when the new cue co-occurs with the prior learned cue, and that this effect was magnified by differences in cue salience. The findings indicate that the acquisition of two semantically redundant cues is influenced by learners' prior language experience. This is further substantiated by a series of experiments by Ellis and Sagarra (2010, 2011), which show that attentional biases are shaped by learners' first language (L1) backgrounds. Learners whose L1s exhibit limited or no morphological marking (e.g., Mandarin) tend to rely more heavily on temporal adverbs, whereas learners from morphologically rich L1 backgrounds (e.g., Spanish) rely less on such adverbial cues. However, additional research reveals that the effects of salience—such as typographical enhancement—do not significantly differ between learners with L1 Chinese and those with L1 English. This suggests that salience itself plays a robust and independent role in non-native language learning (Ellis & Sagarra, 2010).

Further research is needed to investigate how salience functions in more ecologically valid language learning contexts—that is, without pre-training or consideration of language background—to better understand its role in naturalistic non-native language acquisition.

In studies involving control groups who received no pre-training and were exposed only to Latin phrases that consistently included both morphological tense markers and temporal adverbs, results indicated that learners attended equally to both cues when the morphological marking was relatively simple, encoding only tense. However, when the morphological cues became more complex—conveying both tense and person—learners showed a stronger reliance on temporal adverbs. These results highlight the operation of overshadowing mechanisms in language learning.

Despite these insights, much of the existing literature on blocking and overshadowing includes feedback during learning tasks. It remains an open question whether similar learning mechanisms are observable in the absence of explicit feedback. Moreover, in natural language environments, cue availability is sometimes variable rather than consistently present (Cheng & Lu, 2022). Thus, it remains unknown whether overshadowing effects can be observed in more ecologically valid, naturalistic learning contexts where cues to tense do not always occur together, but rather appear stochastically. The current study addresses these gaps by directly investigating overshadowing effects within a statistical learning environment, using a cross-situational learning (CSL) paradigm designed to more closely approximate natural language learning conditions.

The blocking and overshadowing mechanisms

The theoretical foundations of *blocking* and *overshadowing* were demonstrated in a seminal study by Kamin (1967). In his experiments, rats were trained with two stimuli (e.g., a light and a noise) paired with the same outcome (a mild foot shock). In the control condition, where overshadowing was observed, rats were simultaneously exposed to both stimuli and the shock. Although rats responded to both cues, the more salient stimulus (e.g., the light) formed a stronger association with the shock, overshadowing the association with the less salient cue (the noise). In the experimental condition, where blocking was observed, rats first learned to associate one stimulus (e.g., the noise) with the shock. When the light was introduced later alongside the noise, learning about the new cue (light) was significantly impaired.

Chapman and Robbins (1990) extended the investigation of blocking effects into the domain of human perceptual learning. In their study, participants first learned that fluctuations in Stock A (Cue A) reliably predicted movements in the stock market (Outcome X), whereas fluctuations in Stock B (Cue B) were unrelated to the outcome. In a subsequent training phase, both Stock A and Stock B were presented together as predictors of the same outcome. The results revealed that participants learned the association between a newly introduced Cue C, paired with B, more readily than the association between C paired with A. This pattern suggests that prior learning of the A–X association blocked the subsequent learning of the C–X association when C was paired with A.

The result supported that the compound appearance of two cues will cause one cue to be blocked by the other cue that has a stronger association with the outcome, aligning with previous studies (Kamin, 1967; Miles & Jenkins, 1973). However, an important consideration in interpreting these results is the phenomenon of *latent inhibition* (Lubow, 1973; Lubow & Kaplan, 1997). *Latent inhibition* refers to the finding that prior exposure to a stimulus without associating an outcome reduces the ease with which the stimulus can later be associated with an outcome. In Chapman and Robbins' study, prior exposure to Cue B as non-predictive may have rendered it less likely to compete for associative strength during the later learning phase. Consequently, the newly introduced Cue C, when paired with B, faced less associative competition compared to when it was paired with A, which already had a strong pre-established link to the outcome. Thus, the asymmetry in C–X learning between conditions reflects the joint effects of blocking by prior predictive cues and attenuated competition from previously non-predictive cues.

In the language learning context, the frequent co-occurrence of morphological and lexical cues redundantly signaling the same semantic features (e.g., plural "-s" versus "many"; past tense "-ed" versus "yesterday") renders the operation of associative learning mechanisms such as blocking and overshadowing possible. These mechanisms may help explain why the production of morphological cues often falls short of native-like by advanced naturalistic language learners (Pica, 1983). Adult non-native language learners' attentional systems, shaped by their L1 experience, are often biased toward more salient and reliable cues in the input (e.g., Ellis & Sagarra, 2010). Specifically, within language learning context, *overshadowing* indicates that when multiple cues predict the same outcome, the more perceptually salient cue (e.g., a lexical item like "yesterday") dominates learning at the time of exposure, thereby reducing attention to less salient cues such as morphological markers (e.g., "-ed"). This attentional bias may contribute to the relatively late acquisition of morphology in naturalistic language learning, a pattern that is observed in child language development (Dale & Fenson, 1996). Furthermore, overshadowing suggests that when a more salient cue consistently overshadows a less salient one, it forms a stronger association with the outcome over time. As a result, once this dominant cue–outcome link is established, it can inhibit the learning of any association between the less salient cue and the outcome. Thus, if non-native language learners initially rely on salient lexical indicators, this earlier learning may block the subsequent learning of corresponding morphological forms. Supporting this interpretation, research indicates that non-native language learners are typically exposed to more salient lexical cues earlier than more complex morphological cues, increasing the possibility that blocking effects will occur (Bardovi-Harlig, 1992; Meisel, 1987).

To date, it remains underexplored whether overshadowing emerge in naturalistic language learning contexts. In particular, little is known about whether variably available salient lexical cues, such as temporal adverbs ("yesterday"), interfere with the acquisition of corresponding morphological markers (e.g., the past tense "-ed"), in the absence of prior pre-training, unlearning (i.e., unmarking an existing cue–outcome association), as well as feedback. Moreover, it is unclear whether consistent co-occurrence of two redundant cues, again without pretraining, unlearning, or feedback, would elicit overshadowing effects under naturalistic learning conditions. The present study aims to address these questions by examining overshadowing[1] effects under two conditions: one in which lexical and morphological cues are

[1] Since our study does not include a pre-training phase, it more directly tests overshadowing rather than true blocking.

variably present, and another in which both cues are consistently available throughout the learning phase.

Overshadowing and Blocking Effects in SLA

Ellis (2007) tested the blocking theory applied within a language learning paradigm. During training trials, adult participants were exposed to Latin sentences containing both temporal adverbs and verb morphology indicating tense (e.g., *hodie cogito/cogito hodie* "I think today"; *heri cogitavi/cogitavi heri* "I thought yesterday"; *cras cogitabo/cogitabo cras* "I will think tomorrow") and were asked to identify the tense of each sentence, with feedback provided. Before this exposure, one group received pre-training focusing on the meanings of the adverbs, another group was pre-trained on the meanings of the verb forms, and a control group received no pre-training. Results revealed that participants who had been pre-trained on adverbial cues paid significantly less attention to morphological tense markers, demonstrating a robust blocking effect. A smaller blocking effect was also observed in the verb pre-training group, though it was notably weaker. These findings indicated the operation of both blocking and overshadowing effects: prior learning of one cue blocked the subsequent learning of another redundant cue, and the asymmetry in blocking between groups highlighted the role of cue salience. Overall, Ellis (2007) provided evidence that associative blocking phenomena extend to the domain of second language acquisition.

Follow-up studies further explored how blocking and overshadowing effects are modulated by perceptual salience with specific cue types, as filtered through learners' L1 experience. Ellis and Sagarra (2010) conducted two experiments to investigate this issue. In Experiment 1, English-speaking participants were exposed to Latin sentences after receiving pre-training either on temporal adverbs or on verb morphology. When subsequently presented with sentences containing both cues, a strong blocking effect was observed: the more salient cue consistently blocked learning of the less salient one. Experiment 2 compared English and

Chinese L1 speakers using the same paradigm. Results showed that the influence of blocking and overshadowing was moderated by participants' L1 morphological systems. Chinese learners, whose L1 lacks tense morphology, relied significantly more on adverbial cues than English learners, consistent with the idea that prior linguistic experience shapes attentional allocation. These findings were subsequently replicated in later work (Ellis & Sagarra, 2011), reinforcing the conclusion that cue competition effects are modulated both by cue salience and by learners' prior experience.

While these findings clearly demonstrated how prior learning experience influences attentional bias during language acquisition, they also raise questions about how such biases operate under more naturalistic conditions. In natural language environments, cues typically occur variably rather than in strict sequential pre-training. Would a salience-driven learning bias still emerge without prior pre-training? Evidence from the control group in Ellis (2007) suggests otherwise: without pre-training, participants distributed their attention more equally between adverbial and morphological cues, even though adverbs were more perceptually salient. This finding contrasts with Kamin's (1967) animal learning study, where overshadowing was observed even without pre-training. However, further study makes the morphological tense markers more complex and thus, even without pre-training, learners tend to rely on the more salient temporal adverbs (Ellis & Sagarra, 2010). Interestingly, both Ellis's and Kamin's control groups converged on the point that consistent co-occurrence of two predictive cues can enhance the learning of both, aligning with the intersensory redundancy hypothesis (Bahrick et al., 2019), which posits that redundancy across modalities or cue dimensions enhances attention and learning.

Overall, the existing literature highlighted the blocking and overshadowing effect in language learning contexts, comparing the learning of temporal adverbs and morphological tense markers (Ellis, 2007; Ellis, 2008; Ellis & Sagarra, 2010; Ellis & Sagarra, 2011; Ellis &

Sagarra, 2014). However, how participants were trained in the experiments has not fully captured the complexity of natural language learning environments. In these studies, participants were exposed only to sentences, without access to visual referents that could ground the meaning of the linguistic forms. To better understand the mechanisms underlying naturalistic language learning—and to investigate whether there are limits to adult acquisition of morphology through the same processes that support native language development—it is essential to examine morphological learning in more ecologically valid, meaning-grounded environments. Moreover, the extent to which the availability of semantically redundant lexical and morphological cues influences the acquisition of both remains underexplored, particularly in naturalistic language learning environments lacking explicit feedback.

The present study addresses this gap by investigating how the distributional patterns of temporal adverbs and morphological tense markers (i.e., consistently co-occurring versus variably present) affect attention bias. Specifically, we employ a CSL paradigm to explore whether overshadowing effects arise in naturalistic language learning conditions. Relevant cross-situational learning research will be reviewed in the next section.

Cross-situational learning of morphology

The CSL paradigm, which mirrors the ambiguity inherent in uninstructed natural language learning, has been widely used to investigate learners' ability to track form–meaning mappings in controlled laboratory settings (Ge et al., 2025; Monaghan et al., 2021; Rebuschat et al., 2021; Walker et al., 2020; Yu & Smith, 2008). Research has shown that infants are able to rapidly acquire word meanings through this process (for review, see Saffran, 2022). Similarly, adults have been shown to track statistical regularities in the input to support language learning, although studies have primarily focused on learning at the level of word categories (Yu & Smith, 2007; Monaghan et al., 2015), with relatively less attention to smaller linguistic units such as morphology.

In a CSL study investigating morphological learning, Finley (2023) presented adult participants with three objects and a novel auditory word on each trial, after which they were required to infer which visual referent corresponded to the heard word. This setup instantiated the referential ambiguity learners must resolve during naturalistic language acquisition, a defining characteristic of CSL (Saffran, 2022). To specifically test morphological learning, in the experimental condition, suffixes were systematically mapped onto semantic categories, whereas in the control condition, suffixes were assigned randomly. Participants initially had no explicit instruction about form–meaning correspondences and had to guess at first; however, as exposure accumulated, learning emerged both for object labels and for the sublexical suffix regularities.

Finley's (2023) findings demonstrated that participants could not only form general mappings between novel word forms and visual referents but also extract regularities at the morphological level, tracking co-occurrences between suffixes and object categories. However, when the input consists of full sentences—introducing greater auditory complexity and ambiguity compared to single-word trials—adults have been found to struggle with acquiring functional morphological markers (Monaghan et al., 2021; Rebuschat et al., 2021; Walker et al., 2020).

In contrast, Zhu et al. (under review, see also chapter 3) found that adults were able to acquire morphological tense and number markers from two-word sentences (e.g., "Panda walked") in a CSL paradigm. They created a morphologically rich artificial language comprising eight nouns, eight verbs, and morphological tense markers for tense and number, along with subject–verb agreement. In their language, morphological cues were realised with a CV (Consonant–Vowel) syllable structure, making them less phonologically salient than nouns and verbs, which followed a CVCV structure. During each CSL trial, participants were presented with two pictures and heard a sentence, after which they selected the picture, they believed matched the sentence. Learning of each linguistic feature was assessed in test trials where the two pictures differed only with respect to the targeted feature.

Zhu et al. (under review, chapter 3) found that participants' training accuracies exceeded chance levels after only five minutes of exposure, with significant learning observed for content words, morphological markers, and subject–verb agreement features. Notably, the mappings for morphemes were as consistent and transparent as those for content words, which may account for the relatively high accuracy of morphological learning. In contrast, studies such as Rebuschat et al. (2021) employed less transparent mappings for case markers, potentially increasing morphological learning difficulty. Given that other task demands were comparable between lexical and morphological cues in Zhu et al.'s design, and that the primary difference was phonological salience (CV versus CVCV structure), the absence of a learning difference suggests that salience alone did not significantly hinder morphology acquisition. Rather, the morphological cues in Zhu et al.'s study manipulated salience without introducing other factors that typically complicate morphology learning in natural language, such as redundancy (i.e., competition from more salient, co-occurring cues) or low contingency (i.e., morphological forms signalling multiple meanings) (Ellis, 2022). To further investigate the factors influencing morphological acquisition, the present study extends Zhu et al.'s (under review, chapter 3) paradigm by introducing an additional, more salient lexical cue (a temporal adverb) that conveys the same semantic information as the morphological tense marker. According to blocking theory (Kamin, 1967), the presence of a salient, redundant cue should compete for learners' attention and thereby inhibit the acquisition of the corresponding morphological cue. Importantly, no additional lexical marker was introduced for number, leaving morphological number markers free from redundancy effects. This design allows for a direct comparison of learning outcomes for tense and number morphology under conditions of redundancy versus non-redundancy.

Taken together, this study addresses the following research questions.

Research questions and predictions

Our first research question (RQ1) examines the statistical learning among adult learners by asking the following questions:

(RQ1a) Can adults successfully acquire a novel language within the CSL paradigm? In addition, we posed an exploratory question: *Does the availability of the two competing cues*—specifically, *the complexity introduced by overshadowing —influence overall language learning outcomes*?

Previous work (Zhu et al., under review, see also in chapter 3) demonstrated that adults are able to successfully learn novel languages by tracking cross-situational statistics. However, it remains unclear whether the complexity of morphological acquisition, particularly when shaped by cue competition, impacts broader language learning success.

Regarding whether CSL can also facilitate the learning of morphological cues, we further asked the following subsidiary question:

(RQ1b) Can morphological tense and number markers be learned in CSL paradigm?

Building on Zhu et al. (under review, chapter 3), which found successful learning of morphological markers, we expect to replicate the acquisition of morphological number markers in our study. However, the learning of morphological tense markers remains less predictable. In our design, salient temporal adverbs were added, introducing cues encoding the same meaning that may compete for learners' attention and thereby overshadow/block learning of the morphological tense marker. According to blocking theory, the presence of a salient temporal adverb cue could render morphological tense markers effectively unlearnable.

Our research question 2 (RQ2) investigated whether overshadowing/blocking effects apply in the language learning context. We asked the following questions:

(RQ2a) Is the learning of temporal adverbs significantly better than the learning of morphological tenses?

The morphological tense markers, realized in a lower-salience CV form, were less salient than the accompanying temporal adverb. According to blocking theory, the acquisition of morphological tense markers may be impeded by the presence of more salient temporal adverbs. However, findings from Ellis (2007) suggest otherwise: in a control group exposed consistently to both morphological markers and temporal adverbs without pretraining, both forms were learned at similar rates. Notably, when the complexity of morphological markers increases, participants show a significant learning bias towards the temporal adverbs (Ellis & Sagarra, 2010). As the contingencies of morphological tense markers were as simple (one-on-one form-meaning mapping) as Ellis (2007), we predicted that the learning of morphological tense markers would be similar to the temporal adverbs in the consistent condition. In contrast, whether learning bias can be observed in the variable condition is yet difficult to predict.

(RQ2b) Is the learning of morphological number markers significantly better than the learning of morphological tense markers?

The identification of learning differences between morphological tense markers and temporal adverbs alone is insufficient to determine the presence of blocking (RQ2b), as the reduced learning of tense cues could be attributed to factors beyond cue competition. Specifically, because the morphological tense markers are less salient than temporal adverbs and the content words, any failure to acquire morphological markers could alternatively reflect an effect of low salience (Ellis, 2022). The RQ2c was to disentangle these possibilities by comparing the acquisition of morphological tense markers with the learning of number markers, which did not involve competition from a more salient lexical cue. In contrast to morphological tense markers, the number markers, although also lower in salience than content words, did not face competition from an additional lexical cue encoding the same meaning (e.g., no cue like "many" for plurality was introduced). If number cues were learned significantly better than tense cues, this suggests that morphological tense learning was specifically blocked by the temporal adverbs. In contrast, if learning outcomes for tense and number morphology did not differ significantly, it would imply that the difficulty in tense acquisition arises primarily from its lower salience rather than from the overshadowing effects due to the existence of a semantically redundant marker.

Our third research question asked *whether the availability of the two competitive cues influences the magnitude of the overshadowing in the CSL paradigm* (RQ3).

The blocking and overshadowing theory proposed that when both cues associated with the same outcomes consistently co-occur, the associative strength of both would increase. Similarly, the intersensory redundancy hypothesis (Bahrick et al., 2019) posits that the consistent co-occurrence of cues enhances the salience and facilitates the learning of each cue. Therefore, both morphological tense markers and temporal adverbs should be learned more successfully when the two cues consistently co-occur than when they are variably presented. However, whether the magnitude of overshadowing would differ between conditions remains unpredictable.

