Non-adjacent dependency learning: development, domain differences, and memory

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Mariella Paul, M.Sc.
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Dekan: Prof. Dr. Markus Lorenz

Gutachterinnen:
Prof. Dr. Dr. h.c. Angela D. Friederici
Prof. Dr. Nicole Altvater-Mackensen

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Mariella Paul

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Children learn their first language simply by listening to the linguistic utterances provided by their caregivers and other speakers around them. In order to extract meaning and grammatical rules from these utterances, children must track regularities in the input, which are omnipresent in language. The ability to discover and adapt to these statistical regularities in the input is termed statistical learning and has been suggested to be one of the key mechanisms underlying language acquisition. In this thesis, I investigated a special case of statistical learning, non-adjacent dependency (NAD) learning. NADs are grammatical dependencies between distant elements in an utterance, such as *is* and *-ing* in the sentence *Mary is walking*. I examined which factors play a role in the development of NAD learning by illuminating this process from different stand points: the first study compares NAD learning in the linguistic and the non-linguistic domain during the earliest stages of development, at 4 months of age. This study suggests that at this age, NAD learning seems to be domain-specific to language. The second study puts a spotlight on the development of NAD learning in the linguistic domain and proposes that there may be a sensitive period for linguistic NAD learning during early childhood. Finally, the third study shows that children can not only recall newly learned NADs in a test immediately following familiarization, but also recall them after a retention period, which is critical to show more long-term learning. Overall, the findings in this thesis further illuminate how NADs, as a spotlight into language acquisition, are learned, stored in memory, and recalled.

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Chapter 1

Introduction

1.1 Statistical learning

How young children learn the language spoken in their environment has been a much debated topic for decades. Children learn their native language(s) "without intention to learn, and without clear awareness of what [they] know" (Perruchet and Pacton, 2006, pp. 233) and before mastering virtually any other complex skill. They do so simply by listening to the speakers around them, without being taught explicit rules. Interestingly, children excel at language learning before they excel at much else. And not only that, but whereas adults outperform children in virtually every other task, children seem to be better language learners than adults. This applies especially when it comes to learning the complex rules that underlie language, that is, the grammatical structure of language. It has been suggested that grammar learning peaks in infancy and undergoes a critical or sensitive period, that is, that there is a period during childhood where grammar learning is easier than it is later during development (e.g., Hartshorne et al., 2018; Johnson et al., 2016; Senghas et al., 2004; Singleton, 2005).

One of the mechanisms that has been proposed to underlie infants' remarkable ability to learn language is statistical learning (see e.g., Arnon, 2019b; Thiessen et al., 2016). Statistical learning refers to the ability to discover and adapt to statistical patterns in the input. These statistical patterns are omnipresent in language, for example in the distribution of speech sounds (Maye et al., 2002), the mappings between words and their meaning (Vouloumanos, 2008), and the dependencies between different words in phrases (Chemla et al., 2009). One example for these dependencies is number agreement, such as the grammatical agreement between the singular noun *girl* and the singular verb *walks* in the sentence *The girl walks*. Children can discover grammatical rules such as number agreement by tracking the statistical co-occurrence between singular nouns and the verb final *-s* in English.

The role of statistical learning in language acquisition has been a much debated topic since Saffran, Aslin, et al. (1996)'s landmark study that provided a proof of concept for infants' ability to track distributional information in the input. In this study, 8-month-old infants were briefly familiarized with a continuous speech stream containing four nonsense words each made up of three syllables. There were no cues to the existence of these words or to the boundaries between them except transitional probabilities, which were higher within words (1) than between words (0.33). After familiarization, infants' learning was tested with both words (with transitional probabilities of 1 between the syllables) and non-words, that is, strings that were contained in the speech stream during familiarization but spanned word boundaries (and thus had a transitional probability of 0.33 between two of the syllables). Infants were able to discriminate between words and non-words, demonstrating their ability to track distributional information in the input (Saffran, Aslin, et al., 1996; Aslin et al., 1998). The same team of researchers also demonstrated that adults can track distributional information in the same experimental setup (Saffran, Newport, and Aslin, 1996). In the following, I will illustrate different types of statistical learning and discuss both their development and whether they are specific to the linguistic domain or more domain-general.

1.1.1 Adjacent dependencies

The types of dependencies that Saffran and colleagues first studied have since come to be referred to as adjacent dependencies (ADs). That is, the dependencies between the syllables in these studies were defined between neighboring elements. Regarding the domain-specifity or generality of ADs, humans' ability to track this type of dependencies has been demonstrated with artificial languages (Saffran, Newport, and Aslin, 1996; Aslin et al., 1998), natural language stimuli (Pelucchi et al., 2009), and tones (Conway & Christiansen, 2009), as well as in the visual (Kirkham et al., 2002) and the tactile domain (Conway & Christiansen, 2005). However, there are some differences in how ADs are learned across domains; for example, visual statistical learning seems to be facilitated by a parallel presentation of stimuli, while auditory statistical learning is facilitated by simultaneous presentation of stimuli (Conway & Christiansen, 2009). In addition, there seems to be a quantitative advantage for learning ADs from the auditory, compared to the visual and tactile domain (Conway & Christiansen, 2005). Therefore, while ADs can in principle be learned across domains, there are still some differences between domains.

Regarding the development of AD learning, statistical learning had originally be proposed to be age-invariant (Saffran et al., 1997); however, the picture seems to be more complicated than that. At least for dependencies between adjacent elements, statistical learning seems to be present at birth (Bulf et al., 2011; Teinonen et al., 2009). Interestingly, however, the developmental trajectory of statistical learning of ADs seems to depend on the domain: whereas the strength of non-linguistic AD learning increases with age (Arciuli and Simpson, 2011; Bertels et al., 2015; Raviv and Arnon, 2018; Shufaniya and Arnon, 2018), learning in the linguistic domain seems to be age-invariant (Raviv and Arnon, 2018; Saffran et al., 1997; Shufaniya and Arnon, 2018). However, it is important to note that direct investigations of the developmental trajectory of statistical learning of adjacent dependencies have, to the best of my knowledge, only been conducted in children age 5 and older. This is despite the proposal that statistical learning (at least for the linguistic domain) peaks in infancy (see Arnon, 2019b). To sum up, learning ADs is possible across domains, for both infants, and adults, and seems to be age-invariant at least for the linguistic domain.