Methods

Participants

After the exclusion of three participants' data who did not meet the criteria of being native English speakers, our final sample included eighty-two native speakers of English (Mean age = 19.13, SD = 3.55, 61 Women, 18 Men, 2 Binary, 1 Other) that were randomly assigned into two groups: the consistent and variable conditions. Eighty-one participants were undergraduate students, and one was a university staff member. They received either course credit or £5 for their participation. The sample size was estimated employing Monte Carlo simulations of data, which predicted that 40 participants per language group would be sufficient for power of 0.8. Data collection stopped once 40 participants had been assigned to each condition. Further details about our power analysis can be found in our pre-registration link on the public OSF website (https://doi.org/10.17605/OSF.IO/MTBJ4).

The study was approved by the ethics review panel of the Faculty of Arts and Social Sciences at Lancaster University and conducted in accordance with the provisions of the World Medical Association Declaration of Helsinki.

Materials

Artificial language

Vocabulary. The pseudo-words were derived from Zhu et al. (under review, chapter 3), to which we added three new pseudo-words as adverbial cues. Overall, there were 24 pseudo-sound segments, including 19 bisyllabic sounds (CVCV) that served as nouns, verbs, and adverbs, and 5 monosyllabic sound segments (CV) that served as the suffixes. In order to prevent any bias in mapping preference, we randomised three versions of sound-meaning mappings (See Table 1 for one version). The complete versions can be found in Table S-1. The meaning of each sound segment was indicated in one of the two pictures appearing in each trial. Specifically, eight nouns referred to eight distinct animal cartoon characters (panda, pig, lion, mouse, sheep, rabbit, dog, cow), eight verbs referred to eight tasks (cook, work, swim, run, sleep, walk, sing, paint) and three adverbial cues mapped with time indication in a written form in the picture (yesterday, today, tomorrow). Morphological cues were pronounced shorter than lexical cues, as the morphological cues are usually less salient in natural languages. Five monosyllabic sounds (CV) served as the suffixes, including number cues (singular, plural) and tense cues (past, present, future).

Table 1

Artificial language vocabulary as used in this study. There were 8 nouns, 8 verbs, 5 suffixes (tense and number marking), and 3 temporal adverbs. There were three random pseudoword-referent mappings to avoid pre-existing biases. Here, we report one of the randomizations.

Category		Pseudowords	Meaning
Nouns		/faʊlu/	panda
		/fima/	pig
		/fuki/	lion
		/jitu/	mouse
		/kitə/	sheep
		/lipə/	rabbit
		/lutʃi/	dog
		/ʃaji/	cow
Verbs		/naɪpə/	cook
		/patʃu/	work
		/paʃə/	swim
		/siʃə/	run
		/pulə/	sleep
		/suli/	walk
		/masə/	sing
		/tusi/	paint
Morphemes	Number	/saɪ/	singular
		/ti/	plural
	Tense	/nɑ/	past
		/kə/	present

	/paʊ/	future
Temporal adverbs	/jɑpu/	yesterday
	/saɪʧu/	today
	/pɑli/	tomorrow

Every pseudo-sound segment was read and recorded individually by a female native speaker of Portuguese in a monotone. The sound files were first made to have the same amplitude using Praat. They were then combined into two-word sentences, with a 250-millisecond pause between each word. Same as Zhu et al. (under review, chapter 3), the sentences in our study were only presented auditorily without orthographic representation.

Grammar. The sentences adhered to a subject-verb order. In the consistent condition, both tense and temporal adverbs were always presented in every sentence. Each sentence consisted of the following structure: Subject [noun (stem) + morphological cue for number] + Predicate [verb (stem) + morphological cue for tense + morphological cue for number]. For example, for the sentence "Fauluti pachunati jɑpu" meaning "Pandas worked yesterday" was constructed as follows:

/faʊluti paʧunɑti/

Faulu ti pachu na ti

Panda PL work PAST PL

"The pandas worked."

In the variable condition, the availability of tense and temporal adverbs varies. Throughout the experiment, one-third of the sentences did not have adverbs but had morphological cues to tense, and another one-third were without morphological cues to tense but contained adverbs, while the rest contained both morphological and adverb cues to tense.

In contrast, in the consistent condition, the tense cues and temporal adverbs were consistently presented together.

We generated 384 artificial language sentences that were presented in Gorilla (https://gorilla.sc), including 288 training trials, 64 test trials in CSL tasks, and 16 sentences in grammaticality judgment tasks (GJT).

Visual stimuli. One hundred and twenty-eight static images served as the visual referents of the sentence. Each picture shows one or two of the same animals (panda, pig, lion, mouse, sheep, rabbit, dog, cow) performing a task (cook, work, swim, run, sleep, walk, sing, paint). The time of the action is informed by written English words (past, now, future), which were added to each picture to comprise a scene. The experiment was built on the Gorilla Experiment Builder (https://gorilla.sc).

Retrospective verbal reports

We used a questionnaire to gather retrospective verbal reports. These allowed us to determine whether participants were aware of the knowledge (Rebuschat, 2013). The questionnaire was adapted from Rebuschat et al. (2015). We started by asking participants to report any strategies they might have used during the CSL task. Specifically, we asked how they decided which scene was the correct referent of the sentence, whether they were just guessing or whether strategies had been applied. A follow-up question regarding the strategies asked whether their strategies had changed throughout the CSL task. In the following question, we investigated whether they noticed any patterns or rules about the grammatical structure. The questionnaire can be found on our OSF website.

Procedure

After filling out a consent form, participants were instructed to fill out the language background questionnaire. The CSL task followed afterwards, with GJT placed after block 4 and at the end of block 6. Finally, participants filled out the debriefing questionnaire. The entire procedure took around 50 minutes.

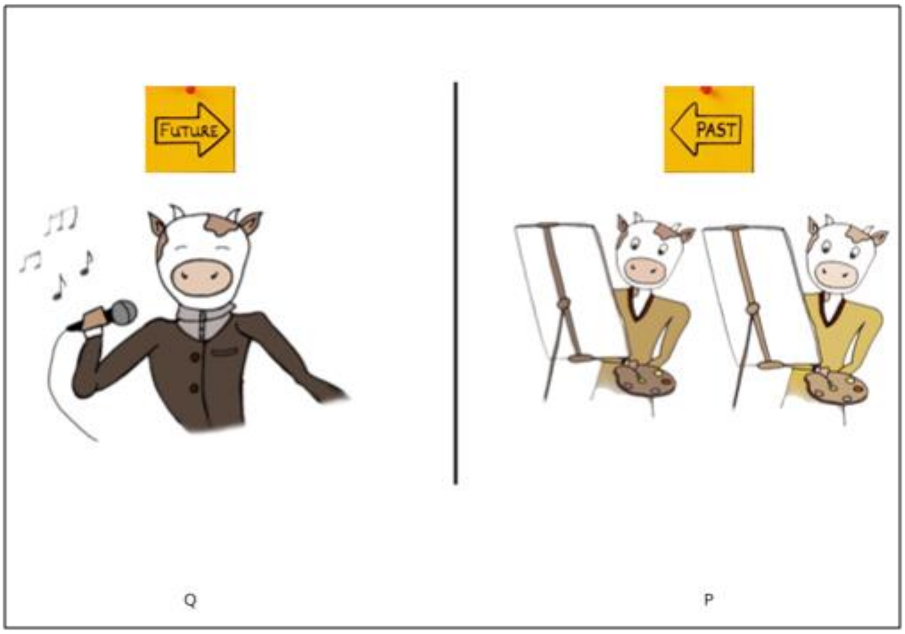
Cross-situational learning task

The CSL task was a sequence of making decisions of sentence-picture mappings, featuring the referential ambiguity in natural language learning. In each trial, participants were asked to choose one of the two pictures that the sentence they heard was referring to. There were two types of trials interleaved - training and test trials.

Training trials. In each training trial, there was a fixation cross that lasted for 500 milliseconds, after which two static images were shown on the screen. One thousand milliseconds after showing the images, participants heard a sentence (with 250 milliseconds between each word) in the artificial language describing one of the two images. The two images in each training trial differed in two to four features (e.g., animal, action, plurality, tense). Upon hearing the sentence, participants had to quickly decide which image it referred to by pressing Q or P on the keyboard to select the image. Figure 1 provides an example of a training trial of the CSL task.

Figure 1

An example of a training trial in the CSL task. Participants were presented with two scenes depicting animal(s) performing an action and playing a single artificial language sentence (e.g., /lu͡tʃisaɪ naɪpəpaʊsaɪ/). *Their task was to decide, as quickly and accurately as possible, which scene the sentence referred to.*



Test trials. The testing trials were identical to training trials except that they were controlled to have only one of the four features (referents for noun, verb, tense, or number) differing between the two images (see Figure 2), enabling us to detect the learning of specific linguistic features.

Figure 2

An example of test trials in the consistent condition. Participants were presented with the same animals doing the same task at different times. However, the two pictures in each test trial differed in only one linguistic feature. After 1000ms, participants heard a sentence *describing one of the pictures (e.g., "/puləsaɪ sulinasaɪ japu/", meaning: Pandas will sing tomorrow.)*

Overall, there were 6 blocks of CSL tasks, including 4 training blocks (blocks 1,2,3 and 5) and 2 mixed training and test blocks (blocks 4 and 6). Each training block contained 48 training trials, and each mixed block comprised 48 training trials and 32 test trials (8 test trials for each linguistic feature) randomly mixed.

The effect of frequency was controlled for each noun, verb, adverb, and morphological cue for number and tense, with the exception of one tense morpheme (past/now/future) appearing one time less than the others in each block, though this discrepancy was evened out across the three blocks. Visual referents in terms of which animal, action, time of the action, and number of the animals were equally presented in both target and foil images within each block, except for time indicators which were balanced across the whole experiment with small discrepancies in frequency within a block.

Grammaticality judgment task (GJT)

We included the GJT to test SV agreement. In each trial, participants heard a sentence in an artificial language. After the sentence played, a question mark appeared, and participants had to press Q if the sentence sounded good or P if it sounded bad. There were 16 GJT trials in total, and we included 8 of them at the end of block 4 and block 6 (four grammatical and four ungrammatical). The artificial language sentences can be found in the data spreadsheets on our OSF site.

Statistical analysis

We analysed the effects of predictors on the performance of CSL tasks by using logistic mixed-effects models (Jaeger, 2008). Our three research questions were tested across three different mixed-effect models.

The first model (RQ1a) was to investigate predictors that might influence the training trial accuracies. Two predictors were tested. Firstly, to test whether language can be learned based on cross-situational statistics over time, we investigate the effect of the block (1 to 6). Secondly, to test whether the distribution of time cues (tense and adverb) had an impact on CSL, we included the condition in the model. The following procedure was applied when we tested the model fit. The null model included intercepts for subjects and items as well as by-subject random slopes for block and by-item random slopes for block, condition, and their interaction. To find the best-fitting model, we tested the model fit by adding fixed effects of block (1 to 6), condition (consistent and variable) and block:condition to the null model sequentially. We tested the quadratic effect for block at the end, as block may exert a non-linear rather than linear effect. We then conducted one-sample t-tests to determine whether the learning of morphological cues was significantly above chance (RQ1b).

Next, we moved on to our second mixed-effect model, investigating whether learning of adverbial was significantly better than tense cues (RQ2a) and whether the learning of tense was influenced by the consistent or variable condition (RQ3). Addressing these questions, we included tense versus adverb cues and condition in the second mixed-effect model with test trial accuracy as the dependent variable. We started from the null model, which included intercepts for subjects and items as well as by-subject random slopes for block and tense versus adverb, by-item random slopes for block and condition. To find the best-fitting model, we tested the model fit by adding fixed effects of block (1 to 6), condition (consistent and variable), tense versus adverb and condition: tense versus adverb, accordingly. If the variables did not improve the model fit, we excluded them from both fixed effects and slopes for by-random effects.

For the third model, we tested whether the learning of number was significantly higher than the learning of tense (RQ2b), and whether the distributional condition effect would influence the discrepancy (RQ3). We performed the same analysis as the second model but changed the adverb cues to number cues.

Results

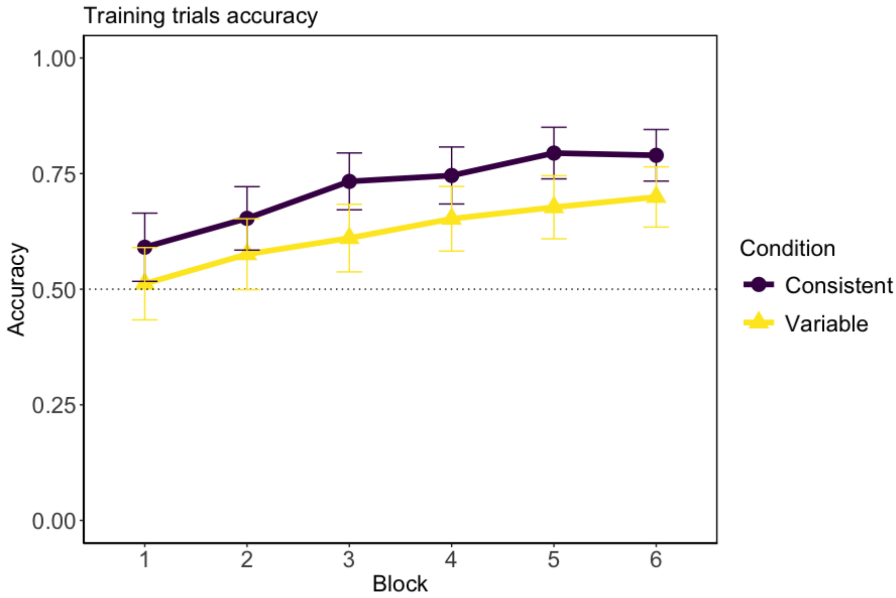
Performance on cross-situational CSL tasks

Training trials

Performance in the training trials for both conditions is shown in Figure 3. The mean accuracies of the training trials in each block and for each condition were specified in Table-S2.

Figure 3

Learning trajectory for the consistent and variable conditions over 6 blocks of training. Error bars represent 95% Confidence Intervals. The dotted line (0.5) shows chance performance.



The first mixed-effect model explored whether adult learners could keep track of CSL statistics to learn a novel language and whether the distribution of temporal adverbs and morphological tense markers influence overall learning. Compared to the null model, adding the fixed effect of block significantly improved the model fit ($\chi2(1) = 51.484$, $p < .001$), therefore, there was evidence that language can be learned based on cross-situational statistics. There was also a significant effect of adding condition ($\chi2(1) = 7.153$, $p = .007$), with participants in the consistent condition performing significantly better than those in the variable condition. Adding the interaction of block and condition did not significantly improve the model fit and it is thus excluded from the final model ($\chi2(1) = 2.536$, $p = .111$). We also found that the quadratic effect for block did not significantly improve the model fit ($\chi2(1) = .22$, $p = .638$). The best-fitting model can be found in Table 2.

Table 2

Best fitting model for participants' accuracy in the training trials of the CSL task.

	training_accuracy				
Predictors	*Odds Ratios*	*std. Error*	*CI*	*Statistic*	*p*

(Intercept)	1.12	0.11	0.93 – 1.35	1.23	0.218
block	1.35	0.05	1.26 – 1.45	8.32	**<0.001**
Condition [Variable]	0.71	0.09	0.56 – 0.90	-2.78	**0.006**

Number of observations: 22393, Participants: 82, Item: 1170, AIC = 25090.0, BIC = 25218.3, log-likelihood = -12529.0.

R syntax: glmer(training_accuracy ~ block + Condition + (1 + block + Condition + block:Condition | item) + (1 + block | ppt) , data=overall_training_dataset_renamed, family = binomial, control=glmerControl (optCtrl = list(maxfun = 50000), optimizer = "nloptwrap", calc.derivs = FALSE))

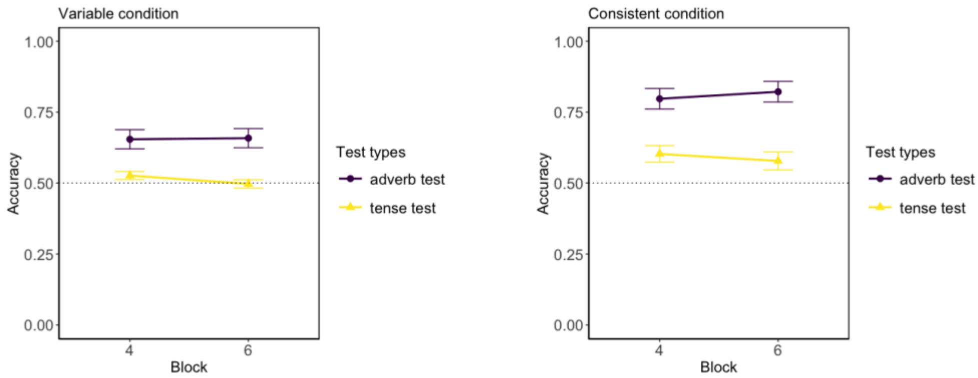
Test trials

In Figures 4A and 4B, we analysed participants' performance on adverb and morphological tense test trials. The accuracies in each type of test trial in each condition can be found in Table S-3 (noun, verb, tense, number, adverb) and S-4 (SV agreement).

Figure 4

Participants' performance in the adverb and tense tests in the consistent and variable conditions. Error bars represent 95% Confidence Intervals. The dotted line (0.5) shows chance performance.

A **B**



To investigate whether the overshadowing effect can be observed and whether the effect differs between conditions, we first need to investigate whether there is a significant difference in performance between morphological tense and adverb tests and whether it interacts with the condition (consistent and variable). We found that adding block as fixed effects did not significantly improve the model fit compared to null model ($\chi2(1) = .487$, $p = .485$). Therefore, block was excluded from the model as a fixed effect. The subsequent inclusion of condition ($\chi2(1) = 7.376$, $p = .007$) significantly improved the model fit, with accuracies in the consistent condition being significantly higher than the accuracies in the variable condition. Morphological tense versus adverb ($\chi2(1) = 35.945$, $p < .001$) was also significant with performance in the adverb test being significantly better than in the morphological tense test. The inclusion of condition: morphological tense versus adverb did not significantly improve fit ($\chi2(1) = 1.311$, $p = .252$). The best-fitting model is shown in Table 3.

Table 3

Best fitting model for testing the effect of time, tense_or_adverb, and condition on participants' accuracy in the morphology test trials of the CSL task (with Consistent condition and adverb tests in the intercept).

	test_accuracy				
Predictors	*Odds Ratios*	*std. Error*	*CI*	*Statistic*	*p*
(Intercept)	5.47	1.07	3.72 – 8.03	8.65	**<0.001**
Condition [Variable]	0.59	0.11	0.41 – 0.87	-2.71	**0.007**
tense or adverb [tense test]	0.31	0.06	0.22 – 0.44	-6.53	**<0.001**

Number of observations: 2515, Participants: 82, Item: 109, AIC = 2969.5, BIC = 3057.0, log-likelihood = -1469.8.

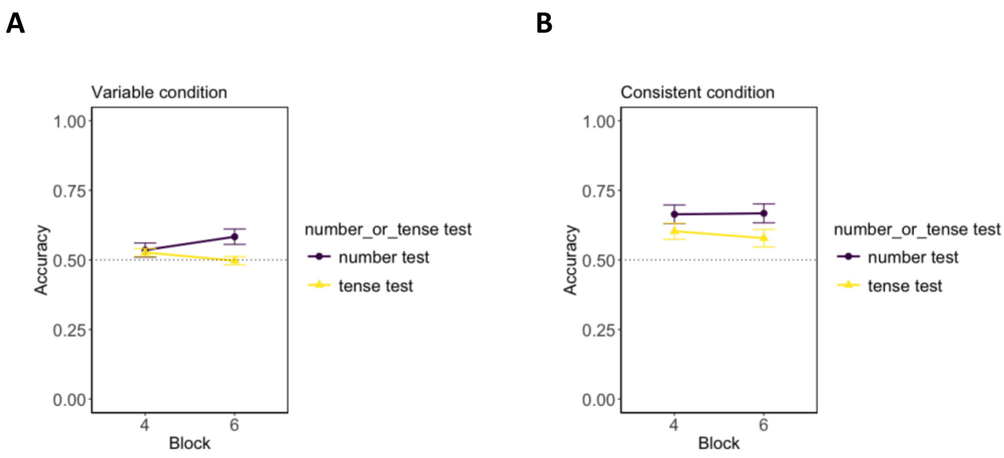
R syntax: test_accuracy ~ Condition + tense_or_adverb + (1 + block + Condition | item) + (1 + tense_or_adverb + block | ppt), data= morphotest, family = binomial, control=glmerControl (optCtrl = list(maxfun = 50000), optimizer = "nloptwrap", calc.derivs = FALSE))

Performance on number and tense tests

Figure 5 displays the performance in the number and tense tests in the consistent and variable conditions.

Figure 5

Participants' performance in the number and tense tests in the consistent and variable conditions. Error bars represent 95% Confidence Intervals. The dotted line (0.5) shows chance performance.



The analysis of results in morphological tense and adverb tests revealed a preference for learning the more salient cue (adverb) over the less salient one that encodes the same meaning (morphological tense). Moreover, in the variable condition, the learning of morphological tense was only at chance level in block 6, which could be a sign of overshadowing. However, it was not yet clear whether the reduction in learning of morphological tense in the variable condition is due to being overshadowed by the learning of adverb, or whether it is because of its less frequent appearance compared to the morphological tense in the consistent condition, or whether it was an effect of both. To discern the effect of adverb and condition – whether they were general affecting learning overall, or whether they were specifically overshadowing morphological tense, we compare the learning of the two morphological cues --- number and morphological tense – in a mixed-effect model. This is because, unlike tense, the morphological cues for number had no competition from another more salient cue that informs the number of the object, but it shares the same degree of salience and same frequency with morphological tense markers. The third mixed-effect model thus investigated whether there was a significant difference between number and morphological tense tests, and whether it was influenced by the distributional conditions of tense and adverb.

We found that adding block as fixed effects did not significantly improve the model fit compared to null model ($\chi2(1) = .302$, $p = .587$). Therefore, block was not further considered as a fixed effect in the model. The inclusion of condition ($\chi2(1) = 7.267$, $p = .007$) significantly improved the model fit, with participants in the consistent condition performing significantly better than those in the variable condition. Number versus tense ($\chi2(1) = 4.038$, $p = .004$) also improved model fit, with number learned significantly better than tense. But the inclusion of condition: number versus tense ($\chi2(1) = .383$, $p = .536$) did not significantly improve fit. The best-fitting model can be found in Table 4.

Table 4

Best fitting model for testing the effect of time, tense_or_number, and condition on participants' accuracy in the morphology test trials of the CSL task (with Consistent condition and number tests in the intercept).

	test_accuracy				
Predictors	*Odds Ratios*	*std. Error*	*CI*	*Statistic*	*p*
(Intercept)	2.21	0.33	1.65 – 2.97	5.29	**<0.001**
number or tense [tense test]	0.74	0.11	0.56 – 0.98	-2.07	**0.038**
Condition [Variable]	0.62	0.11	0.44 – 0.87	-2.76	**0.006**

Number of observations: 2501, Participants: 82, Item: 141, AIC = 3257.7, BIC = 3345.1, log-likelihood = -1613.8.

R syntax: test_accuracy ~ number_or_tense + Condition + (1 + block + Condition | item) + (1 + block + number_or_tense | ppt), data= morphotest, family = binomial, control=glmerControl (optCtrl = list(maxfun = 50000), optimizer = "nloptwrap", calc.derivs = FALSE))

The learning difference between morphological number and tense markers further indicated without the competition of attention from other more salient cues (number markers), learning would be significantly higher, further confirming the effect of overshadowing. Overall, our findings tend to suggest that the learning of tense was overshadowed by the learning of adverbs across the conditions, the magnitudes of which did not seem to be influenced by the availability of morphological tense and temporal adverbs.

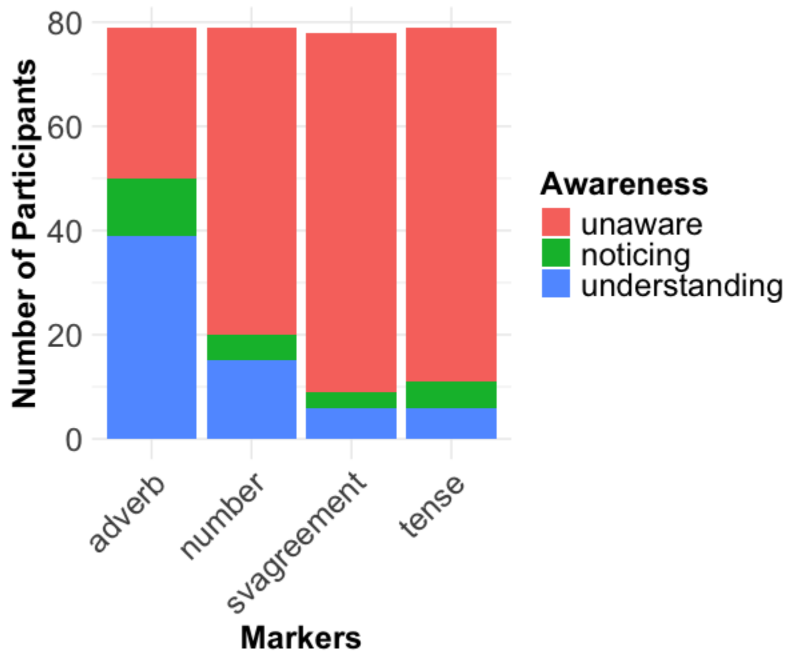
Retrospective verbal reports

Participants' answers to the debriefing questions were coded following the guidance of Rebuschat et al.'s (2015) coding scheme of awareness, ranking from full awareness (understanding), partial awareness (noticing), and complete unawareness (unaware). Participants who reported the pattern of SV agreement (Q3), and the form-meaning mappings for past, present, future (Q4-5), singular, plural (Q6) were considered "understanding". Those who only mentioned noticing the repetition of a cue (Q3) or mentioning tense or adverb (Q4-5) or number (Q6) without specifying the mapping would be considered "noticing". Participants who did not report tense, number or SV agreement were coded as "unaware".

Following the criteria outlined above, the awareness of each marker was shown in Figure 6.

Figure 6

The number of participants at different degrees aware of each marker

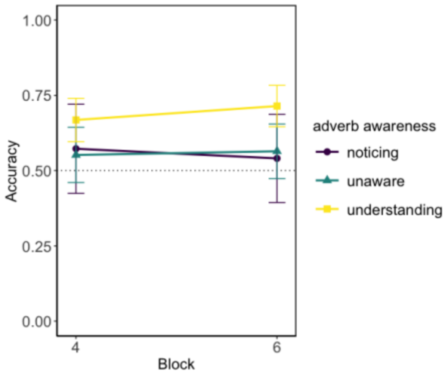


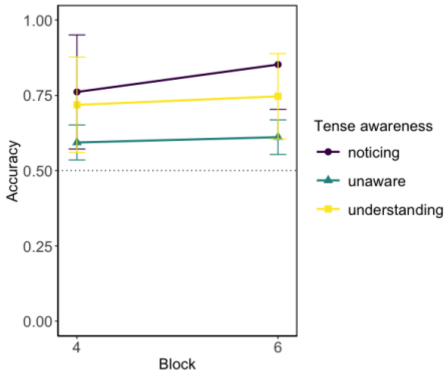
Accuracies of CSL tasks between participants who showed different levels of awareness in their debriefing questionnaires can be found in Figure 7. We found participants performed significantly better when they were fully aware of the linguistic features, except for morphological tense markers, which may be due to participants not making an effort to report the meaning of each distinction of morphological tense markers (past, present, future), instead only indicating that they were all referred to tense in their debriefing questionnaire. This could lead to misclassifying full awareness as noticing based on our coding scheme.

Figure 7

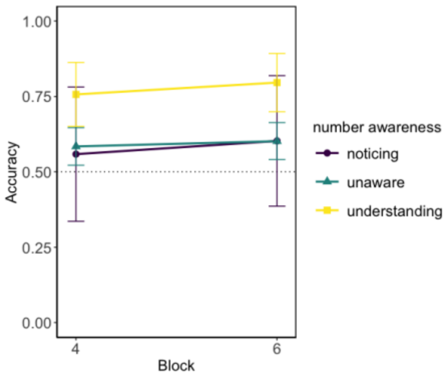
Participants' accuracy on CSL tasks and GJT: comparisons between participants who reported being from full awareness (understanding) to unawareness (unaware) of adverbial (7A) and morphological cues (7B-7D). Note. Error bars represent 95% Confidence Intervals.

A **B**

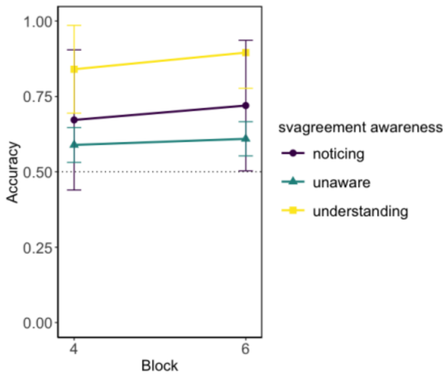

Accuracy
1.00
0.75
0.50
0.25
0.00
4
6
Block
adverb awareness
noticing
unaware
understanding


Accuracy
1.00
0.75
0.50
0.25
0.00
4
6
Block
Tense awareness
noticing
unaware
understanding

C


Accuracy
1.00
0.75
0.50
0.25
0.00
4
6
Block
number awareness
noticing
unaware
understanding

D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Discussion

In this study, we tested the predictions of overshadowing mechanisms within a language learning context. Analogous to Kamin's (1967) experiments, in which a light (stimulus A) and a noise (stimulus B) were both associated with the same outcome (a mild foot shock), morphological tense and temporal adverbs in language similarly encode the same underlying meaning (time of the event). Kamin's findings suggest that prior learning of association A-X can block subsequent learning of B-X when the stimuli A and B are then presented together, whereas consistent simultaneous exposure to both stimuli (without pre-exposure) allows both associations to accrue. However, in natural language learning environments, morphological and lexical cues for a given outcome, such as tense, do not consistently co-occur; rather, their availability is typically variable (Cheng & Lu, 2022). Building on this framework, the present study investigates whether the availability of morphological and lexical cues influences the magnitude of overshadowing in language learning. Specifically, we manipulated the availability of morphological and adverbial markers for tense, presenting them either consistently or variably during exposure. Results from the variable condition are intended to shed light on whether overshadowing and blocking emerge under the condition that more closely approximates naturalistic language learning.

To simulate natural language learning, we adopted a CSL paradigm in which participants were exposed to audio-visual input and were tasked with inferring the ambiguous referential mappings of a novel sentence and picture that indicates the sentence, replicating challenges faced in real-world language acquisition (Quine, 1960). For the auditory stimuli, we constructed an artificial language comprising nouns, verbs, morphological and adverbial markers for tense, morphological markers for number, and SV agreement. In addition to testing the associative learning theory in language learning, this study also contributes to understanding the learnability of morphological cues by adult learners under naturalistic input conditions.

Our first research question (RQ1) investigated statistical learning among adult learners. Firstly, we asked whether adults could learn a novel language (RQ1a). Previous CSL studies have demonstrated that adults are able to track form–meaning mappings based on cross-situational statistics, from word-level processing (e.g., Yu & Smith, 2007) to more complex sentence-level structures (e.g., Rebuschat et al., 2021). However, research on statistical learning of morphological features remains limited. While adults were demonstrated that they can learn morphological markers that indicate abstract semantic categories via CSL (Finley, 2023), studies have also shown that they struggle to acquire case markers, particularly when the referential structure is complex (Monaghan et al., 2021; Rebuschat et al., 2021; Walker et al., 2020). In contrast, when visual referents map transparently onto linguistic features, more robust morphology learning has been observed (Zhu et al., under review, see also in chapter 3). In the present study, we increased the complexity by introducing a temporal adverbial cue alongside morphological tense markers. Results from the training trials revealed strong overall learning across conditions: participants performed above chance after only five minutes of exposure in both experimental conditions, with accuracies increasing steadily over time, consistent with previous sentence-based CSL studies (e.g., Zhu et al., under review, chapter 3).

We also asked whether the availability of competing morphological cues would influence overall language learning outcomes. Results show a significant effect of condition on training trial accuracy, indicating that the presence of competing redundant cues adversely impacted learning trajectories. Previous findings in Zhu et al. (under review, see also in chapter 5) demonstrated the effect of salience on morphology learning, however, it did not influence the overall learning of the language. Our findings suggest that the availability of redundant, salient cues may exert a broader influence on language learning, beyond the localised difficulty of acquiring specific low-salience features. Hence, *relative* rather than *absolute* salience impacts learning of morphological targets.

We further asked whether morphological tense and number markers can be learned in CSL paradigm (RQ1b). Test trial results indicated that morphological features were successfully acquired, except for morphological tense markers in the variable condition (see Figure 5). These findings are broadly consistent with previous work by Zhu et al. (under review, chapter 3; under review, chapter 5), which demonstrated that adults can rapidly track cross-situational statistics, including morphological patterns. However, the failure to acquire tense morphology in the variable condition contrasts with the successful learning of tense cues observed in Zhu et al.s' study. This contrast suggests that adults can acquire morphological features through cross-situational statistics even when morphological markers are less salient than accompanying content words. Critically, however, when morphological markers are both low in salience and compete with a more salient lexical cue encoding the same meaning in a natural learning environment, where morphological markers are variably available, learning can be significantly blocked. This pattern supports the view that cue competition is a major source of difficulty in morphological acquisition.

Our second research question investigated whether overshadowing/blocking effects apply in the language learning context. Specifically, we asked whether adverbs would be learned significantly better than morphological tense markers (RQ2a) and whether morphological number markers would be learned significantly better than morphological tense markers (RQ2b). Previous studies on blocking and overshadowing theory posit that the co-occurrence of two stimuli encoding the same meaning, when one stimulus is more salient than the other, elicits an overshadowing effect and a blocking effect if pre-training of one stimulus is involved (Kamin, 1967). The present study extends this literature by investigating whether overshadowing effects emerge without pre-training when two redundant stimuli are either variably or consistently available. In the present study, we found that temporal adverbs were learned significantly better than morphological tense markers across both conditions, which aligns with predictions from blocking and overshadowing theory. However, alternative explanations remain possible. The less successful morphological tense learning, compared to temporal adverbs, could also arise from the effect of low salience (Zhu et al., under review, chapter 5). To further isolate the mechanism, we compared learning outcomes for morphological tense and number markers. In our experiment, participants were exposed to sentences where morphological number markers were not accompanied by a salient lexical marker that indicates the number of subjects. Without the lexical competitors, morphological number markers were found to be acquired significantly better than morphological tense markers in both conditions, which supports the view that tense learning has been negatively influenced by the existence of the semantically redundant and more salient temporal adverbs. However, another possibility for numbers to be learned better could be that numbers might require less cognitive effort to learn due to the difference in the number of distinctions for number (2 for number: singular and plural) and tense (3 for tense: past, present and future). Yet, results in the participants of L1 English group in Zhu et al. (under review, chapter 3), where both morphological cues were free from cue competition, have shown that learning between number and tense was similar. This finding tentatively supports that the number was learned better due to the lack of redundant, more salient markers rather than the distinction differences. Together, these findings provide strong evidence that blocking and overshadowing effects, as predicted by associative learning studies (e.g., Jones & Haselgrove, 2013; Kamin, 1967; Kruschke, 2006; Rescorla & Wagner, 1972), extend to more naturalistic language learning, consistent with findings in Ellis (2007) and a series of subsequent studies (Ellis, 2008; Ellis & Sagarra, 2010; Ellis & Sagarra, 2011; Ellis & Sagarra, 2014).

The overshadowing effect observed in both groups suggests that redundancy poses a substantial challenge for naturalistic adult learners. This is in contrast to Tal and Arnon (2022)'s work, where they found that redundancy is beneficial for learning. The reason for the different findings could be attributed to differences in the type of redundancy implemented, the learner populations studied, and the relative salience of the cues. In Tal and Arnon's study, the redundant cues—case marking and fixed word order—were complementary and consistently aligned, enhancing learnability without competing for attention. In contrast, the present study involved semantically redundant but perceptually competing cues (salient temporal adverbs vs. low-salience morphological tense markers). This created a cue competition environment, where the more salient lexical markers overshadowed the learning of the morphological markers. Thus, while redundancy can be beneficial when cues reinforce each other, it may hinder learning when cues compete.

Overall, the results in our study indicated that overshadowing effects apply within a naturalistic language learning context where cue availability is variable. While prior findings have highlighted the importance of learning sequence on morphology learning (Ellis, 2006; Ellis, 2007; Ellis & Sagarra, 2010), our study further extend the findings in a natural language learning paradigm.