1.1.2 Repetition-based dependencies

Another commonly investigated type of dependencies are repetition-based dependencies. Repetition-based dependencies are characterized by containing two identical elements (e.g., ga-ti-ti). To formalize dependencies, ADs are usually represented as AB or ABC, where each letter stands for one element of the dependency. In comparison, repetition-based dependencies are formalized as AAB, ABB, or ABA. That is, two of the elements in a repetition-based dependencies are identical or, in other words, one element is repeated. Repetition-based dependency learning (also referred to as abstract rule learning) was first demonstrated by Marcus et al. (1999). In this study, 7-month-old infants were familiarized with an artificial language that either consisted of ABB dependencies (e.g., ga-ti-ti) or ABA dependencies (e.g., ga-ti-ga). They were then tested with words consisting of previously unheard syllables, of which half followed the rules of the familiarized language (e.g., wa-fu-fu for an ABB infant or wa-fu-wa for an ABA infant) and half violated these rules (e.g., wa-fu-wa for an ABB infant and wa-fu-fu for an ABA infant). Infants were able to distinguish the words following the familiarized rules from the words violating these rules, indicating that they learned and generalized the rule (Marcus et al., 1999). While the sub-types of repetition-based dependencies can be classified as either adjacent (AAB, ABB) or non-adjacent (ABA), in this thesis, I consider repetition-based dependencies as a separate type of dependencies, because the development and domain-generality of learning of repetition-based dependencies differs from both ADs and non-adjacent dependency (NAD; discussed below) learning.

Unlike ADs, learning repetition-based dependencies was originally suggested to be domain-specific for language. In particular, infants were shown to be able to learn repetition-based dependencies from speech better than from matched non-speech sounds, such as tones or animal sounds (Marcus et al., 2007). However, subsequent studies showed that infants were able to learn repetition-based dependencies from non-speech stimuli under certain conditions, such as at a younger age (Dawson & Gerken, 2009) and when the stimuli were perceived as carrying meaning (Ferguson and Lew-Williams, 2016; Saffran et al., 2007). Indeed, a recent meta-analysis demonstrated that the observed learning advantage is not necessarily due to a domain-specific feature, but rather holds for any meaningful stimulus compared to meaningless stimuli (Rabagliati et al., 2019). A follow-up experiment confirmed the results of this meta-analysis by demonstrating that infants only learned repetition-based dependencies from sequences of gestures if infants were primed to perceive these gestures as communicative prior to familiarization (Rabagliati et al., 2019).

Regarding the development of learning repetition-based dependencies, these dependencies can already be learned at birth, but only when the repetition is between adjacent (ABB), rather than non-adjacent elements (ABA; Gervain et al., 2008). Dawson and Gerken (2009) proposed that abstract rule learning declined with age, based on their findings that 4-month-old infants learned repetition-based dependencies from both musical chords and tones, whereas for 7-month-old infants, there was no evidence for learning in either case. While the meta-analysis by Rabagliati and colleagues confirmed the direction of this age effect effect (i.e., a decline with age between 4 and 13 months of age), this effect was not significant when all developmental studies of repetition-based dependency learning were considered together. Even when considering the effect of stimulus (for both speech vs. non-speech and meaningful vs. meaningless), there was no significant effect of age (Rabagliati et al., 2019). Investigations of repetition-based dependency learning in older children and adults, and especially direct comparisons across a broader age range than in Rabagliati and colleagues' metanalysis (which only included infants between 4 and 13 months; Rabagliati et al., 2019) are, to the best of my knowledge, missing. While there is evidence that adults can learn repetition-based dependencies (Chen et al., 2015), there are, to the best of my knowledge, no comparisons regarding the strength of learning in adults or older children compared to infants. To summarize, learning repetition-based dependencies is possible for both infants and adults, seems to be age-invariant, and is possible across domains as long as the stimuli are meaningful.

1.1.3 Non-adjacent dependencies

A third type of dependencies are non-adjacent dependencies (NADs). NADs can be formalized in the form AXB, where A predicts B, forming the dependent elements of the NAD, and X is one or more intervening elements. For example, in the sentence *Mary is walking*, the auxiliary *is* predicts the verb suffix *-ing*, constituting the dependent elements of the NAD. The intervening element in this case is the verb stem *walk-*; however, there could also be several intervening elements, such as in the sentence *Mary is often walking*. NADs are a crucial part of any natural language. For example, NADs are present in subject-verb agreement (e.g., *Mary walks*) and tense-marking (e.g., *Mary was walking*). Compared to learning ADs, learning NADs seems to be more cognitively complex (Gómez and Maye, 2005; also see Wilson et al., 2018), has a delayed development (Aslin et al., 1998; Culbertson et al., 2016; Gómez and Maye, 2005; Saffran, Aslin, et al., 1996), and is subserved by different neural networks than AD learning (Conway et al., 2020). These differences may be at least partly due to NADs placing higher working memory demands on the learner (Gómez and Maye, 2005). In order to successfully process or learn NADs, the listener must keep the first element (A) of the NAD in memory until they encounter the second element of the NAD (B), spanning the duration of the intervening elements (X). Indeed, the number of intervening elements limits learning for both infants (Höhle et al., 2006; Santelmann, 1998) and adults (Grama et al., 2013), indicating working memory constraints.

There are two common approaches to study how NADs are learned and processed. Here, I will use NAD learning to refer to the ability to learn novel NADs (usually while in the lab) and NAD processing to refer to processing and comprehension of NADs in one's native language (which participants typically learned outside of the lab). NAD learning is usually studied using artificial grammar learning (AGL) paradigms, while NAD processing is typically studied using natural language paradigms. In the following, I will briefly explain both approaches. In AGL studies, the elements of NADs are often realized as single syllables, tones, or images (depending on the domain). For illustration purposes, I will discuss a linguistic study as an example of a typical AGL experiment. In a seminal study, Gómez (2002) tested both infants' and adults' ability to learn NADs with an AGL paradigm. Participants were first familiarized with one of two artificial grammars. In these artificial grammars, words consisted of 4 syllables (e.g., *pel-wadim-rud* for language 1 and *pel wadim jic* for language 2), where the first and the last syllable formed the dependent elements of the NAD and the two middle syllables formed the intervening elements. ADs were kept constant for both artificial grammars, so in order to distinguish between the two artificial grammars, participants were required to learn the NADs. During a subsequent test phase, participants were tested with 50% words from the familiarized language (e.g., *pel-wadim-rud*) and 50% words from the non-familiarized language (e.g., *pel wadim jic*), which to the participant, violated the rules underlying the familiarized NADs. Both infants and adults were able to distinguish familiarized NADs from violations, providing evidence that they learned the NADs (Gómez, 2002).