Our third research question (RQ3) asked whether the availability of competing cues influences the magnitude of the overshadowing in the CSL paradigm. Specifically, we examined whether consistent versus variable availability of cues would modulate the degree of overshadowing. Firstly, we found that consistent co-occurrence has been shown to boost the learning of both stimuli. Both morphological tenses and temporal adverbs were acquired significantly better than in the consistent condition, indicating that consistent exposure to both morphological and lexical markers benefits learning (Bahrick et al., 2019). While the consistent exposure to the redundant cues facilitates learning, it does not alleviate the learning difficulty of morphological cues from being overshadowed by the more salient semantically redundant cues. We found that results from the second model did not show a significant interaction between condition and cue type (adverb vs. tense), nor did the third model show a significant interaction between condition and cue type (tense vs. number). These findings jointly suggest that the magnitude of the overshadowing effect is not significantly altered by the availability of the cues. Although consistent co-occurrence appears to facilitate overall learning, our results indicate that further focused training on morphological forms remains necessary, as the overshadowing effect exerted by more salient lexical cues persists regardless of whether there is variable or consistent exposure to each cue individually. The findings have important implications for classroom-based instruction: For example, if more salient lexical cues overshadow the learning of morphological forms, this suggests the need for targeted attention to form-meaning mappings in instructional contexts.

Conclusion

In this study, we investigated how the distributional properties of morphological and lexical cues influence learning outcomes, testing the predictions of overshadowing theory (Kamin, 1967) within a lab-based naturalistic language learning context using CSL. We found that morphological tense markers were blocked by temporal adverbs under conditions where the two cues were variably available. In contrast, when morphological and adverbial cues were consistently presented together, learning of both the less salient morphological tense markers and the more salient temporal adverbs was enhanced. Our findings contribute to extending the understanding of the overshadowing learning mechanism by demonstrating that availability of the two competing cues modulates the acquisition rates but not the degree of cue competition during language learning.

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Supplementary Materials

Table S-1

Artificial language: three random sound-meaning mappings

Noun	Version 1	Version 2	Version 3
panda	/faʊlu/	/pulə/	/kitə/
pig	/fima/	/faʊlu/	/paʧu/
lion	/fuki/	/fuki/	/suli/
mouse	/jitu/	/fima/	/pulə/
sheep	/kitə/	/siʃə/	/faʊlu/
rabbit	/lipə/	/ʃaji/	/fuki/
dog	/luʧi/	/tusi/	/jitu/
cow	/ʃaji/	/masə/	/ʃaji/
Verb	**Version 1**	**Version 2**	**Version 3**
cook	/naɪpə/	/jitu/	/paʃə/
work	/paʧu/	/naɪpə/	/luʧi/
swim	/paʃə/	/lipə/	/masə/
run	/siʃə/	/paʧu/	/fima/
sleep	/pulə/	/paʃə/	/tusi/
walk	/suli/	/luʧi/	/lipə/
sing	/masə/	/suli/	/naɪpə/
paint	/tusi/	/kitə/	/siʃə/
Tense cue	**Version 1**	**Version 2**	**Version 3**
past	/nɑ/	/kə/	/saɪ/
now	/kə/	/paʊ/	/nɑ/

future	/paʊ/	/nɑ/	/ti/
Number cue	**Version 1**	**Version 2**	**Version 3**
one	/saɪ/	/ti/	/kə/
two	/ti/	/saɪ/	/paʊ/
Adverb	**Version 1**	**Version 2**	**Version 3**
yesterday	/pali/	/pali/	/japu/
today	/japu/	/saɪtʃu/	/pali/
tomorrow	/saɪtʃu/	/japu/	/saɪtʃu/

Table S-2

Performance in each condition across 6 blocks – training trials only

Group		Blocks					
		1	2	3	4	5	6
Consistent	M	.59	.65	.73	.75	.79	.79
	SD	.48	.44	.40	.40	.36	.36
Variable	M	.51	.58	.62	.65	.68	.70
	SD	.49	.49	.46	.44	.43	.41

Table S-3

These are the results of CSL test trials

Group	Test types		Blocks	
			4	6
Consistent	Nouns	M	.62	.72

		SD	.19	.23
	Verbs	M	.57	.64
		SD	.14	.22
	Number morphemes	M	.66	.67
		SD	.21	.22
	Tense morphemes	M	.60	.58
		SD	.18	.20
	Adverbs	M	.80	.82
		SD	.23	.23
Variable	Nouns	M	.62	.66
		SD	.17	.19
	Verbs	M	.56	.57
		SD	.09	.14
	Number morphemes	M	.54	.58
		SD	.16	.17
	Tense morphemes	M	.53	.50
		SD	.09	.09
	Adverbs	M	.65	.66
		SD	.22	.21

Table S-4

These are the results of the GJT

	Test	

		1	2
Consistent	M	.57	.64
	SD	.12	.18
Variable	M	.64	.63
	SD	.09	.15

Note. Asterisks indicate performance below chance, * $p < .05$, ** $p < .001$.

5. Publishable paper 3: How salience shapes the statistical learning of non-native morphology (first round of under review with *Second Language Research*)

Page number: 146-191

Abstract

Previous research suggests that grammatical morphemes are particularly challenging for language learners because they often have low acoustic salience (e.g., Ellis, 2022). This study investigates how acoustic salience influences morphological acquisition in a cross-situational statistical learning (CSL) context. Participants were exposed to an artificial language containing grammatical morphemes that varied systematically in either acoustic salience (syllabicity and sonority) across conditions. There was a significant effect of acoustic salience on the CSL of morphology, but not on the overall language acquisition. The observed importance of perceptual salience underscores the importance of extra training and exposure for using grammatical cues low in acoustic salience.

***Keywords*:** cross-situational learning, statistical learning, language acquisition, morphology, perceptual salience

Introduction

Adults acquiring a non-native language in natural environments often struggle to learn and use grammatical morphemes accurately (Dey et al., 2024; Sagarra, 2014). Research suggests that many learners experience morphological fossilisation, a stage in which the acquisition of morphological features plateaus and becomes resistant to further input (Schmidt, 1984; White, 2003), while their vocabulary continues to grow (Perdue, 1993). For example, even high-proficiency non-native English speakers may omit the past tense marker "-ed" (Lardiere, 1998) or exhibit reduced sensitivity to grammatical errors (Jiang, 2007; VanPatten et al., 2021). Although grammatical morphemes are also acquired relatively late during the development of native languages (L1s), fully proficient L1 speakers typically do not experience ongoing difficulties with grammar (Brown, 1973).

One possible explanation for non-native language learners' persistent difficulties with morphological features, compared to L1 learners, is that their attention is disproportionately drawn to lexical rather than to grammatical markers. According to Ellis and colleagues, when exposed to phrases with verbs with tense morphemes and temporal adverbs, adult learners tend to focus on temporal adverbs that have previously proven reliable and easy to retrieve over less salient morphological markers (Sagarra & Ellis, 2013; Ellis, 2007; Cintrón-Valentín & Ellis, 2016). Because adults have already learned to focus their attention on these salient forms, especially when lexical and morphological markers co-occur and convey similar meanings. In such cases, the morphological markers may receive less attention, leading to delayed or incomplete acquisition. In contrast, L1 learners—particularly children—may be less susceptible to this bias, as their lexical systems and retrieval capacities are still developing. Without strong prior expectations or entrenched preferences, children may be more likely to distribute attention across both lexical and morphological cues, facilitating more balanced acquisition of form–meaning mappings (Clahsen & Felser, 2006). While this account emphasises the role of salience and learned attention on the redundant cues, a key question remains: Are non-native language learners' attention driven primarily by cue salience alone, or by the combined effect of salience and redundancy between the semantically redundant lexical and morphological cues? Research by Ellis and colleagues has suggested that the greater learning of temporal adverbs may be explained by their semantic overlap with morphological tense, which could lead to a suppression effect on the learning of morphology. However, an alternative explanation is that morphological tense is simply less perceptually salient than temporal adverbs, and that this difference in salience, rather than semantic redundancy, accounts for the disparity in learning. The present study examines this distinction by investigating the extent to which perceptual salience alone influences adult learners' acquisition of morphological tense, with the broader aim of shedding light on factors contributing to differences between L1 and non-native language acquisition.

Perceptual salience in SLA studies

The perceptual salience of morphological markers can be influenced by multiple factors, including psychophysical properties (e.g., acoustic salience, such as duration and syllabicity), linguistic context, surprisal (unexpectedness of the form), and external influences such as emotional, motivational, and cognitive states (Ellis, 2017). This study focuses on the role of psychophysical salience in morphology acquisition, specifically examining acoustic salience by manipulating the sonority (loudness) and syllabicity (presence of a syllable) of morphological cues. While the low perceptual salience of morphological markers is often cited as a key factor in explaining difficulties with morphological acquisition, this claim has received limited direct empirical investigation (Ellis, 2022; Goldschneider & DeKeyser, 2001).

A primary obstacle to empirical verification is the difficulty of accurately measuring learners' perception of linguistic forms (Bell, Trofimovich and Collins, 2015). Previous research examining the acquisition of English past tense forms ([t], [d], and syllabic affixes) demonstrates the influence of sonority and syllabicity (Riches, 2005). According to the Sonority Hierarchy, the English past tense markers [t] and [d] are among the least sonorous sounds (Baroni, 2014). However, when the consonant follows a vowel, forming a syllable (e.g. head-ed), the resulting morpheme becomes acoustically more salient and thus easier for language learners to perceive and acquire. In contrast, single-consonant morphemes ([t] and [d]) are significantly less perceptible, particularly in implicit learning contexts (Bell et al., 2015; Strachan and Trofimovich, 2019). These studies support the idea that cue salience affects morphological learning. However, it remains unclear how varying degrees of salience in grammatical morphemes across different languages might affect their learnability. For example, the schwa vowel [ə], a weak vowel, frequently appears at the ends of grammatical morphemes across various languages (Fehringer, 2004). Conversely, in languages like Japanese, grammatical morphemes are often realised with more acoustically salient, strong vowels such as [a] (e.g., the past tense morpheme [ta]). While existing studies (e.g., Riches, 2005) indicate that perceptual salience, such as the sonority of the past tense, influences morphological acquisition, the relative learnability of morphemes containing strong versus weak vowels is still unexplored. The current study aims to address this gap by comparing the role of syllabicity and sonority differences (strong vowel vs. schwa) in acquiring non-native tense and number suffixes. To investigate this, the study manipulates the perceptual salience of morphological markers as a between-groups variable, focusing on contrasts in both syllabicity and vowel strength.

Another possible explanation for why naturalistic learners often struggle to attain native-like proficiency in morphology concerns age-related differences in statistical learning abilities. Statistical learning—the capacity to implicitly detect distributional regularities in the environment—has been shown to underpin the acquisition of novel linguistic forms

(Rebuschat, 2022; Williams & Rebuschat, 2023). Research by Newport (2019) comparing younger children, older children, and adults revealed a developmental decline in the ability to abstract grammatical rules from probabilistic input. While younger learners tended to generalise beyond surface-level patterns, adult learners were more likely to reproduce the statistical distribution encountered in the input without extracting underlying rules. This pattern may help explain why adult learners, particularly in naturalistic contexts, often struggle with morphological generalisation.

Further support for this account comes from studies using cross-situational learning (CSL), a paradigm that engages statistical learning mechanisms by requiring learners to map linguistic forms to meanings across variable contexts. Recent work suggests that difficulties in morphological acquisition may stem not only from distributional input itself, but also from challenges in comprehension processes required to interpret form-meaning mappings (Monaghan et al., 2021; Rebuschat et al., 2021; Walker et al., 2020). At the same time, other CSL studies have reported successful morphological learning, indicating that under certain conditions, adult learners can acquire grammatical morphology through implicit exposure (Finley, 2023; Zhu et al., under review, chapter 3).

Building on these findings, the present study investigates whether adult learners are able to extract and generalise grammatical morphemes through exposure to cross-situational statistics, focusing on both comprehension and generalisation ability. In summary, this study seeks to advance our understanding of morphology learnability in a statistical learning environment. At the within-group level, we examine whether learners' ability to track distributional patterns, through co-occurring visual and auditory cues, facilitates the acquisition of morphology, using a CSL paradigm. The following section outlines the CSL framework and reviews key findings from prior research, followed by descriptions of the CSL paradigm we employed to investigate morphological acquisition in detail.

Cross-situational learning of morphology

The CSL paradigm provides an effective framework for investigating immersive aspects of naturalistic language learning within controlled laboratory settings. In CSL tasks, learners encounter auditory information (whether it is word(s) or sentence(s)) and multiple possible visual referents simultaneously, resembling how referring meaning works within the ambiguous natural language acquisition scenarios (Siskind, 1996). Language learning in an uninstructed, naturalistic environment is inherently challenging, as spoken segments within speech often correspond to multiple possible referents in the surrounding context. Learners overcome this referential ambiguity gradually through repeated encounters, as consistent co-occurrences between auditory cues and visual referents progressively clarify meanings. The CSL paradigm replicates this type of referential ambiguity, presenting learners with multiple potential referents paired with auditory cues, each cue possibly corresponding to any of the presented referents. Over successive trials in the CSL task, learners' increasing accuracy reflects their successful tracking of statistical regularities inherent in the input.

To date, CSL has demonstrated effectiveness primarily in the acquisition of nouns (e.g., Ge, Monaghan, and Rebuschat, 2025; Suanda and Namy, 2012; Vlach and DeBrock, 2019), verbs (e.g., Monaghan et al., 2015; Scott & Fisher, 2012), and basic word order patterns (e.g., Rebuschat et al., 2021). However, research on CSL-based acquisition of morphological markers remains limited. Existing research has shown that adults can effectively track segments of words (morphemes) associated with indirect visual referents (categories of the objects) (Finley, 2023), but natural language acquisition is inherently more complex, involving simultaneous exposure to vocabulary and morphosyntax rather than isolated elements. To date, few empirical studies have explicitly investigated whether learners can successfully track cross-situational statistical relationships within sentence-scene mappings. Rebuschat et al. (2021) provided evidence that case markers could be learned from sentence-based cross-situational statistics, although this occurred only under conditions of low referential ambiguity (Experiment 2), highlighting the role of referential clarity in morphological acquisition (see also Walker et al., 2020; Monaghan et al., 2021). Relatedly, Zhu et al. (under review, chapter 3) examined sentence-based CSL of morphology, exposing participants to two scenes paired with one auditory sentence containing a noun, an intransitive verb (of the form CVCV), morphological cues for number and tense (of the form CV), and double-marked subject-verb agreement. Over 504 trials, learners demonstrated robust acquisition across linguistic domains (vocabulary and morphosyntax), suggesting adult learners can effectively track complex cross-situational statistics simultaneously.

However, the successful morphological learning reported in Rebuschat et al. (2021) and Zhu et al. (under review, chapter 3) may, in part, be attributed to the relatively high perceptual salience of the morphological cues used, specifically, their CV structure (Ellis, 2022). By contrast, morphological markers in natural languages, such as the English past tense suffix, are often far less salient. This again highlights the need to directly examine the role of salience in morphological learning.

In our previous work in chapter 3 and 4, we consistently found that number morphology was acquired more successfully than tense morphology, despite both being equally salient (CV forms). While this could be explained by input frequency, another plausible explanation is that the number, which involves only two contrastive distinctions (singular vs. plural), is inherently easier to learn than tense, which involves three (past, present, future). This raises the exploratory question of whether morphological categories with fewer contrastive distinctions are more learnable. We investigate this by manipulating the presence or absence of overt morphological marking to simulate default forms, which leads to having only two distinctions for tense marking and one distinction in number marking.

In sum, the current study aims to further clarify the factors contributing to morphological learning difficulties by explicitly testing the effects of perceptual salience and the number of contrastive distinctions. Using a CSL paradigm adapted from Zhu et al. (under review, chapter 3), we compare outcomes across three experimental groups exposed to artificial languages differing in cue salience: a high-salience group, a low-salience group, and a low-salience group with default forms.

Furthermore, we explore the relative ease of noun and verb acquisition within CSL paradigms. Previous studies consistently indicate a noun-learning advantage over verb learning among children (e.g., Childers & Tomasello, 2002, 2003), with similar tendencies observed in adults, though the evidence is less conclusive (Monaghan et al., 2015; Zhu et al., under review, chapter 3). An exception is reported by Rebuschat et al. (2021), who found superior verb learning relative to nouns. As an exploratory investigation, this study also examines whether adult learners exhibit a noun preference within the CSL context.

Research questions and predictions

Building on the preceding discussion, we formulated the following research questions.

First, can adult learners use cross-situational statistics to acquire both lexical and morphological features? (RQ1) Based on prior findings in Zhu et al. (under review, chapter 3), we predicted that adult learners would successfully acquire all linguistic features.

Second, does perceptual salience affect morphological learning within a CSL paradigm? (RQ2) To address this question, we first explored whether the acoustic salience of grammatical morphemes significantly affects their learnability in a CSL context (RQ2a). Specifically, we examined the roles of syllabicity and sonority in CSL of morphology. Prior studies have documented that the syllable suffix is easier to learn than a single consonant (e.g., Bell et al., 2015; Strachan & Trofimovich, 2019). Consequently, we predicted that more acoustically salient morphemes would be acquired more readily than less salient forms. However, the influence of sonority difference within vowels, particularly whether strong vowels facilitate greater learning success than weak vowels, remains uncertain and is therefore an open area of investigation in this study.

Third, we further asked whether the number of distinctions impacts the CSL of non-native morphology (RQ3). Here, we predicted that the number of contrastive distinctions would influence morphological acquisition. More specifically, we anticipated that less contrastive distinctions would reduce cognitive demands, thereby being beneficial for learning.

Fourth, as an exploratory question, we asked whether nouns were easier to learn for adult learners (RQ4). According to the findings of previous studies (e.g., Zhu et al., under review, chapter 3), we expected to replicate the results of noun preference.

Methods

Participants

We recruited 117 native speakers of English. Participants received remuneration in the form of either £5 Amazon voucher or course credits from their home institution. Six participants were subsequently excluded as they did not meet the inclusion criterion of being native English speakers. Thus, the final sample consisted of 111 participants (Mean age = 24.33, SD = 9.56; 83 females, 27 males, 1 preferred not to specify). Participants were randomly assigned to one of three experimental conditions: high salience, low salience, and low salience with default group. The sample size was determined through Monte Carlo simulations, which indicated that 35 participants per group would provide sufficient statistical power (0.8) for medium-sized main effects. Further details regarding the power analysis are available in our pre-registration on our OSF project site (please follow this link).

The study was approved by the ethics review panel of the Faculty of Arts and Social Sciences at Lancaster University and conducted in accordance with the guidelines outlined by the World Medical Association Declaration of Helsinki.

Materials

Artificial Language

Vocabulary. The pseudowords and their visual referents used in this study were adapted from Zhu et al. (under review, chapter 3). The vocabulary consisted of 24 disyllabic pseudowords and five monosyllabic Portuguese pseudowords.

The 24 disyllabic pseudowords were selected to represent either noun or verb referents visually. Twelve pseudowords were randomly associated with one of 12 cartoon animal characters, the remaining 12 with actions performed by these characters. Four of these cartoon characters and actions only occurred at the end of the experiment to test generalization. Table 1 contains the pronunciation and meaning of the pseudowords.

The five monosyllabic pseudowords were used as grammatical morphemes in the study. Three of these morphemes served as tense markers (past, present, future), and two as number markers (singular, plural). To examine the effect of perceptual salience, we manipulated the sonority of the tense morphemes. As shown in Table 2, tense morphemes in the high-salience condition consisted of consonant-vowel (CV) syllables, where the vowel was a strong vowel or a diphthong (e.g., [na], [pau]). In contrast, the tense morphemes in the low-salience condition were less acoustically prominent syllables composed of a consonant and a weak vowel (schwa), such as [nə] or [pə]. We also manipulated the syllabicity of number morphemes between conditions. In the high-salience condition, number morphemes followed the same CV structure with a strong vowel or diphthong (e.g., [ti], [sai]). Conversely, in the low-salience condition, number morphemes were consonant-only forms without vowels. Table 2 contains the five monosyllabic pseudowords and illustrate the salience manipulation across conditions.

All phonemes and syllables of the artificial language were individually recorded in monotone by a female native Portuguese speaker, thus using sounds unfamiliar to the native-English-speaking participants. These audio recordings were subsequently combined into sentences in Gorilla, an online experimental platform (https://gorilla.sc).

Table 1

The 24 disyllabic pseudowords were randomly associated with nouns or verbs. Trained *pseudowords were used to train participants and to test them on retention of trained items. The* novel *pseudowords only occurred at the end of the experiment to test generalisation.*

Category	**Item type**	**Pseudowords**	
Noun	Trained	/faʊlu/ (panda)	/kitɔ/ (sheep)
		/fima/ (pig)	/lipɛ/ (rabbit)
		/fuki/ (lion)	/luʧi/ (dog)
		/jitu/ (mouse)	/ʃaki/ (cow)
	Novel	/kaupɔ/ (bear)	/miku/ (giraffe)
		/nuka/ (wolf)	/piʃɛ/ (cat)
Verb	Trained	/naɪpɔ/ (cook)	/pula/ (sleep)
		/paʧu/ (work)	/suli/ (walk)
		/paʃɔ/ (swim)	/masa/ (sing)
		/siʃɛ/ (run)	/tusi/ (paint)
	Novel	/sifa/ (laugh)	/naʊmu/ (dance)
		/luma/ (pray)	/paʧu/ (sit)

Table 2

The five monosyllabic pseudowords used as grammatical morphemes. Three of the pseudowords were used as tense markers and two as number markers. To examine the effect of perceptual salience, we manipulated the sonority of the tense morphemes and the syllabicity of number morphemes across experimental conditions.

Category		**Experimental conditions**		
		High salient	Low salient	Low salient default
Tense	Past	/na/	/nə/	/nə/
	Present	/ko/	/kə/	∅
	Future	/pau/	/pə/	/pə/
Number	Singular	/sai/	/z/	∅
	Plural	/ti/	/d/	/d/

Grammar. Nouns, verbs and grammatical morphemes were combined into simple intransitive sentences following subject-verb (SV) order. Sentence subjects consisted of nouns marked with number morphemes, and verbs were sequentially marked with both tense and number morphemes.

An example sentence from the high-salience condition is given below:

(1) /faʊluti paʧunɑti/

Faulu-ti pachu-na-ti

Panda-PL work-PAST- PL

"The pandas worked."

In total, we created 386 sentences in the artificial language. Of these, 288 sentences were used in the CSL task and 98 in the grammaticality judgment task (GJT).

Visual referents. We used the animal cartoon characters from Zhu et al. (under review, chapter 3) but created additional illustrations to test for generalisation (four new animals, four new actions, see Table 1). To indicate temporality, we used symbols: a left arrow above the animal drawings indicated past, a circle represented the present, and a right arrow the future. To indicate number, we simply displayed the same animal twice for plural and once for singular. Figure 1 provides an example of a training trial in the CSL task.

Procedure

Participants received a weblink directing them to the experiment, which was completed on the Gorilla experimental platform. After a sound check, participants provided informed consent and completed a language background questionnaire. They then completed the CSL task and the GJT. The specific sequence in which they conducted these tasks is detailed in Table 3. At the end of the experiment, participants were asked to complete a debriefing questionnaire designed to assess their awareness of the knowledge acquired during the experiment (Rebuschat, 2013). The entire experimental session lasted approximately 60 minutes.

Table 3

The research design: Participants were exposed to 386 sentences over 10 blocks. Participants first completed four CSL task blocks, followed by a GJT block, followed by another two CSL blocks and one GJT block. In these blocks, we only used trained items. After these, participants completed the generalization CSL block and GJT. In these final blocks, we used novel nouns and verbs to test generalization.

Task	1	2	3	4	5	6	7	8	9	10
CSL										
GJT										

Key

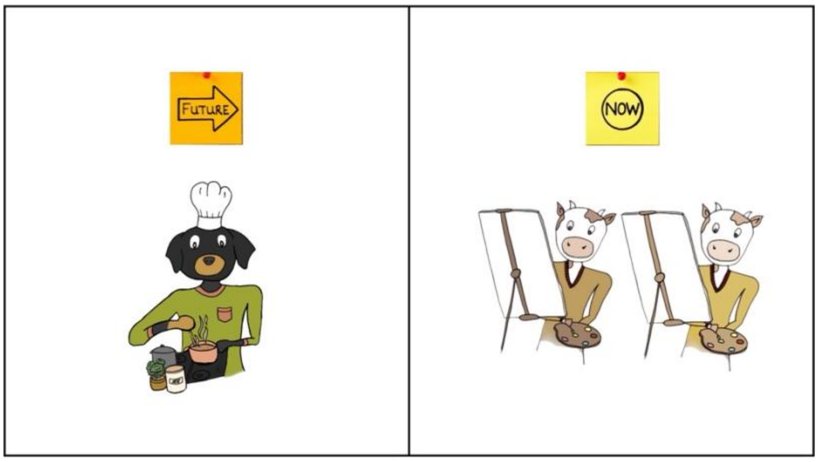
	48 CSL training trials (with trained items)
	48 CSL training trials mixed with 32 CSL test trials (with trained items)
	8 grammaticality judgment trials (with trained items)
	12 CSL generalization trials (with novel items)
	6 grammaticality judgment trials (with novel items)

Cross-situational learning task

We trained and tested participants' acquisition of the artificial language nouns, verbs and morphemes by means of a CSL task. In each CSL trial, participants first saw a fixation cross displayed for 500 milliseconds, followed by the simultaneous presentation of two static scenes, one on the left side of the screen, one on the right. One second after the scenes appeared, participants heard an artificial language sentence describing one of the two scenes. Their task was to determine, as quickly and accurately as possible, which scene the sentence corresponded to by pressing 'Q' (for the left scene) or 'P' (for the right scene) on the keyboard. The subsequent trial started after a response was provided. Participants were not informed that they were being tested. Figure 1 illustrates an example of a CSL training trial.

Figure 1

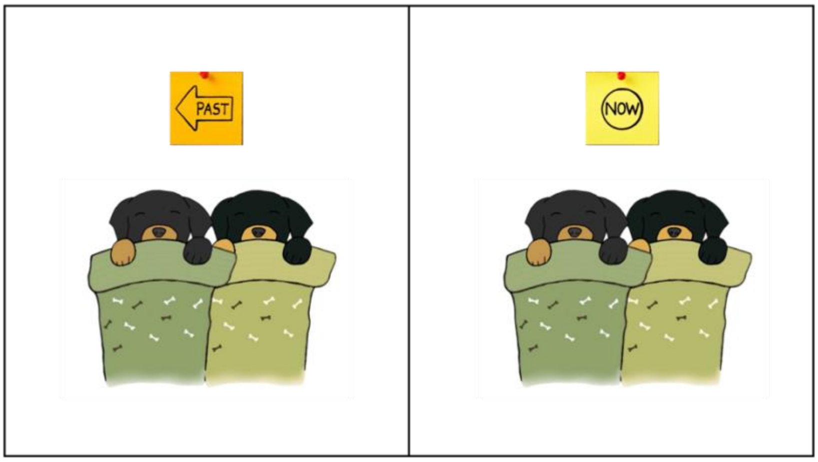
An example of a training trial in the CSL task. Participants were presented with two scenes depicting animals performing an action and played a single artificial language sentence (e.g., /lut̠ʃisaɪ naɪpəpaʊsaɪ/). *Their task was to decide, as quickly and accurately as possible, which scene the sentence referred to.*



There were three types of CSL trials: training, testing, and generalisation. In the *training* trials (Blocks 1-4, 6-7), the target and foil scenes differed in more than one aspect. For example, scenes might differ with regards to the animal characters, their number, their actions and/or the temporal cues. In contrast, in the *test* trials (Blocks 4 and 7), the two scenes differed only in one aspect. This allowed for precise measurement of participants' learning of specific linguistic features during the test trials. For example, the two scenes might show the same animal characters performing the same action but with different temporal cues. This allowed us to test the acquisition of tense. Figure 2 illustrates such a test trial. Finally, in the *generalisation* trials, the target and foil scene differed only in one aspect, just like the test trials. However, to test generalisation, participants saw novel animal characters and novel actions to determine if they had acquired the tense and number marking.

Figure 2

An example of a test trial in the CSL task. In test trials, the two scenes only differed in one aspect (e.g., temporal cue, as in the example below).



We carefully balanced the frequency of each noun, verb, and morpheme across all blocks, as well as the frequency and screen location (left or right) of target and foil scenes. Nevertheless, an unavoidable frequency imbalance existed between number and tense morphemes, given that tense included three distinctions (past, present, future), while number had only two (singular, plural). Trial sequence was randomized for each participant across blocks.

Grammaticality judgment task

We assessed participants' acquisition of subject-verb (SV) agreement by means of a GJT. Each trial consisted of the presentation of an auditory artificial language sentence without accompanying visual cues. After the sentence finished playing, participants saw a question mark on the screen and were required to press 'Q' if the sentence sounded grammatical or 'P' if it sounded ungrammatical, in relation to the artificial language. Participants were instructed to respond as quickly and accurately as possible. Half the trials were grammatical, the other half ungrammatical. In ungrammatical trials, the number morphemes attached to the noun did not agree with the ones attached to the verbs. In the regular test blocks (Block 5 and 8), we used trained nouns, verbs and morphemes. In the generalisation test block (Block 10), we use novel nouns and verbs but the trained morphemes. Trial sequence was randomized for each participant across blocks. The artificial language sentences used in this task can be accessed via our OSF site.

Statistical analysis

Logistic mixed-effects models (Jaeger, 2008) were employed to analyse our research questions. In these analyses, accuracy was modelled as a binary dependent variable.

The first mixed-effects model examined factors influencing accuracy during training trials. Starting with a null model containing random intercepts for subjects and items, as well as random slopes for block (by-subject and by-item), we incrementally added fixed effects—block, experimental condition (high-salience, low-salience, low-salience with default), and their interaction (block × condition)—to determine the best-fitting model. Additionally, we tested for a quadratic effect of block after accounting for other fixed effects, to evaluate whether learning followed a linear trajectory or showed more complex temporal dynamics.

Subsequent analyses focused specifically on morphology test trials. We explored whether performance varied across different grammatical morpheme types and was influenced by condition and the interaction between morphological test type and condition (morphology type × condition). Given potential learning effects due to increased frequency between Blocks 4 and 7, block was also included as a fixed effect. The null model for morphology test trials included random intercepts for subjects and items, random slopes by items for block, and random slopes by subjects for block, morphotesttype, and their interaction.

In the third mixed-effect model, as an exploratory analysis, we examined participants' performance on noun and verb tests separately. For this analysis, the null model included random intercepts for subjects and items, by-subject random slopes for block and noun_or_verb, and by-item random slopes for block.

The final mixed-effects model investigated whether morphology tests with novel items perform differently between conditions. The null model included random intercepts for subjects and items, random slopes by items for condition, and random slopes by subjects for test type.

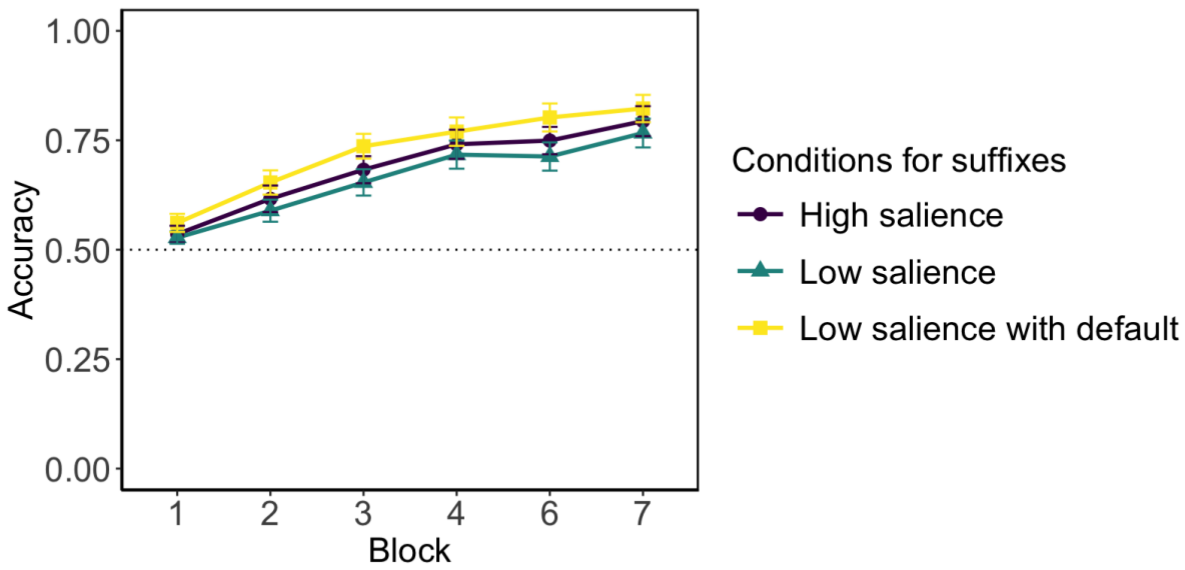
Results

Performance on the training trials

Figure 3 visualises the learning trajectory across blocks, with detailed mean accuracy data presented in Table S1.

Figure 3

Mean accuracy across training trials of the CSL task. Error bars indicate 95% confidence intervals. The dotted horizontal line (0.5) represents chance-level performance.



We used a mixed-effects model to investigate predictors influencing accuracy during training trials, addressing our first research question regarding whether adult learners can utilise cross-situational statistics to acquire novel morphology.

Compared to a baseline model containing only random effects, including the fixed effect of Block significantly improved the model fit, $\chi^2(1) = 83.82$, $p < .001$. However, neither the addition of Condition, $\chi^2(2) = 1.76$, $p = .415$, nor the Block-by-Condition interaction, $\chi^2(2) = 3.25$, $p = .197$, significantly enhanced the model, and both were thus excluded. Additionally, testing a quadratic effect for Block revealed no significant improvement, $\chi^2(1) = .021$, $p = .884$, and it was also omitted. The final, best-fitting model for training accuracy is detailed in Table 4.

Table 4

The best fitting model for participants' accuracy in the training trials of the CSL task.

	training_accuracy				
Predictors	*Odds Ratios*	*std. Error*	*CI*	*Statistic*	*p*
(Intercept)	0.79	0.05	0.70 – 0.89	-4.00	**<0.001**
block	1.50	0.06	1.40 – 1.62	10.96	**<0.001**

Number of observations: 30372, Participants: 111, Item: 581, AIC = 32416.7, BIC = 32483.2, log-likelihood = -16200.3.

R syntax: glmer(training_accuracy ~ block + (1 + block | item) + (1 + block | ppt), data=overall_training_dataset_renamed, family = binomial, control=glmerControl (optCtrl = list(maxfun = 50000), optimizer = "nloptwrap", calc.derivs = FALSE))

This model revealed a significant main effect of Block, logit estimate = .408, SE = .037, $p < .001$, indicating progressive learning over the six blocks. These findings tend to suggest that adult learners can learn a novel language by tracking cross-situational statistics (RQ1). However, the insignificant effects from Condition and the Block-by-Condition interaction provide no evidence that the perceptual salience of morphological cues affected overall CSL of the novel language.

Performance on the test trials

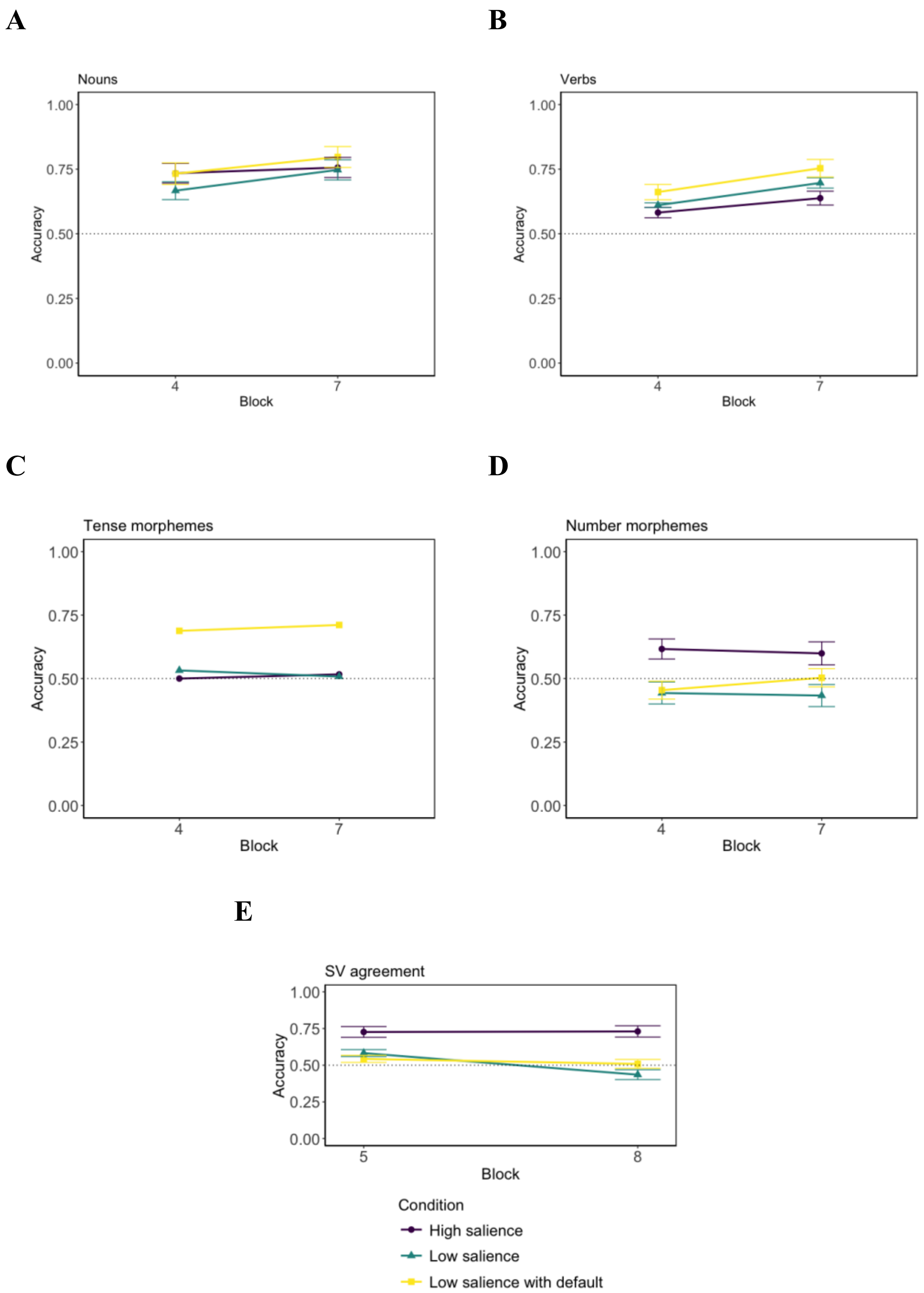
Although training trial accuracy reflects general language acquisition through CSL, it does not specify which linguistic features were learned. To address this, we first analysed participants' performance on the test trials of the CSL task (Blocks 4 and 7) and of the grammaticality judgment task (Block 5 and 8). To test for generalisation, we subsequently analysed the performance on the generalisation trials of the CSL task (Block 9, with novel items) and of the GJT (Block 10, with novel items).