To study the processing of NADs, studies use NADs in the participants' native language. For example, Santelmann (1998) exposed infants to sentences containing NADs in their native language (e.g., *At the bakery, everybody is baking bread*), as well as sentences containing NAD violations (e.g., **At the bakery, everybody can baking bread*). Infants at 18 months were able to distinguish sentences containing grammatical NADs from sentences containing NAD violations, indicating that they had learned the NADs in their native language. Taken together, NAD learning and NAD processing are typically studied using artificial grammars and participants' native language, respectively. Native language studies are more naturalistic and allow for testing participants' existing knowledge of their native language rather than learning. AGL studies offer the benefit of being well-controlled and allow to investigate participants' learning of NADs during the experiment.

Using AGL paradigms, adults have been shown to be able to learn NADs from syllables (e.g., Gómez and Maye, 2005), sentences in a foreign language (e.g., Mueller et al., 2009), tones (e.g., Creel et al., 2004), and videos (e.g., Endress and Wood, 2011). However, adults' NAD learning has also been shown to be limited in several regards. In particular, adults seem to need some kind of additional cues to learn NADs. These cues can include perceptual similarity of the dependent elements (easing association of the dependent elements; Newport and Aslin, 2004; Onnis et al., 2005), acoustic pauses before and after NADs (easing the detection of boundaries between NADs and the surrounding speech stream; Mueller et al., 2008; Peña, 2002), prosodic salience (highlighting the dependent elements by making them either more or less salient than the intervening elements; Grama et al., 2016), a high variability of the intervening elements of the NADs (increasing the salience of the less variable dependent elements; Gómez, 2002), and the presence of an active task (drawing participants' attention to the NADs Pacton and Perruchet, 2008; Pacton et al., 2015). Each of these studies demonstrated successful NAD learning in the presence of (at least one of) these cues, but no or only limited evidence for learning in their absence (see also Wilson et al., 2018 for a review). This observation holds not only for linguistic NAD learning, but also for NAD learning in the non-linguistic auditory domain (e.g., Creel et al., 2004; Endress, 2010; Gebhart et al., 2009). These findings point to similarities in adults' learning of NADs in the linguistic and non-linguistic auditory domain; however, studies directly comparing NAD learning across domains have been rare.

1.2 Development of NAD learning

Similar to adults, children are also able to learn NADs around 14 - 15 months in artifical grammars (e.g., Gómez and Maye, 2005) and to process (at least some) NADs in their native language (e.g., Culbertson et al., 2016), as indicated by behavioral studies. For younger children, there is mixed evidence, with some studies finding no evidence for NAD learning (Gómez and Maye, 2005) and some studies showing learning, but only with additional cues, such as a segmented speech stream (Marchetto and Bonatti, 2013; Marchetto and Bonatti, 2015) or when infants were familiarized with the dependent elements of the NADs as adjacent dependencies first (Lany & Gómez, 2008). In the following two paragraphs, I will discuss developmental studies of NAD learning, first using artificial grammars, and second using children's native language.

I will first illustrate a typical example of an AGL study with infants using Gómez and Maye (2005) as an example. In this study, infants 12, 15, and 18 months of age were familiarized with NADs of the form AXB in an artificial grammar using the headturn-preference procedure (HPP). In this study, the NADs were realized as four-syllable "words", (e.g., *pel-wadim-jic*; similar to Gómez (2002), described in section 1.1.3). In the headturn-preference procedure, a preference for familiar items (in this case, familiarized NADs) indicates a less mature response than a preference for novel items (in this case, NAD violations; Hunter and Ames, 1988). Gómez and Maye (2005) found no evidence that 12-month-old infants detected NAD violations. Only at 15 months did infants succeed to detect NAD violations, indicated by a preference for the familiarized NADs (familiarity preference). At 18 months, children also detected the NAD violations; however, the detection was indicated by a preference for violations (novelty preference) at this age. Following the Hunter and Ames model (Hunter & Ames, 1988), this shift from familiarity to novelty preference was interpreted as a maturing of NAD learning between 15 and 18 months of age. Based on these data, the authors reasoned that 15-month-old infants can detect NAD violations, but NAD learning is not yet fully mature at this age (Gómez and Maye, 2005). Further, there is evidence that infants starting at 15 months of age can not only track NADs, but also generalize them to previously unheard examples (Gómez, 2002). Moreover, infants' NAD learning from artificial grammars is linked to their language comprehension and production (Frost et al., 2020; Lany and Shoaib, 2019), indicating that NAD learning may be a good index of children's early language development more generally.

Starting in the second year of life, children can not only learn NADs from artificial grammars, but also detect violations in NADs in their native language. For example, infants learning English and German are able to detect violations in NADs between an auxiliary and a verb suffix (e.g., *is -ing* phrases) in their mother tongue at 18 months, as long as the dependent elements are not more than 3 syllables apart; at 15 months, however, there was no evidence for NAD learning (Höhle et al., 2006; Santelmann, 1998). Similarly, in French, infants are able to detect NAD violations starting between 14 and 18 months (Culbertson et al., 2016; Nazzi et al., 2011; van Heugten and Shi, 2010). However, violation detection alone is not enough to indicate that children have learned the underlying morphological rule or understand the NAD's meaning. Instead, infants may rely on surface-level phonological features of the NADs, that is, they may track the co-occurence of the sounds of the dependent elements. For example, when first learning to recognize *is- ing* phrases, children may be tracking the co-occurence of the two morphemes or parts of the morphemes (e.g., the co-occurence of the two *i*-sounds). This would allow them to detect violations in *is- ing* constructions (e.g., **The baker can baking bread*. This ability may be in place much earlier than the ability to learn the morphological rules underlying the NAD. In particular, the ability to comprehend NADs, that is, being able to use NADs to solve a word-picture matching task, seems to only be in place starting at 30 months (Legendre et al., 2010; Legendre et al., 2014), or even much later, at 5-6 years (e.g., Johnson et al., 2016), depending on the language (Legendre et al., 2014). Taken together, behavioral evidence suggests that children can detect NAD violations in both their native language and artificial grammars in the second year of life, but only learn the underlying rule and understand the NAD's meaning later during development.