Test trials with trained items

Figures 4a–4d depict the accuracy of participants in the test trials of the CSL task (Blocks 4 and 7), across the different parts of speech (nouns, verbs, number and tense morphemes). Figure 4e depicts the accuracy on the GJT (Blocks 5 and 8), which allowed us to test SV agreement. The detailed data is provided in Tables S2–S3. One-sample t-tests were conducted to examine whether accuracies for each linguistic feature exceeded chance-level performance; detailed outcomes by condition are reported in Tables S4–S6. The results indicate that morphological features can be learned via CSL but only under certain circumstances, contributing to answering RQ1.

Figure 4

Mean accuracy across test trials of the CSL task (Blocks 4 and 7, Figures 4a to 4d) and of the GJTs (Blocks 5 and 8, Figure 4e). Error bars represent 95% confidence intervals, with the dotted line (0.5) indicating chance performance.



To further evaluate how acoustic salience and number of distinctions affected different morphological features (RQ2), we fitted a mixed-effects model predicting accuracy in morphological tests. We found that adding Block did not significantly improve the model ($\chi^2(1) = .269$, $p = .604$) and thus it was excluded as a fixed effect. The inclusion of morphology type alone was also not significant ($\chi^2(2) = 4.60$, p = .100). However, the inclusion of Condition ($\chi^2(2) = 14.67$, p < .001), and the morphology-type-by-Condition interaction ($\chi^2(6) = 33.66$, p < .001), significantly improved the model, which indicates morphology learning was influenced by perceptual salience of grammatical morphemes, addressing research question 2. The best-fitting model is summarised in Table 5.

Table 5

Best fitting model for testing the effect of time, morphology test type, and condition on participants' accuracy in the morphology test trials of the CSL task (with low salience condition and number morphemes tests in the intercept).

	Test Accuracy				
Predictors	*Odds Ratios*	*std. Error*	*CI*	*Statistic*	*p*
(Intercept)	0.69	0.15	0.46 – 1.05	-1.73	0.084
Condition [Low salience with default]	1.24	0.34	0.73 – 2.12	0.80	0.424
Condition [High salience]	2.52	0.78	1.38 – 4.63	2.99	**0.003**
Condition [Low salience] × morphotesttypeSV agreement tests	1.33	0.35	0.79 – 2.23	1.08	0.279
Condition [Low salience with default] × morphotesttypeSV agreement tests	1.16	0.31	0.69 – 1.95	0.56	0.577

Condition [High salience] × morphotesttypeSV agreement tests	1.78	0.51	1.02 – 3.12	2.02	**0.043**
Condition [Low salience] × morphotesttypeTense morphemes tests	1.65	0.45	0.96 – 2.82	1.82	0.069
Condition [Low salience with default] × morphotesttypeTense morphemes tests	3.28	0.92	1.89 – 5.69	4.23	**<0.001**
Condition [High salience] × morphotesttypeTense morphemes tests	0.60	0.18	0.34 – 1.07	-1.72	0.085

Number of observations: 5130, Participants: 111, Item: 126, AIC = 6511.3, BIC = 6611.0, log-likelihood = -3239.6.

R syntax: test_accuracy ~ Condition + morphotesttype:Condition + (1 | item) + (1 + morphotesttype | ppt), data= morphotest, family = binomial, control=glmerControl (optCtrl = list(maxfun = 50000), optimizer = "nloptwrap", calc.derivs = FALSE))

In order to unpack the interaction, we found that there was significantly higher performance in number morpheme tests within the high-salience group compared to the low-salience group (logit estimate = .926, SE = .310, p = .003), while no significant difference was found between the low-salience and low-salience-with-default conditions (logit estimate = .218, SE = .272, p = .424). Re-levelling the model to use tense morphemes as the reference category showed significantly better tense morpheme learning in the low-salience-with-default group compared to the low-salience group (logit estimate = .906, SE = .242, $p < .001$), but no difference between high-salience and low-salience groups (logit estimate = -.080, SE = .297, $p = .788$). Additionally, performance in SV agreement was significantly higher in the high-salience condition compared to low-salience (logit estimate = 1.218, SE = .281, $p < .001$), with no significant difference between low-salience and low salience with default conditions (logit estimate = .080, SE = .240, $p = .738$).

We also further analysed whether there is a difference between singular and plural cues or between past, present or future tenses within different conditions (See Figure S1 and Figure S2, Table S7 and Table S8). No significant difference was found within number or within tense, indicating the perceptual salience we identified was an overall effect instead of just singular or plural, or either past, present, or future tense being learned significantly better.

Additionally, we explored performance differences between nouns and verbs using a mixed-effects model (RQ3). We found that including Block ($\chi^2(1) = 10.041$, $p = .002$) was significant. Also, including noun_or_verb ($\chi^2(1) = 22.834$, $p < .001$) was significant, with noun tests consistently yielding higher accuracy than verb tests. The best-fitting model is shown in Table 6.

Table 6

Best fitting model for testing the effect of time, content word test type, and condition on participants' accuracy in the nouns and verbs test trials of the CSL task.

	Test Accuracy				
Predictors	*Odds Ratios*	*std. Error*	*CI*	*Statistic*	*p*
(Intercept)	1.56	0.47	0.86 – 2.83	1.47	0.142

block	1.24	0.07	1.11 – 1.39	3.87	**<0.001**
noun or verb [Verbs]	0.46	0.07	0.33 – 0.62	-4.99	**<0.001**

Number of observations: 3354, Participants: 111, Item: 82, AIC = 3793.7, BIC = 3867.1, log-likelihood = -1884.8.

R syntax: test_accuracy ~ block + noun_or_verb + (1 + block | item) + (1 + noun_or_verb + block | ppt), data= nounverb, family = binomial, control=glmerControl (optCtrl = list(maxfun = 50000), optimizer = "nloptwrap", calc.derivs = FALSE))

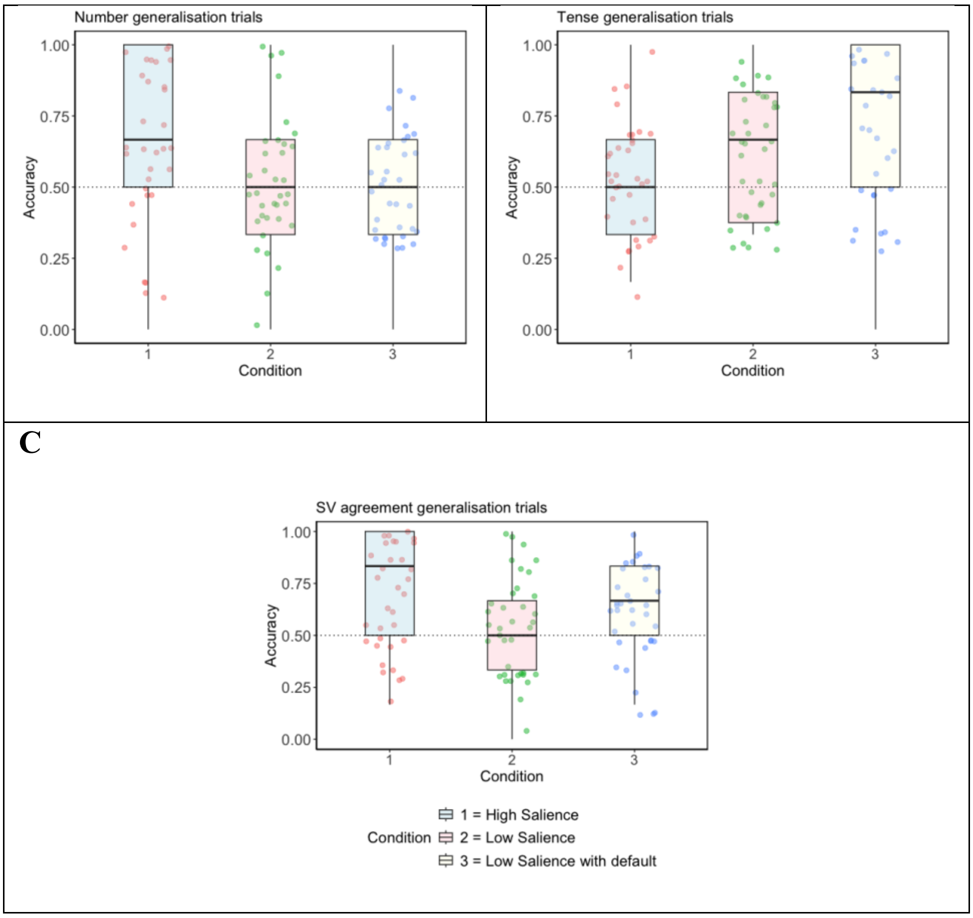
Test trials with novel items

We analysed results from generalisation trials (Blocks 9 and 10) to determine whether participants were able to apply the morphological patterns and SV agreement to novel, untrained lexical items (RQ1). Figure 5 displays generalisation task performance across conditions.

Figure 5

Mean accuracy across generalisation trials of the CSL task (Block 9, Figures 5a and 5b) and of the GJT (Block 10, Figure 5c). Error bars represent 95% confidence intervals, with the dotted line (0.5) indicating chance performance.

A	**B**



To investigate whether morphology tests with novel items perform differently between conditions. We found that adding condition ($\chi2(2) = 3.967$, $p = .138$) and test type ($\chi2(2) = 2.254$, $p = .324$) did not significantly improve the model fit, adding Condition*test type significantly improved the model fit ($\chi2(4) = 14.709$, $p = .005$). The best-fitting model can be found in Table 7.

Table 7

Best fitting model for testing the effect of condition, and test type on participants' accuracy in the morphology test trials with novel items.

	Correct				
Predictors	*Odds Ratios*	*std. Error*	*CI*	*Statistic*	*p*

(Intercept)	2.26	0.54	1.41 – 3.61	3.40	**0.001**
Condition [Low salience]	0.46	0.14	0.25 – 0.84	-2.50	**0.012**
Condition [Low salience with default]	0.46	0.16	0.23 – 0.93	-2.17	**0.030**
testtype [generalisation tense test]	0.57	0.16	0.32 – 1.00	-1.98	**0.048**
testtype [SV agreement]	1.28	0.37	0.72 – 2.27	0.84	0.399
Condition [Low salience] × testtype [generalisation tense test]	2.84	1.05	1.38 – 5.84	2.83	**0.005**
Condition [Low salience with default] × testtype [generalisation tense test]	4.85	2.14	2.04 – 11.50	3.58	**<0.001**
Condition [Low salience] × testtype [SV agreement]	0.83	0.31	0.40 – 1.72	-0.49	0.621
Condition [Low salience with default] × testtype [SV agreement]	1.27	0.56	0.53 – 3.00	0.54	0.592

Number of observations: 1998, Participants: 111, Item: 51, AIC = 2605.8, BIC = 2723.4, log-likelihood = -1281.9.

R syntax: Correct ~ Condition*testtype + (1 +Condition| item) + (1 + testtype | ppt), data=overall_gentest_dataset, family = binomial, control=glmerControl (optCtrl = list(maxfun = 50000), optimizer = "nloptwrap", calc.derivs = FALSE))

In the test trials with novel items, we found that in the number test, participants in the high-salience condition performed significantly better than the low-salience (logit estimate = -.785, SE = .314, p = .012) and low-salience with default conditions (logit estimate = -.773, SE = .356, p = .030). In the tense test, we found no significant differences between high salience and low salience conditions (logit estimate = .259, SE = .287, p = .367). We found that low salience with default condition was significantly better than high salience condition (logit estimate = .806, SE = .338, p = .017). The difference between low salience and low salience with default conditions was only marginally significant (logit estimate = .806, SE = .338, p = .017). In SV agreement test, we found that participants in high-salience condition performed significantly better than those in low-salience condition (logit estimate = -.904, SE = .306, p = .003). However, the difference between high-salience and low-salience with default conditions was not significant (logit estimate = -.501, SE = .349, p = .151). No significant difference was found between low salience and low salience with default conditions (logit estimate = .432, SE = .311, p = .164).

Overall, results in the test trials with novel items indicated that number morphemes in the high salience condition /sai/ /ti/, tense morphemes in the low salience /nə/ /kə/ /pə/ and low salience with default condition /nə/ Ø /pə/ were learned from strings of sentences with trained items, and seemed to have been further processed.

Discussion

In this study, we investigated the effect of perceptual salience, specifically acoustic salience of the grammatical cues, on the acquisition of non-native morphology in a CSL environment. In our CSL task, participants were repeatedly presented with auditory sentences in a novel artificial language, accompanied by visual referents, without receiving any explicit instruction or feedback. This task simulated the type of referential ambiguity encountered by learners acquiring a language naturally. We manipulated the acoustic salience of the grammatical morphemes in the artificial language participants heard, comparing learning outcomes between an acoustically high-salience and low-salience group. Furthermore, we explored whether the number of distinctions influences the morphology learning, by comparing the performance between participants in the low-salience group (tense markers have 3 distinctions, number markers have 2 distinctions) and those in the low-salience with default group (tense markers have 2 distinctions and number markers have 1 distinction).

While most previous CSL studies have predominantly focused on the acquisition of isolated words (e.g., Ge et al., 2025; Monaghan et al., 2015; Suanda & Namy, 2012; Vlach & DeBrock, 2019), the current study extended to explore whether cross-situational statistical information can support more complex sentence-to-scene mappings. We found that adult learners can track more complex, sentence-based cross-situational statistics to rapidly learn a non-native language. Specifically, accuracy in the training trials across the three groups was above-chance level starting from the first training block and steadily increased over the six blocks. The observed effectiveness of CSL statistics in promoting learning is consistent with findings reported in prior sentence-driven CSL studies (Rebuschat et al., 2021; Zhu et al., under review, chapter 3).

The first research question explored whether adult learners can use cross-situational statistics to acquire both lexical and morphological features. Examining performance on test trials further revealed that while nouns and verbs were reliably learned across all conditions, the acquisition of grammatical morphology, however, varied both across experimental groups and among different morpheme types. This will be further discussed below.

Participants in the high-salience group demonstrated above-chance performance in tests for number morphemes and SV agreement but not in the other two conditions, which implies that morphological features can be learned in a high-salience syllable (CV) form but not when it is in a consonant-only form that is of low salience. However, the learning of tense morphemes in the high salience condition was only at a chance level, even though they were in CV form. This finding contrasts with earlier results from Zhu et al. (under review, chapter 3). This discrepancy may be attributable to differences in the duration of the tense morphemes used across the two studies. In the current study, the duration of the tense morphemes was shorter than that utilised in Zhu et al. (under review, chapter 3), and they are also shorter than the number morphemes in the current study, which is an unintentional limitation of this study. Overall, our results tend to suggest that morphological features can be learned when it is salient and have a long duration.

We further investigated whether learners generalise morphological knowledge acquired via CSL. In the generalisation task, we found evidence suggesting that learners engaged in deeper processing of cross-situational statistics, meaning they may have successfully formed the associations between morphological forms and their meanings and acquired syntactic knowledge as SV agreement was learned, especially when the grammatical morphemes were acoustically salient. Specifically, we found that number morphemes in the high-salience condition were successfully acquired in both non-generalisation and generalisation CSL tasks. Similarly, participants demonstrated further processing of SV agreement in the high-salience group and tense morphemes in the low-salience with default group during the generalisation tasks. Our results thus contradict earlier findings that adult learners typically do not generalise from distributional statistics (Newport, 2019). However, this discrepancy could be due to the relatively limited number of generalisation trials used in our study (18 generalisation items). This limitation might also account for unexpected findings, such as the successful generalisation of tense morphemes in the low-salience condition and SV agreement in the low-salience with default condition, despite these morphemes not being learned reliably in the non-generalisation tasks.

The role of perceptual salience in morphological learning

Our second research question investigated whether perceptual salience impacts the CSL of morphological cues. To examine this, we manipulated the sonority and syllabicity of grammatical morphemes within our artificial language. Results showed significantly better learning of number morphemes in the high-salience group (/sai/, /ti/) compared to the low-salience group (/z/, /d/), indicating a clear effect of syllabicity on the CSL of morphology. This finding aligns with earlier studies examining English past tense acquisition, which reported that the low acoustic salience of certain forms ([t], [d]) presents significant challenges for non-native langauge learners (Bell et al., 2015; Strachan & Trofimovich, 2019). The substantial difference in the acquisition of number morphemes between high- and low-salience groups indicates the effect of salience and thus provides empirical support for the usage-based explanation regarding morphological learning difficulties (DeKeyser, 2005; Ellis, 2022). Furthermore, this suggests that perceptual salience—specifically syllabicity—may constrain learners' non-native morphological acquisition in contexts.