Based on these findings, there seem to be two developmental stages of NAD learning. During the first stage, children are able to detect NAD violations based on the surface-level phonological features of the dependent elements. In the second stage, children are also able to learn the underlying morphological rule and comprehend the meaning of the NAD. A recent study provided evidence for these developmental stages and the difference in representations of the NADs between them (Culbertson et al., 2016). In this study, children were presented with NADs encoding subject-verb agreement in their native language (French). Six different age groups between 14 and 24 months were tested using the headturn-preference procedure. The Hunter and Ames model (Hunter & Ames, 1988) distinguishes between two different directions of preference in the headturn-preference paradigm: a preference for previously seen (or heard), familiar items (familiariarity preference) and a preference for previously unseen (or heard), novel items (novelty preference). The model suggests that novelty preference is a more mature response than familiarity preference, that is, younger infants are expected to show a familiarity preference and older infants a novelty preference, given that all other factors (such as stimuli and task difficulty) are kept constant. Based on the Hunter and Ames model, Culbertson et al. (2016) expected to observe a shift from a preference for familiar items (in this case, grammatical NADs) in younger children to a preference for novel items (in this case, NAD violations) in older children. Culbertson et al. (2016) found this shift between 14 months (at which point children showed a preference for grammatical NADs) and 18 months of age (at which point children showed a preference for NAD violations). Interestingly, however, 21-month-old children again showed the more immature preference for grammatical NADs (familiarity preference), while at 24 months, children showed the more mature preference for NAD violations (novelty preference). Thus, there were two cycles of a shift from familiarity to novelty preference, indicating two different developmental stages of NAD learning (Culbertson et al., 2016). Based on these findings, the authors suggested that during the first stage, children learned the surface-level phonological features of the dependent elements of the NADs, while during the second stage, children learned the higher-level morphological rules.

1.3 Neurophysiological evidence of NAD learning during development

The existence of two developmental stages of NAD learning was further supported by a series of studies investigating NAD learning using event-related potentials (ERPs). Using ERPs offers several advantages: (1) ERPs are a safe, non-invasive, and implicit measure that can be used with pre-verbal infants who cannot yet be asked to give overt behavioral responses and can even be used with infants who can not yet hold up their head and thus cannot participate in HPP experiments; (2) ERPs have a temporal resolution on the order of milliseconds and can thus be used to make precise inferences about the timing of cognitive processes; (3) many ERP components are well-studied in infant, child and adult populations and can be used to make inferences about the nature of the underlying cognitive processes. Therefore, ERPs are a useful tool to study language acquisition, including the development of NAD learning.

Using ERPs, infants were shown to be able to detect NAD violations at a much younger age than demonstrated in behavioral studies (Friederici et al., 2011; Mueller et al., 2012). For example, Friederici et al. (2011) familiarized 4-month-old infants with Italian sentences containing NADs between an auxiliary and a verb stem (e.g., *La sorella sta cantando; The sister is singing*). Infants were then tested with correct sentences (i.e., containing familiarized NADs) and incorrect sentences (i.e., containing NAD violations). Infants were able to detect NAD violations, indicated by a late, positive ERP response to incorrect compared to correct sentences. This late, positive ERP response was interpreted to indicate implicit, associative learning of either the full (*sta X-ando*) or a partial phonological form (e.g., -a X-a–o; Friederici et al., 2011).

Interestingly, recent ERP and functional near-infrared spectroscopy (fNIRS) support the existence of two developmental stages of NAD learning. These studies showed that children up to the age of 2 years learned NADs under passive listening conditions, whereas older children (Mueller et al., 2019; van der Kant et al., 2020) and adults (Friederici et al., 2013; Mueller et al., 2012) did not show evidence for NAD learning when tested under the same conditions (i.e., passive listening).

It is possible that attentional mechanisms play a role in the different developmental stages of NAD learning. Whereas adults struggle to learn NADs under passive listening conditions (Friederici et al., 2013; Mueller et al., 2012), they are able to learn NADs when they are presented with either an active task (Mueller et al., 2012; Pacton and Perruchet, 2008; Pacton et al., 2015) or additional cues in the input (e.g., Gómez, 2002; Mueller et al., 2008; Newport and Aslin, 2004; Peña, 2002). Both an active task and additional cues may help guide the learners' attention to the NADs, facilitating NAD learning. The idea that NAD learning processes differ for attention-driven, active learning compared to passive listening is supported by the finding that adults show different ERP responses to NAD violations under active task conditions than infants do under passive listening conditions. Whereas infants show a late positive ERP component for NAD violations compared to familiarized NADs (Friederici et al., 2011), adults show an N400-like negativity followed by an anterior P3a component (Mueller et al., 2009; see also Citron et al., 2011). This N400-like negativity was interpreted to indicate difficulties with lexical access for the NAD violations. This would indicate that adult learners attempted to lexicalize the NADs. The P3a-component was interpreted as

TABLE 1.1: Overview of the proposal of two developmental stages of NAD learning

	Stage 1	Stage 2
Age	Up to 2 years	Starting at 3-4 years
Learning process	Associative, phon. features	Controlled, morph. features
NAD learning (passive listening)	Yes	Only with additional cues

phon. - phonological, morph. - morphological

attentional orienting to the suffix (i.e., the second dependent element of the NAD), indicating not necessarily violation detection, but the involvement of attentional processes (Mueller et al., 2012). Therefore, the presence of an active task seems to help guide adult learners' attention to the NAD.

Taken together, the available evidence of the development of NAD learning suggests the existence of two developmental stages. Up to the age of 2 years, children seem to learn NADs via surface-level phonological features (Culbertson et al., 2016) and are able to do so under passive listening conditions (Mueller et al., 2019), indicating associative learning (Friederici et al., 2011). Starting around 3-4 years of age, children and adults learn the higher-level morphological features of NADs (Culbertson et al., 2016) and struggle to learn under passive listening conditions (Mueller et al., 2012; Mueller et al., 2019), indicating less automatic, but more controlled learning (see table 1).

1.4 A sensitive period of NAD learning?

The observation that the ability to learn NADs under passive listening conditions (without additional cues) decreases during development (from stage 1 to stage 2; see table 1) may point to a sensitive period of NAD learning. A sensitive period refers to a limited developmental period during which learning a particular skill is easier than during other developmental periods (e.g., Knudsen, 2004). In the most extreme cases of sensitive periods, it is not only easier to learn said skill during this period, but not possible to learn it outside of this period; this is referred to a critical period (Lenneberg, 1967). Originally, grammar learning had been proposed to undergo such a critical period. In a landmark study, Johnson and Newport (1989) tested native Korean and Chinese speakers who had immigrated to the United States at different ages and had thus been exposed to English as a second language for a varying amount of time (3 - 26 years). Johnson and Newport (1989) found an advantage for earlier second language learners over later second language learners across several tests of grammatical knowledge, which the authors interpreted as evidence for a critical period. However, the results of this study have since been called into question. While the original study controlled for many external measures that may confound the effect of learners' age of arrival, a later study showed that the advantage for earlier learners disappeared when controlling for education (Flege et al., 1999). Instead, more recent accounts propose that grammar learning undergoes a sensitive, rather than a critical period (e.g., Knudsen, 2004). Indeed, Hakuta et al. (2016) demonstrated the effect of age and education on the decline of the ability to learn the grammar of a second language were linear, speaking in favor of a sensitive, rather than a critical period, for which a non-linear effect would be expected.

As outlined in section 1.1, different types of statistical learning follow different developmental trajectories and thus may or may not undergo a sensitive period. Learning both ADs (at least in the linguistic domain; Raviv and Arnon, 2018; Saffran et al., 1997; Shufaniya and Arnon, 2018) and repetition-based dependencies (Rabagliati et al., 2019) seems to be age-invariant, indicating that there is no sensitive period at play. Learning NADs under passive listening conditions, on the other hand, seems to decline with age (as reviewed 1.3), making NAD learning a possible candidate for a sensitive period.

Previous studies comparing NAD learning under passive listening conditions across different age groups (Culbertson et al., 2016; van der Kant et al., 2020; Mueller et al., 2019) may provide first evidence for a sensitive period. For example, van der Kant et al. (2020) provided evidence for a discontinuity in learning linguistic NADs under passive listening conditions between 2 and 3 years, but whether the transition is linear (i.e., pointing to a sensitive period) was not tested. Culbertson et al. (2016) demonstrated that there is a gradual change from familiarity (grammaticality) to novelty (ungrammaticality) preference within the two developmental stages of NAD learning, but did not look at the transition between these stages. First evidence for children's ability to learn NADs under passive listening also after entering the second stage of NAD learning comes from Mueller et al. (2019) who showed that whereas only 2-year-old children could learn NADs under passive listening at the group-level, some 4-year-old children were still able to learn the NADs (based on individual differences in pitch processing). However, direct evidence for a sensitive period, such as evidence for a linear transition between the two developmental stages of NAD, is lacking. Similarly, studies investigating NAD learning during the second developmental stage (that is, starting at 3-4 years of age) have been rare. For example, it remains to be seen whether older children can learn NADs under active task conditions (as would be predicted based on the two developmental stages of NAD learning) and when NAD learning becomes fully mature, or adult-like. Taken together, first evidence points towards a sensitive period of NAD learning. In the following, I will discuss some of the defining features of sensitive periods and how they relate to NAD learning.

Sensitive periods are driven by two factors, experience and brain plasticity (Knudsen, 2004). In the following, I will argue that both factors also contribute to NAD learning. In order to learn a skill that undergoes a sensitive period, the learner must make certain experiences during a certain time. For example, in order to proficiently acquire (at least some) aspects of language, humans must be exposed to a sufficient amount and quality of input in that language early in life (Newport and Aslin, 2004; Weber-Fox and Neville, 1996). Experience has also been shown to play a role in the development of NAD learning. Infants' NAD learning in artificial grammars (Frost et al., 2020; Lany and Shoaib, 2019) and NAD processing in their native language (Lany and Shoaib, 2019) have both been linked to their language development more generally (measured by standardized language tests). More directly, Lany and Shoaib (2019) demonstrated that individual differences in children's NAD learning in an artificial grammar correlates with their NAD processing in their native language.

While experience shapes whether and how a skill is learned during a sensitive period, brain plasticity drives when a sensitive period opens and closes. There is evidence that the development of associative learning, which may characterize the first developmental stage of NAD learning, is linked to developmental changes in brain structure and plasticity (see Skeide and Friederici, 2016). In particular, associative NAD learning likely recruits posterior temporal brain regions as well as frontal regions (in particular, the premotor region; Friederici, 2012; Gervain et al., 2008; Gervain et al., 2011). These regions are connected via two fiber pathways, of which the ventral pathway is already myelinated at birth (Perani et al., 2011), whereas the dorsal pathway (the arcuate fasciculus) undergoes ongoing maturation until early adulthood (Skeide et al., 2016). The ventral pathway may therefore underlie infants' ability to learn NADs in an associative manner (see Friederici et al., 2011; Skeide and Friederici, 2016). The development of the arcuate fasciculus along with prefrontal regions, on the other hand, may enable older children and adults to learn in a more controlled manner (see Skeide and Friederici, 2016), possibly blocking the ability to learn NADs in an associative manner, reflected in older children's and adults' struggle to learn NADs under passive listening conditions (Mueller et al., 2012; Mueller et al., 2019; van der Kant et al., 2020). Indeed, prefrontal areas have been shown to play a role in adults' NAD learning (Friederici et al., 2013). When adults' prefrontal cortex was inhibited using transcranial direct current stimulation during NAD learning, their ERP responses changed from an N400-like component and a P3a to a late positivity (Friederici et al., 2013), resembling the ERP response of infants in the same paradigm (Friederici et al., 2011). Based on these results, Friederici et al. (2013) suggested that adults' learning goes from controlled to associative when their prefrontal cortex is inhibited.