Additionally, our study explored whether there would be significant differences in morphological learning between morphemes ending in a strong vowel versus those ending in a weak vowel. Although strong vowels are acoustically more sonorous than weak vowels, the salience contrast between vowels (e.g., /na/ versus /nə/) was smaller than the contrast provided by syllabicity differences (e.g., /sai/ versus /z/). Consequently, we found no significant difference between tense morpheme acquisition in the high-salience condition (strong vowel) and the low-salience condition (weak vowel), suggesting that this level of salience contrast (strong vs. weak vowels) may not strongly influence morphological learning in a CSL context. However, the potential confounding influence of morpheme duration cannot be dismissed, as the tense morphemes in both conditions were relatively brief. The unlearning of tense morphemes under both high and low salience conditions may have resulted from an unintended influence of syllable duration, which could have masked the effect of vowel sonority.

The influence of the number of distinctions on morphological learning

As an exploratory question, we investigated whether the number of distinctions influences the CSL of morphology. In our study, we found no significant effect of the number of distinctions on participants' acquisition of number morphemes or SV agreement. However, we observed its effect on the learning of tense morphemes, with participants in the low-salience group with default forms showing significantly better acquisition of tense morphemes compared to those in the low-salience group without defaults. Our findings gave implications that having a default form potentially eases the memory demand; however, it might have only been effective when the cognitive command is highly contrasted, like three CV distinctions vs two CV distinctions.

Finally, in another exploratory question, we explored whether nouns were easier to learn for adult learners. We found that nouns were learned significantly better than verbs, which is consistent with previous findings on noun preference (Monaghan et al., 2015; Zhu et al., under review, chapter 3).

Conclusion

Our study explored the interplay between morphology and phonology within a cross-situational statistical learning environment that provided both auditory and visual information necessary for language learning. Our study replicated the results in Zhu et al. (under review, chapter 3) that adult learners still possess the ability to learn a language based on statistics. We identified a significant effect of perceptual salience on the CSL of morphology but not on the overall language acquisition. The observed importance of perceptual salience underscores the importance of extra training for morphological cues with low acoustic saliency. Our study contributes empirical evidence to the usage-based perspective on morphological learning difficulties by showing how salience affects morphology learning in a simulated natural language environment (DeKeyser, 2005; Ellis, 2022).

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Supplementary Materials

Table S1

Performance in each salience group across 6 blocks – training trials only

Group		Blocks					
		1	2	3	4	6	7
High salience	M	.54	.62	.68	.74	.75	.79
	SD	.12	.18	.19	.20	.19	.21
Low salience	M	.53	.59	.65	.72	.71	.77
	SD	.09	.16	.19	.20	.20	.20
Low salience with default	M	.56	.65	.74	.77	.80	.82
	SD	.12	.17	.17	.19	.19	.19

Table S2

These are the results of CSL test trials

Group	Test types		Blocks	
			4	7
High salience	Nouns	M	.73	.76
		SD	.23	.24
	Verbs	M	.58	.64
		SD	.12	.16
	Number morphemes	M	.62	.60
		SD	.24	.28
	Tense morphemes	M	.50	.52
		SD	.20	.24
Low salience	Nouns	M	.67	.75
		SD	.21	.24
	Verbs	M	.61	.70
		SD	.05	.12
	Number morphemes	M	.44	.43
		SD	.27	.27
	Tense morphemes	M	.53	.51
		SD	.19	.18

Low salience with default	Nouns	M	.73	.80
		SD	.25	.24
	Verbs	M	.66	.75
		SD	.18	.20
	Number morphemes	M	.45	.50
		SD	.21	.22
	Tense morphemes	M	.69	.71
		SD	.24	.27

Table S3

These are the results of the GJT

		Test	
		1	2
High salience	M	.73	.73
	SD	.22	.23
Low salience	M	.58	.44
	SD	.15	.21
Low salience with default	M	.54	.51
	SD	.15	.18

Note. Asterisks indicate performance below chance, * p < .05, ** p < .001.

Table S4

One-sample t-tests and Cohen's d for performance against chance level (0.5) for each test type, at each test block in the high salience group.

Block	Test Type	t(35)	Cohen's d	p-value
Block 4	Nouns	5.68	.93	< .001
	Verbs	2.60	.43	< .001
	Number Morphemes	2.95	.48	.010
	Tense Morphemes	0.00	0.00	1.00
Block 5	SV Agreement	6.14	1.01	< .001
Block 6	Nouns	6.56	1.08	< .001
	Verbs	3.87	.64	< .001
	Number Morphemes	2.18	.36	.040
	Tense Morphemes	.42	.07	.680
Block 7	SV Agreement	6.02	.99	< .001

Table S5

One-sample t-tests and Cohen's d for performance against chance level (0.5) for each test type, at each test block in the low salience group.

Block	Test Type	t(35)	Cohen's d	p-value
Block 4	Nouns	3.90	.63	.010
	Verbs	4.12	.67	.046
	Number Morphemes	-1.31	.21	.198
	Tense Morphemes	1.04	.17	.31
Block 5	SV Agreement	3.51	.57	.001
Block 6	Nouns	5.70	.93	< .001
	Verbs	6.33	1.03	< .001
	Number Morphemes	-1.54	.25	.132
	Tense Morphemes	.27	.04	.790
Block 7	SV Agreement	-1.91	.31	.064

Table S6

One-sample t-tests and Cohen's d for performance against chance level (0.5) for each test type, at each test block in the low salience with default group.

Block	Test Type	t(35)	Cohen's d	p-value
Block 4	Nouns	5.93	.99	< .001
	Verbs	4.50	.75	< .001
	Number Morphemes	-1.29	.22	.204

	Tense Morphemes	4.78	.80	<.001
Block 5	SV Agreement	1.78	.30	.083
Block 6	Nouns	7.70	1.28	< .001
	Verbs	7.44	1.24	< .001
	Number Morphemes	.09	.01	.931
	Tense Morphemes	4.70	.78	<.001
Block 7	SV Agreement	.28	.05	.780

Table S7

These are the results of tense test trials

Group	Test types		Blocks	
			4	7
High salience	Past	M	.54	.55
		SD	.36	.30
	Present	M	.46	.50
		SD	.32	.35
	Future	M	.51	.49
		SD	.29	.41

Low salience	Past	M	.53	.60
		SD	.34	.29
	Present	M	.61	.48
		SD	.29	.28
	Future	M	.46	.43
		SD	.32	.35
Low salience with default	Past	M	.69	.73
		SD	.46	.32
	Present	M	.74	.73
		SD	.39	.36
	Future	M	.63	.66
		SD	.50	.38

Figure S1

These are the results of tense test trials

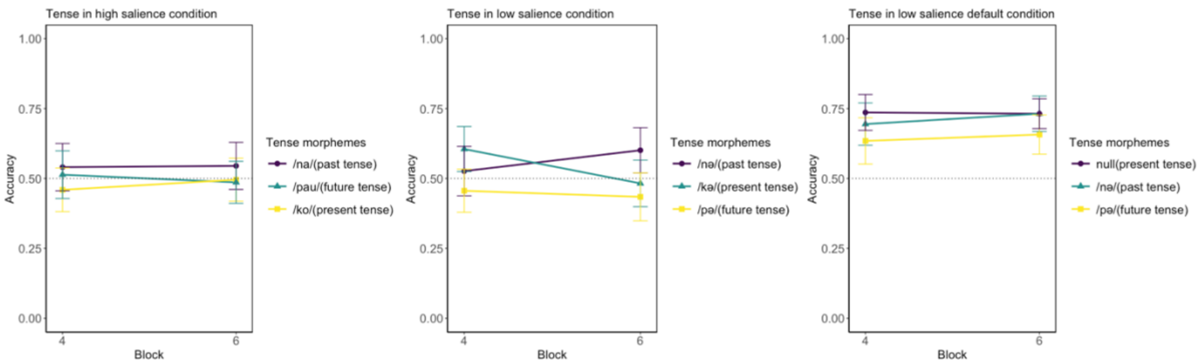


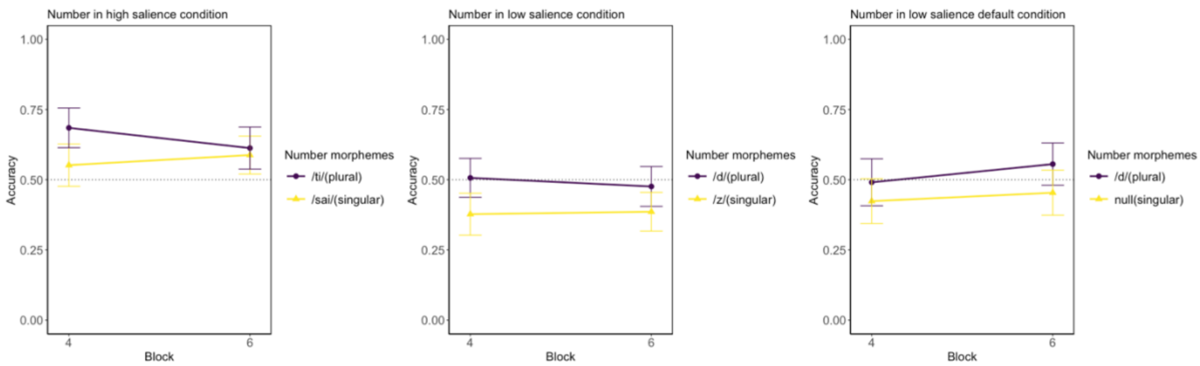
Table S8

These are the results of number test trials

Group	Test types		Blocks	
			4	7
High salience	Singular	M	.55	.59
		SD	.32	.36
	Plural	M	.68	.61
		SD	.29	.31
Low salience	Singular	M	.38	.39
		SD	.30	.33
	Plural	M	.51	.48
		SD	.35	.34
Low salience with default	Singular	M	.42	.45
		SD	.28	.28
	Plural	M	.49	.56
		SD	.27	.32

Figure S2

These are the results of number test trials



6. General discussion

6.1 Summary of key findings

This dissertation investigated the learnability of morphological features through CSL, which enabled the investigation of learners' ability to learn a novel language by constantly solving the ambiguity in the statistical world, without any explicit instruction or feedback. Across three experimental studies, I demonstrated that inflectional morphology, specifically number, tense, and SV agreement, can be successfully acquired within a sentence-based CSL paradigm. In addition to establishing the adults' statistical learning ability in the CSL paradigm, this thesis examined key factors that have been proposed to influence the learnability of morphology.

DeKeyser (2005) identified five factors that may individually or collectively influence the learnability of morphological structures: properties of non-native languages, L1 transfer effects, age-related factors, individual learner differences, and learning contexts (e.g., immersion in a native-speaking environment versus classroom instruction). In previous comprehensive review articles, three specific characteristics of morphology were consistently identified as contributing to its learning difficulty: low acoustic salience, which hinders form recognition; low transparency or contingency in form-meaning mappings (e.g., the English morpheme "-s" can indicate plurality or possession); and redundancy in morphological cues, where some cues are more easily acquired than others despite serving overlapping semantic or functional roles (DeKeyser, 2005; Ellis, 2022). Among the proposed factors, the effect of redundancy on morphology acquisition was largely empirically studied (e.g., Ellis, 2007; Ellis & Sagarra, 2010a; Ellis & Sagarra, 2010b; Ellis & Sagarra, 2011), while the effect of acoustic salience as well as the transparency was less investigated. Over three studies, I explored the impact of L1 morphological complexity, cue redundancy, and perceptual salience, each of which was shown to modulate learning outcomes in the CSL context. The table below demonstrates that the structure of the thesis is concluded by three studies, which overall fit together to investigate the learnability of morphology, from the aspect of L1 transfer (L1 morphological complexity), properties of L2 (redundancy and perceptual salience).

Table 1. The structure of the thesis.

Factors that shape the learnability of morphology	Tested
L1 morphological complexity	Study 1
Redundancy effect	Study 2
Perceptual salience	Study 3

In the following sections, I will first review the key results from each of the studies before considering in more detail the main themes that each study addresses.

In Study 1, I investigated how L1 morphological complexity influences the learning of non-native morphology in this context. Adopting the paradigm used in Rebuschat et al. (2021), in each CSL trial, participants heard a sentence while viewing two visual scenes (one correct, one foil), and were asked to select the visual scene that matched the sentence they heard. To explore the effect of L1 morphological complexity on non-native morphology learning, native speakers of Mandarin, English and German were recruited, ranging from morphologically poor to rich languages. Mandarin does not have inflectional morphology, which is in contrast with English and German inflectionally mark number and tense. However, German is morphologically richer language than English. In each trial, participants heard a two-word intransitive sentence containing a noun, a verb, and inflectional morphemes marking number, tense, and SV agreement (double marked). We then investigate the theories of whether non-native morphology acquisition was influenced by L1 morphology complexity as a whole, or whether feature-by-feature transfer.

Learners' language learning backgrounds were found to be influential in non-native morphology acquisition, however, this was in a surprising way. Results showed that morphologically rich L1 does not necessarily predict more successful learning in non-native morphology learning, as L1 Mandarin and German speakers outperformed L1 English speakers, especially in acquiring number and tense morphology. Post hoc analyses confirmed that both groups scored significantly higher than the English group on these features. For SV agreement, the Mandarin group outperformed the German group, while the English group did not differ significantly from either. The lower learning in the L1 English group could be attributed to the second language learning backgrounds as most of the recruited L1 English speakers were reported to be monolingual or low proficiency in an additional language, while most participants in the other two groups reported to have acquired an additional language with high proficiency.

Study 2 continues to examine the effect of redundancy. Based on findings from associative learning studies, the two cues associated with the same meaning/function would compete for attention. Two learning mechanisms towards this have been proposed: one is *blocking*, which emphasises the effect of learning sequence that the prior learned cue would block the learning of the other cue; another one is *overshadowing*, which emphasises that the effect of innate salience difference of the two cues, with the more salience cue overshadowing the learning of the other cue (Kamin, 1967). In natural languages, the meaning/functions for morphological markers and lexical or phrasal markers can often be redundant. For example, tense could be expressed in both morphological form at the end of a verb (e.g.,"-ed") or in adverbial form ("yesterday"). The number could also be expressed in either morphological form (e.g., "-s") or lexical form (e.g., "many"). This is similar to how two cues are associated with the same outcome in associative learning studies. Ellis (2007) tested the blocking mechanisms in the language learning context and found that the prior learning of verbs (ending with tense morphemes) could block the subsequent learning of temporal adverbs. The same effect was found the other way around, but with more of an effect, as temporal adverbs are more salient than tense morphemes. However, natural language learning is more related to the *overshadowing* effect as the learning was more incidental rather than sequential, and morphological and its corresponding lexical forms that encode the same meaning usually differ in their inherent acoustic salience. Study 2 addressed this gap of investigating the *overshadowing* in language learning context, specifically I examine how the presence of redundancy, such as temporal adverbs (e.g., “yesterday”) and morphological tense markers (e.g., “-ed”), affects language learning in CSL, without any pre-training of the verbs or adverbs. Moreover, while previous studies exposed participants to consistent availability of both tense morphemes and temporal adverbs (Ellis, 2007; Ellis & Sagarra, 2010a; Ellis & Sagarra, 2010b; Ellis & Sagarra, 2011). Yet, morphological and lexical cues usually occur variably rather than consistently in the natural language environment. Therefore, the consistent and variable availability of morphological and lexical cues becomes the between-group manipulation in study 2.

Results showed that consistent cue availability facilitates CSL, as participants in the consistent condition (where adverbial and morphological cues always co-occurred) outperformed those in the variable condition (where cues appeared inconsistently). Adverbial cues were acquired more successfully than morphological tense cues in both conditions, which tentatively supports the associative learning theory that the more salient cues might overshadow the learning of the less salient ones. To further evaluate the effect of overshadowing, study 2 compared the learning of the tense and number morphemes. Unlike tense, number morphemes had no competing lexical cues and were of the same saliency as tense cues – both were in CV (consonant + vowel) form. Results showed that number morphemes were acquired more successfully than tense morphemes across both conditions, reinforcing the interpretation that cue competition, rather than salience alone, was responsible for the lower learning of tense morphemes. This result highlighted the effect of the perceptual salience of inflectional morphology theory (Ellis, 2022).

Interestingly, results also showed that the overshadowing effect was not influenced by the availability of the two redundant cues, although the consistent condition supported higher overall accuracy. This suggests that while consistent co-occurrence enhances general learning, it does not fully overcome learners' attentional bias toward more salient cues (modulated by the number of syllables). Note that besides the number of syllables, salience is also influenced by many other aspects, such as the primacy effects, relating to the position in the sentence, and the recency effect (how recently you have encountered it), or the order effect (Gass et al., 2018). How salience of a morpheme is perceived can also differ between learners with different L1s (Ellis & Sagarra, 2011).

Overall, the findings from study 2 demonstrate that morphological learning in CSL is shaped by the cue competition and input distribution. When a salient lexical cue overlaps functionally/semantically with a less salient morphological cue, it can interfere with the acquisition of the latter, posing a challenge for learners in naturalistic learning environments where such redundancy is common.

Study 2 established that two cues to tense resulted in the most salient being relied on more. In study 3, we investigated whether the salience of the morphological cue alone affected learning. This enabled us to determine whether the morphological training is necessary outside of controlling the input of distribution of the redundant cues. Study 3 had two aims: one was to investigate how perceptual salience (e.g., syllabicity, sonority) influences the acquisition of grammatical morphemes in CSL. For this, we manipulated the perceptual salience of the morphemes in terms of syllabicity in number morphemes and sonority in tense morphemes between high salient and low salient groups. Another goal of study 3 was to explore whether the number of distinctions of morphological cues (e.g., there are three distinctions for tense: past, present, future) would affect non-native morphology learning. We therefore included another condition where the present tense and singular cues were set as default.

We found that while overall language learning did not differ significantly between groups, salience and default marking had clear effects on specific grammatical features. Participants in the high-salience condition outperformed those in the low-salience group on number morphemes and SV agreement. Tense morphology, however, was not reliably learned by any group. Results in the generalisation task further found that the presence of a default form facilitated acquisition.

In sum, study 3 provides further evidence that salience and cue distinctiveness play a crucial role in shaping both the acquisition and generalisation of grammatical features in CSL.

Across studies 1 and 2, we found explicit awareness of morphological patterns was closely linked to learning success. Participants who reported noticing or identifying morphological rules, even partially, achieved significantly higher accuracy across morphological features. This effect highlights the important role of awareness in supporting language learning, even in an implicit learning context. Additionally, a consistent pattern was found across three studies that nouns were acquired more successfully than verbs, regardless of conditions. This supports the well-established noun bias in both L1 and non-native language acquisition (Childers & Tomasello, 2002; Monaghan et al., 2015), likely due to the higher concreteness, imageability, and referential stability of nouns compared to verbs.

Moreover, a common question we investigate over three studies is whether morphological features can be learned in the CSL paradigm. While previous studies tend to use known word stems or train substantially on the word stems before introducing the morphology, results over our three studies showed that morphological features (number markers, tense markers, SV agreement) were found to be learnable without any explicit instruction or corrective feedback. This is a major achievement, which implies that morphological features can be learned simultaneously with lexical items by adult learners.

Overall, study 1 demonstrated robust morphological learning across participants with L1 that vary in morphological complexity, ranging from morphologically poor (Mandarin), to impoverished (English), to rich (German). Motivated by these findings, the subsequent studies aimed to identify factors influencing this robustness in morphological acquisition. In study 2, I examined the role of redundancy and found that morphological learning remained strong when the two cues encoding the same meaning were consistently available. However, the presence of a more salient, redundant lexical cue tended to overshadow the learning of the corresponding morphological cue. Importantly, the consistent co-occurrence of both cues facilitated learning. Building on this, study 3 investigated whether the robustness observed in the previous studies could be attributed to the high perceptual salience of the morphological cues, specifically those in CV form. The results indicated that while perceptual salience did modulate the learning of individual morphological cues, it did not significantly impact overall language learning. The following sections will first discuss the robust learning found across three studies, before elaborating on each of these studies in greater detail.

6.2 Statistical learning of non-native morphology

The overarching goal of this thesis was to examine whether adult learners can acquire grammatical morphology through exposure to cross-situational statistics. Across three studies, the results provide strong support for the view that adults can learn not only the lexical items but also the abstract grammatical morphology based on cross-situational statistics, without any instructions or feedback. These findings align with the predictions of usage-based and emergentist models (Ellis, 2002; 2006; 2022), which posit that linguistic knowledge emerges from learners' sensitivity to distributional patterns in the input. While prior CSL research has established that adults can acquire word-referent mappings by tracking co-occurrence across trials (Yu & Smith, 2007), the current studies extend this learning capacity to morphosyntactic domains.

Importantly, the nature of the morphological features themselves shaped learning outcomes in ways that reflect broader processing constraints in adult SLA. Inflectional number was consistently the most successfully acquired feature. Its relatively transparent mapping to visual referents (e.g., singular vs. plural agents) and consistent form-meaning contingency likely supported this success. This is consistent with Ellis's (2022) emphasis on cue contingency and transparency as central to learnability. In contrast, Inflectional tense proved more difficult to acquire, particularly when it was redundant with a more salient temporal adverb. This difficulty echoes Ellis and Sagarra's (2010a, 2010b) findings on blocking effects, where learners focus on the most salient cue in the input, often lexical, and fail to acquire morphologically redundant information. Our results confirm that this effect persists even under implicit CSL conditions, indicating that attentional biases can emerge purely from the distributional properties of the input, without explicit instruction or training. The learning of SV agreement offers a more nuanced picture. Although it is generally considered abstract and difficult due to its lack of semantic transparency (Slabakova, 2014), learners in the current studies showed consistent learning, especially when cues were perceptually salient. This suggests that even relatively opaque grammatical features can be acquired via CSL, provided they are reliably and transparently encoded in the input.

Taken together, these results suggest that adults can acquire grammatical morphology through CSL, however, this learning is shaped by the transparency of the features. CSL appears to be a viable mechanism for adult learners to acquire both lexical and grammatical features when the linguistic environment provides rich and consistent exposure. However, the learnability of individual morphological forms is not equal: those that are referentially transparent (like number) are acquired more easily than those that are redundant or abstract (like tense or SV agreement). These findings thus advance our understanding of adult morphological learning and contribute empirical support to the theoretical models that emphasise statistic-driven grammar acquisition (Ellis, 2022). While previous research has demonstrated the effects of input frequency and ambiguity on language learning, it remains underexplored whether other factors such as L1 influence commonly discussed in second language acquisition affect the learning of form–meaning mappings. Moreover, although CSL studies have provided valuable insights, much of the existing work is still in its early stages and has primarily focused on frequency effects. Less attention has been given to other important dimensions of input quality beyond ambiguity at the form–meaning level. Specifically, the roles of redundancy and perceptual salience, both frequently identified as contributors to the difficulty of morphological learning, have yet to be systematically examined in CSL paradigms (Dekeyser, 2005; Ellis, 2022).

6.3 The role of L1 morphology complexity in CSL

Study 1 of the dissertation examines the effect of cross-linguistic transfer, specifically whether the adults' L1 morphology complexity affects the acquisition of non-native morphology through CSL. Prior research has offered competing accounts: one suggesting that L1 morphological richness facilitates a broad, wholesale transfer of morphological sensitivity (van der Slik et al., 2019; Rothman, 2011), and another proposing feature-by-feature transfer based on structural overlap between the L1 and the target language (Westergaard et al., 2017; Slabakova, 2017). The results of the current study provide support for both perspectives, though not in a uniform or deterministic fashion. Overall, participants' performance in the CSL paradigm showed that L1 background influenced the rate and extent of learning. L1 German and Mandarin speakers demonstrated significantly higher accuracy than L1 English speakers on training trials, showing the effect of L1 background. This shows that the underlying cause of this advantage appears to be more complex than morphological richness alone. One explanation for L1 Mandarin speakers performed significantly better despite having a morphologically poor L1 is that their performance may reflect the transfer of conceptual analogues rather than direct morphological forms, as transfer can occur in multifaceted ways (Rothman, 2015). For example, in Mandarin, tense is typically marked through adverbs or aspectual particles (e.g., 了 /le/, 过 /guo/), which may have made Mandarin speakers more receptive to identifying tense-like meanings even when expressed as bound morphemes in the CSL language, despite their L1 being morphologically poorly expressed. L1 Phonological transfer could be another reason that explains the significantly better performance in the German and Mandarin groups. Both tense and number are often expressed with CV form in German and Mandarin, but not in English.

For number and tense morphology, L1 German groups outperformed the Mandarin group, consistent with the wholesale transfer hypotheses. First, these two features exist in German but not in Mandarin. Second, German has higher overall morphology complexity than Mandarin. Therefore, it could also be that learners with morphology-rich L1 have an overall advantage in non-native morphology learning. In contrast, for SV agreement, L1 Mandarin speakers performed significantly better than L1 German speakers. This result suggests a possible negative transfer from L1 German, as the SV agreement is structurally similar to the adjective-noun agreement in German. Our result supports the view that transfer can be both positive and negative (Puig-Mayenco et al., 2020).

Limitation from participants' language learning background

It is important to note that participants' previously learned languages were not systematically controlled in the three studies of this thesis. In study 1, we ensured that participants in the English and Mandarin groups had not learned a morphologically rich non-native language; however, their language learning backgrounds still varied considerably in terms of the number of languages acquired, length of exposure, learning contexts, and proficiency levels. As a result, for many participants, learning the target language likely operated within a third language (L3) acquisition framework. In such cases, cross-linguistic transfer can originate not only from the first language (L1), but also from previously acquired non-native languages. This differs from typical second language (L2) acquisition, where transfer is usually L1-driven. In L3/Ln acquisition, transfer patterns are more complex and may be influenced by factors such as metalinguistic knowledge/awareness bilinguals (Bono, 2011), bi-/multilingualism that might have effects on executive function (Gallo et al., 2022), and quantitative/qualitative differences in L3/Ln acquisition (e.g., González Alonso et al., 2025; Rothman et al., 2015).

For example, a possible explanation for the superior performance of the Mandarin and German groups in study 1 may lie in their greater experience with, and awareness of, explicit language knowledge (Bono, 2011). Participants from these groups are more likely to have engaged in formal, classroom-based language learning, where explicit instruction is emphasized. This contrasts with many L1 English participants, who often have limited exposure to foreign language learning and typically lower proficiency in additional languages. Notably, a substantial proportion of the Mandarin and German L1 participants in our study had already achieved high proficiency in at least one non-native language, suggesting a higher degree of metalinguistic awareness and familiarity with structured language learning. This prior experience may have contributed to their advantage in acquiring morphological features in the target language.

Moreover, L3/Ln acquisition has the additional advantage of providing learners with both quantitative and qualitative access to a wider range of grammatical representations, compared to L2 acquisition. For instance, among Mandarin L1 speakers in Study 1, prior experience with a typologically closer L2, such as English, may have played a more significant role in learning the target language than their L1 alone, especially since this group outperformed the English L1 group. Alternatively, the observed advantage could stem from a combination of L1 phonological transfer (e.g., both Mandarin and German often mark tense and number using syllabic CV structures, whereas English tends to use consonantal endings) and typological transfer from L2. Such combined effects may explain why both Mandarin and German L1 speakers performed better than English L1 speakers. These findings align with current theories suggesting that transfer in L3 acquisition can originate from either L1, L2, or both, depending on various linguistic and cognitive factors.

In sum, the findings suggest that L1 alone cannot explain the variant of acquisition, suggesting that transfer may come from both L1s and all previous learned languages. Results also tentatively suggest that negative transfer could occur when it is structurally similar but connected with a different function.

6.4 The role of redundancy in CSL

Study 2 was motivated by Ellis's work on cue redundancy (inflectional tense vs. temporal adverb) in non-native tense acquisition, which concerns a key learning mechanism *blocking* (e.g., Ellis, 2006, 2007; Ellis & Sagarra, 2010a, 2010b, 2011). Ellis's experiments found that learning the first cue (e.g., inflectional tense) often inhibited acquisition of the subsequent one (e.g., temporal adverb), highlighting the importance of learning sequence in non-native morphology acquisition. Moreover, they found that prior learning of temporal adverbs blocks more of the learning of inflectional tense, compared to the other way around, which demonstrated that cue salience modulates the blocking effect. However, these studies employed sequential training that does not reflect the variability of cue occurrence in natural language input. It remains unclear whether the blocking effect would still emerge in natural language learning without pre-training. Given that temporal adverbs are more salient than inflectional tense, they might be learned earlier regardless, due to a mechanism known as *overshadowing* (Kamin, 1967). To address this gap, Study 2 examines whether *overshadowing* arises in a CSL environment that mimics naturalistic input. Building on Study 1, we introduced a redundant, salient temporal adverb to test whether the learning of the temporal adverb would overshadow the learning of inflectional tense. Additionally, reflecting on how cues occur variably rather than consistently, we also manipulated cue availability, comparing a consistent condition, where both cues always co-occurred, with a variable condition, where co-occurrence was stochastic, to assess how distributional properties modulate cue competition.

Results show that the overall learning in the consistent condition was significantly higher than the variable condition, which suggests that the consistent occurrence of the semantically redundant cues benefits the overall non-native language learning (Ellis, 2007; Bahrick et al., 2019). Results in the variable condition also critically extend prior work by Ellis & Sagarra (2010a, 2010b), which demonstrated that pre-training on a salient cue (e.g., adverb) could block learning of a subsequent less salient cue (e.g., tense morpheme). Here, we show that even without sequential pre-training, cue competition arises naturally from within the input itself.

Despite the effect of cue availability, we also found the superiority of adverb learning over tense learning exists in both conditions. Importantly, the contrast between tense and number morphology provides a powerful test case for isolating between the effect of cue salience alone and the effect of sequential learning driven by salience difference. Both were marked by low-salience CV morphemes and appeared with equivalent frequency (though with different numbers of distinctions), yet number cues were learned significantly better. Since the number had no competing lexical cue, the difference in performance cannot be attributed to salience or frequency. This finding strengthens the argument that morphological cues were actively overshadowed by the presence of a more salient, semantically redundant cue, confirming an overshadowing effect, wherein learners preferentially attend to the more perceptually salient cue when both encode the same meaning. The finding that overshadowing emerged even without pre-training diverges from results in Ellis's (2007) control group, where participants distributed attention equally across redundant cues without pre-training. This divergence suggests that naturalistic learning environments, where ambiguous form-meaning mapping is required, may amplify the effects of salience-driven attention more than previously observed in reading-only processing paradigms.

Interestingly, despite the consistent co-occurrence of adverb and tense cues improving overall accuracy, the interaction between cue type (adverb vs. tense) and condition (consistent vs. variable) was not statistically significant. This suggests that consistent exposure supports overall learning but does not eliminate attentional bias toward salient cues. Thus, distributional consistency enhances performance but cannot fully override the overshadowing effect.

Taken together, these results demonstrate that the overshadowing learning mechanism apply robustly in adult learning, even in ecologically valid, meaning-grounded contexts. Unlike earlier studies (e.g., Ellis, 2007) testing the *blocking effect* relied on explicit pre-training or isolated sentence presentation, this study reveals that naturalistic input variability and internal cue salience are sufficient to trigger cue competition effects. These findings critically refine the scope of associative learning theories in SLA, showing that cue salience and redundancy interact with input distribution to shape learners' attention and acquisition pathways.

6.5 The role of salience in CSL

Study 3 investigates whether the role of perceptual salience in modulating the learnability of non-native morphology learning in CSL, another factor that was theoretically hypothesised to influence the learnability of morphology. The between-group (high salience vs low salience) manipulation is the salience of inflectional tense and number cues.

Additionally, results in study 2 showed that number morphemes were learned more effectively than tense morphemes, likely due to the presence of more salient temporal adverbs, competing attention for learning tense morphemes. However, another possible reason could be the difference in the number of grammatical distinctions: number distinctions are binary (singular vs. plural), whereas tense distinctions are ternary (past, present, future), which may influence learning difficulty, as fewer distinctions might be easier to parse and learn. Therefore, this gap was also addressed in study 3. To investigate whether the number of distinctions would make a difference in learning, we compare the learning between groups with or without a default form (default group: present was unmarked for tense; singular was unmarked for number).

One of the key experimental manipulations in this study was the variation of the acoustic salience of morphological markers. Number morphemes were manipulated via syllabicity (CV vs. consonant-only), and tense morphemes via sonority (strong vowels vs. weak schwa). Results showed that participants exposed to highly salient CV morphemes (e.g., /sai/, /ti/ for number) significantly outperformed those exposed to low-salience forms (e.g., /z/, /d/ for number) in both CSL and generalisation tasks. However, this conclusion is not consistent with the findings in tense morphemes. While tense morphemes were salient (CV) form, the learning of tense cues was only at a chance level for the high salience and low salience groups. One plausible explanation is that the tense morphemes had shorter durations than the number morphemes, which was an unintentional limitation of the current design. If this interpretation holds, it suggests that duration plays a more influential role than syllabicity in cue salience, a potential field for future research direction in CSL paradigms.

In contrast, tense was found to be learnable with a default form in the category. This indicates that fewer distinctions can enhance morphological acquisition under certain conditions. It is likely that the presence of a default baseline reduces cognitive load, providing a reference point that facilitates solving the puzzle of form-meaning mapping. Notably, this advantage was most evident for tense morphemes, which were otherwise difficult to learn in both high- and low-salience conditions. This may indicate that default forms are particularly helpful for acquiring paradigms with three-way contrasts (past, present, future), as they reduce the memory burden of learning multiple marked forms simultaneously.

6.6 Limitations and further directions

This thesis provides evidence that adult learners are capable of acquiring non-native morphology through CSL. However, several limitations should be noted here, informing directions for future research.

First, while CSL was proven effective for the acquisition of number, tense, and subject-verb agreement morphology, the artificial language used in all three studies inevitably simplified aspects of real language input. For instance, the number cues were double-marked, both at the end of nouns and verbs, to represent the SV agreement, with the exact same morpheme. However, the agreement in natural language was less transparent in terms of contingency. The SV agreement in English, for example, with "s" mapping plural when it is placed at the end of nouns, and singular when it is at the end of verbs. Such form-meaning contingency poses a learning difficulty (Ellis, 2022). In contrast, the double marking in our paradigm creates consistent form-meaning mapping, making SV agreement easier to learn. Moreover, the double marking in our artificial language was identical forms marking twice on the number, at the end of the subject and the object. Such non-adjacent dependencies were evidenced to be easier to learn if the dependency is similar in form (Newport & Aslin, 2004). Thus, the SV agreement in our paradigm did not fully reflect the difficulty of acquiring SV agreement in a natural language environment, an unintentional limitation.

Second, the diverse language learning backgrounds of our participants add an important layer of nuance to their language learning performance. L2 learning experience may influence L3/Ln acquisition through factors such as enhanced metalinguistic awareness and broader access to morphological knowledge. This consideration is particularly important for interpreting the results of study 1, and it will also undoubtedly add nuance to the findings of studies 2 and 3. Future studies should disentangle these effects by controlling for learners' full language background, including their non-native language learning experiences, and consider including learners from typologically diverse L1s.

Finally, study 3 showed that high acoustic salience enhances learning, specifically for the acquisition of number morphemes but not for the tense morphemes. This is potentially due to the shorter duration of tense morphemes, which is a limitation of study 3. Interestingly, tense morphemes in the default condition were better learned than in the low-salience condition without a default form, suggesting that having a default may scaffold rule learning by reducing processing load. However, previous studies about markedness usually involve the manipulation of frequencies to reflect natural language distributional features, which study 3 did not cover. This limitation reduces the ecological validity of our artificial language.

Overall, these studies indicate that while CSL is a promising model for understanding early stages of non-native morphology acquisition, its effectiveness is conditioned by learners' language learning background, the structure of the input, and the perceptual salience of the morphological features themselves. Future research should continue to explore how language learning background and properties of morphology, such as perceptual salience, redundancy and contingency are filtered by L1 or previously learned languages, and how they jointly constrain the success of CSL-based learning.

7. Conclusion

This thesis investigated the learnability of non-native morphology through CSL, using three studies to examine how different factors shape learners' ability to acquire novel lexical and morphological features from distributional input. Together, the studies demonstrate that CSL supports adult learners' acquisition of content words and morphological features. However, the learning of morphological features tend to be influenced by adult learners' language learning background, the existence of the semantically/functionally redundant and inherently more salient lexical cue, as well as perceptual salience of the morphological cues. These findings contribute to the theoretical understanding of implicit grammar learning by demonstrating that adults retain a robust capacity for statistical learning. This suggests that limitations in ultimate attainment may not stem solely from biological constraints. In addition, the results offer further empirical support for usage-based approaches, reinforcing the idea that frequency plays a key role in driving language learning. Importantly, our findings also extend this framework by showing that the acquisition of form–meaning mappings is influenced by more than just input frequency. The factors identified in our studies highlight that it is not only the quantity but also the quality of language input that shapes the learnability of morphology (DeKeyser, 2005; Ellis, 2022).

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