1.5 Domain-generality of NAD learning during development

The studies reviewed in sections 1.2 and 1.3 pointing to different developmental stages of NAD learning were almost exclusively conducted in the linguistic domain; however, the question arises whether this developmental pattern also holds in the non-linguistic auditory domain. Studies of the development of non-linguistic NAD learning have been rare, but our recent study has directly compared the development of NAD learning in the linguistic and the non-linguistic auditory domain (van der Kant et al., 2020). This study tested children at 2 and 3 years of age with the same Italian sentences as a previous study with infants (Friederici et al., 2011), as well as tone sequences derived from and directly comparable to these Italian sentences. We found opposite patterns for the linguistic and the non-linguistic domain: In the linguistic domain, we found evidence for learning in 2-year-old, but not 3-year-old children. In contrast, in the non-linguistic domain, we found evidence for learning in 3-year-old, but not 2-year-old children. This finding of different developmental trajectories for linguistic and non-linguistic NAD learning is supported by studies investigating the development of ADs (Raviv and Arnon, 2018; Shufaniya and Arnon, 2018). Therefore, while there are similarities for NAD learning in the linguistic and non-linguistic auditory domain for adults (section 1.1.3), NAD learning seems to follow a different developmental trajectory in these domains.

However, it is still unclear at what point in development non-linguistic NAD learning diverges from linguistic NAD learning. While the development of linguistic NAD learning has been studied extensively (see sections 1.2 and 1.3), to the best of my knowledge, there are no studies of non-linguistic auditory NAD learning below 2 years of age (with van der Kant et al., 2020 being the only study of non-linguistic auditory NAD under the age of 3).

1.6 The role of memory in NAD learning

A central question in the field of NAD learning is how NADs are stored in memory. Proposals that are specific for NAD learning or statistical learning more broadly are, to the best of my knowledge, currently missing. However, more general proposals for how newly acquired knowledge is stored and consolidated exist (McClelland et al., 1995) and have been extended into the domain of language learning (i.e., word learning; Davis and Gaskell, 2009). Specifically, it has been proposed that newly learned words are stored via two complementary learning systems: a hippocampal system that rapidly forms representations of the learned items but does not abstract them; and a neocortical system that forms more abstract representations that are generalized beyond the specific context they were first encountered in. While new words would be processed by both systems, the hippocampal systems stores memories immediately, but not in a long-term fashion; representations of new words only become long-term once they are consolidated by the neocortical system, which occurs via repetitions of the learned material (McClelland et al., 1995; Davis and Gaskell, 2009). Critically, this consolidation and transfer from the hippocampal system to the neocortical system is facilitated by sleep in both children and adults (Henderson et al., 2012; Smith et al., 2018; Tamminen et al., 2010). Therefore, sleep plays an important role in memory consolidation (see also Backhaus et al., 2008); Diekelmann and Born, 2010).

While it is not yet clear how newly learned NADs are stored in memory, first studies have shown that sleep plays a role in the consolidation of learned NADs. Gómez et al. (2006) familiarized 15-month-old children with NADs using the same stimuli as Gómez (2002) (discussed in section 1.1.3). After a delay of four hours, infants were tested using a mixture of familiarized NADs and NAD violations. Crucially, during this delay, children either napped (sleep group) or stayed awake (wake group). Infants in the wake group were able to detect NAD violations when the stimuli were identical to the ones used in familiarization, indicating that they learned the NADs. However, there was no evidence for any abstraction away from the exact stimuli used during familiarization. Children in the sleep group, on the other hand, seem to have learned a more abstract relationship between the NADs that they could apply to novel stimuli not identical to the familiarized stimuli (although similar). Based on these results, the authors suggested that sleep plays a role in memory traces of NADs, as well as abstraction away from specific exemplars of NADs and generalization of the learned dependencies to new but similar stimuli (see also Frost and Monaghan, 2017 for similar findings in adults). These findings would be in line with a complementary learning systems account and therefore provide first some evidence that the complementary learning systems account may also apply to NAD learning (McClelland et al., 1995; Davis and Gaskell, 2009).

Research questions

The present thesis aims to advance our understanding of the development of NAD learning from early infancy to later childhood. To address this aim, three major research questions are evaluated:

I. Is NAD learning domain-specific for language or domain-general during the earliest stages of development? That is, do young infants learn non-linguistic NADs in the same manner as they learn linguistic NADs? (see chapter 2; Paul et al., in prep)

II. Does NAD learning under passive listening undergo a sensitive period? That is, does the development of linguistic NAD learning under passive listening conditions decrease gradually as the transition from a first stage of associative learning of phonological features to a second stage of controlled learning of morpho-syntactic features occurs? (see chapter 3; Paul et al., 2021).

III. How are learned NADs stored in memory? What is the role of sleep for mental representations of NADs? (see chapter 4; Schaadt & Paul et al., 2020).

Chapter 2

Experiment 1: Domain-specificity of NAD learning during early development

2.1 Introduction

Statistical learning (SL), that is, the ability to track distributional information in the input, has been studied extensively in the last decades. SL has been demonstrated to be present across development, in both infancy (e.g., Saffran, Aslin, et al., 1996; Aslin et al., 1998) and adulthood (e.g., Saffran, Newport, et al., 1996; Conway and Christiansen, 2005), and to be present even already at birth (Bulf et al., 2011; Teinonen et al., 2009). Interestingly, even at the earliest stages of development, infants can track the distributional information, that is, co-occurrence frequencies in the input, regardless of whether they are presented in the auditory (Teinonen et al., 2009) or visual domain (Bulf et al., 2011) and regardless of whether the input is linguistic (Saffran, Aslin, et al., 1996; Aslin et al., 1998) or non-linguistic (Saffran et al., 1999). They can also do so for different types of dependencies (Gervain et al., 2008; Winkler et al., 2018). In particular, two studies demonstrated that even newborns can track distributional information in the form of transitional probabilities between adjacent elements both in the linguistic auditory domain (Teinonen et al., 2009) and in the non-linguistic visual domain (Bulf et al., 2011). This ability extends to repetiion-based dependencies, defined by a repetition of one of the dependent elements (e.g., ABB, AAB). Interestingly, however, newborns only seem to be able to learn these patterns when the repetition occurs between adjacent elements (e.g., ABB, AAB) but not between non-adjacent elements (e.g., ABA) (Gervain et al., 2008). These non-adjacent repetiion-based dependencies are only learned later, starting around 4-7 months (Dawson and Gerken, 2009; Gervain and Werker, 2013; Marcus et al., 1999; see also Winkler et al., 2018).

Whereas learning adjacent dependencies seems to be possible across domains, learning non-adjacent dependencies (NADs) across different domains has been less well studied, especially when the dependencies were not repetiion-based. Learning NADs between non-identical elements is likely different from repetiion-based dependencies, because it requires learning arbitrary relations (see Wilson et al., 2018). That is, NADs between non-identical elements are likely more difficult to learn because the identity-relation in repetiion-based dependencies may be more perceptually salient. In line with this, NADs have been shown to be easier to learn when the dependent elements share phonological or other perceptual features (e.g., Creel et al., 2004; Gebhart et al., 2009; Onnis et al., 2005). Moreover, NADs between non-identical elements correspond more closely to natural language learning because NADs between non-identical elements are ubiquitous in language, such as in tense-marking (e.g., *The sister was singing*, subject-verb agreement (e.g., *The sister sings*), whereas repetitions are more rare in natural languages (although they do occur, referred to as reduplication; see e.g., Kajitani, 2005; Nadarajan, 2006). To distinguish between these two types of NADs, in this paper, we will use the term NAD to refer to dependencies between non-identical elements.

For adults, NAD learning seems to be possible across the linguistic and non-linguistic domain. For example, Gómez (2002) demonstrated that adults were in principle able to learn NADs from non-words consisting of four syllables (e.g., *pel-wadim-rud*). Similarly, adults have been shown to be able to learn NADs from non-linguistic tones (Creel et al., 2004; Endress, 2010) and noises (Gebhart et al., 2009). Interestingly, adults' NAD learning also seems to underlie similar restrictions in both domains, with a facilitating effect of perceptual cues for the linguistic (Grama et al., 2016; Newport and Aslin, 2004; Mueller et al., 2008; Peña, 2002) as well as the non-linguistic auditory domain (Creel et al., 2004; Endress, 2010;

Gebhart et al., 2009). Taken together, although direct comparisons are lacking, adults seem to be able to learn NADs across domains, with similar limitations at least for the linguistic and non-linguistic auditory domain.

In the developmental literature, NAD learning has been well-studied for the linguistic but not the non-linguistic domain. Behaviorally, the onset of linguistic NAD learning has been found to occur between 12 and 15 months (Gómez and Maye, 2005; Lany and Gómez, 2008; Marchetto and Bonatti, 2013; Marchetto and Bonatti, 2015). Interestingly, however, event-related potential (ERP) studies were able to provide evidence for a much earlier onset of the ability to track NADs in linguistic material (Friederici et al., 2011; Mueller et al., 2012). For example, Friederici et al. (2011) familiarized 4-month-old infants with sentences in a foreign language (Italian) containing NADs between an auxiliary and a suffix. After familiarization, infants were shown to be able to detect violations of the familiarized NADs, indicated by a difference in ERP responses to NAD violations compared to familiarized NADs. This and similar studies (e.g., Mueller et al., 2012; see also Winkler et al., 2018) put the onset of infants' ability to track NADs in linguistic input at the first few months of life. The subsequent development of linguistic NAD learning during early childhood has been investigated by numerous studies (e.g., Culbertson et al., 2016; Frost et al., 2020; Gómez and Maye, 2005; Lany and Shoaib, 2019; Marchetto and Bonatti, 2013; Marchetto and Bonatti, 2015). A series of studies using electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) has shown that the strength of linguistic NAD learning under passive listening conditions decreases during early childhood (Mueller et al., 2019; Paul et al., 2021; van der Kant et al., 2020). Our recent study (Paul et al., 2021) also provided first evidence that NAD learning under passive listening conditions may be undergoing a sensitive period in the linguistic domain. This would indicate that in the linguistic domain, there is a period during early childhood in which learning NADs is easier than during later childhood.

In the non-linguistic domain, however, much less is known about the development of NAD learning. Indeed, only recently has there been the first study of non-linguistic NAD learning below the age of 3 years (van der Kant et al., 2020). This study directly compared 2- and 3-year-old children's ability to learn NADs in the linguistic and the non-linguistic domain by means of functional near-infrared spectroscopy (fNIRS). They familiarized children with the same Italian sentences as a previous ERP study (Friederici et al., 2011) and with directly comparable tone sequences, both containing NADs (between an auxiliary and a suffix and between the fifth and the seventh and eighth tone, respectively). Children were able to detect NAD violations in the linguistic material at 2 but not 3 years. Interestingly, this pattern was reversed for the non-linguistic domain – here, only the 3-year-old but not the 2-year-old children learned the NADs between tones. This was interpreted as a difference in the developmental trajectory for the linguistic compared to the non-linguistic auditory domain (van der Kant et al., 2020). This recent study allowed first insights into the different developmental trajectories of linguistic and non-linguistic NAD learning; however, when these developmental trajectories diverge remains an open question.

In the current study, we aim to address the following research questions: Do young infants possess the ability to learn NADs in the non-linguistic domain? And therefore, is NAD learning at the earliest stages of development domain-general or specific to language? To address these questions, we tested 4-month-old infants with the non-linguistic tone sequences used in a recent developmental study comparing linguistic and non-linguistic NAD learning (van der Kant et al., 2020). These tone sequences are also directly comparable to the linguistic material used in a previous ERP study with 4-month-old infants (Friederici et al., 2011). Therefore, we can use them to compare infants' NAD learning in the linguistic domain in the study by Friederici and colleagues to infants' NAD learning in the non-linguistic domain in the present study study. We preregistered two hypotheses: First, if 4-month-old infants were able to learn NADs in the non-linguistic domain, we would expect to see a significant difference in infants' ERP responses to NAD violations compared to familiarized NADs. Second, if similar processes underlay infants' NAD learning in the linguistic and non-linguistic auditory domain, we would further expect to see a similar ERP response in the non-linguistic as in the linguistic domain (i.e., a positive-going ERP response between 600 and 1000 ms after the onset of the second dependent element of the NAD).

2.2 Methods

2.2.1 Participants

20 4-month-old infants (mean age: 4.13 months, SD: 0.31 months, 7 girls) participated in this study. All children grew in up in a monolingual German environment and had no familial history of reading disorders. Caregivers gave written informed consent for their children's participation in the study. The Medical Faculty of the University of Leipzig provided ethical approval for this study. 42 additional children were excluded from the analysis, either because of fussiness during the data collection, or because of poor data quality (i.e., they contributed less than 8 artefact-free EEG trials per condition across all test phases).

The present sample is a preliminary sample because testing had to be paused due to COVID-19-related restrictions. The final, preregistered sample of 34 infants will be completed once testing can resume.

2.2.2 Stimuli

The tone sequences in the present study were taken from van der Kant et al. (2020). These stimuli were created to be directly comparable to linguistic stimuli (Italian sentences) in previous studies (e.g., Friederici et al., 2011; Mueller et al., 2009). In particular, each syllable of the Italian sentences was exchanged with a pure tone using Praat (Boersma and Weenink, 2016), yielding sequences of eight tones (see Figure 2.1). The NADs are defined between the fifth tone (first dependent element) and the seventh and eighth tones (second dependent element). All tone positions were realized as two tokens (two different tones), with the exception of the sixth position, which was realized as 32 different tones (Figure 2.1). Incorrect tone sequences were created by switching the last two tones (the second dependent element of the NAD). The frequency of all tones was between 500 and 2000 Hz, covering the most important frequencies of human speech, and were generated as equal steps on a logarithmic scale to be perceived as equidistant in pitch. Each tone was 270 ms long, with 60 ms pauses between tones. Overall, tone sequences were 2.58 s long. The tone sequences were matched to the Italian sentences (Friederici et al., 2011) on mean overall duration, mean duration of the individual tones and syllables, and overall duration of pauses. Please see van der Kant et al. (2020) for more information about the tone stimuli.

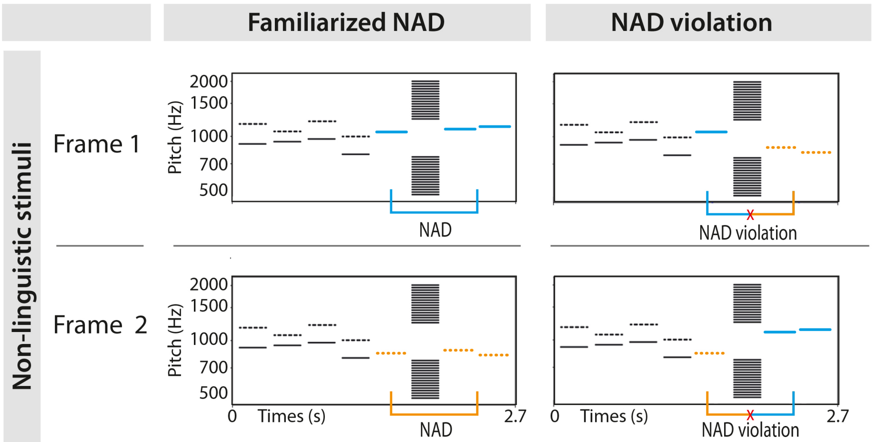

FIGURE 2.1: Visualization of the non-linguistic stimuli. Unicolored brackets visualize dependencies between the fifth tone and the two last tones. Bicolored brackets and red crosses indicate dependency violations.

2.2.3 Procedure

During the EEG experiments, infants were seated or laid on the caregiver's lap in a soundproof booth. Each EEG experiment consisted of four familiarization phases (3.3 minutes), consisting of 64 correct sequences (overall 256 sequences). Each familiarization phase was followed by a test phase (1.3 minutes), consisting of 8 correct and 8 incorrect sentences (overall 32 sequences per condition; see Figure 2.2). We counterbalanced which tone combinations (correct or incorrect in Figure 2.1) infants were familiarized with. Regardless of which tone combinations infants were familiarized with, we will refer to sequences presented in the familiarization phases as correct sequences. The inter-stimulus-intervals (ISI) were 580 ms in the familiarization phases and 1380 ms in the test phases. Between learning and test phases, there was a pause of 2780 ms. As in Friederici et al. (2011), the EEG experiment took approximately 20 min.

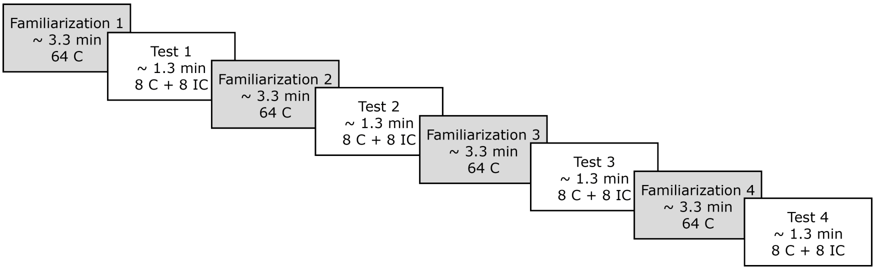

FIGURE 2.2: Experimental procedure: alternating familiarization and test phases. Participants listened to four familiarization phases (64 correct trials each) alternated with four test phases (eight correct and eight incorrect trials each). C: correct, IC: incorrect. Figure taken from Paul et al. (2021).

2.2.4 Data recording and analysis

EEG data were recorded from 24 Ag/AgCl electrodes (FP1, F7, F3, Fz, F4, F8, FC5, FC6, T7, C3, Cz, C4, T8, CP5, CP6, P7, P3, Pz, P4, P8, O1, O2, TP9, and TP10) placed according to the International 10-20 System of Electrode Placement and secured in an elastic electrode cap (Easycap GmbH, Herrsching, Germany). Cz served as an online reference during recording. Electrooculograms (EOG) were recorded supraorbitally and infraorbitally to the right eye from FP2 and V-, respectively, as well as laterally to the left and right eye from F9 and F10, respectively. The signal was digitized with a sampling rate of 500 Hz.

The EEG data were preprocessed using the Fieldtrip toolbox (Oostenveld et al., 2011) implemented in Matlab (The MathWorks, 2017). The signal was re-referenced offline to the linked mastoids (the algebraic average of TP9 and TP10) and downsampled to 250 Hz. We applied a kaiser-windowed finite-impulse response high-pass filter with half-amplitude cutoff (-6 dB) of 0.3 Hz and and a transition width of 0.3 Hz and a low-pass filter with a half-amplitude cutoff (-6dB) of 30 Hz and a transition width of 5 Hz and otherwise identical filter settings. Data were segmented and timelocked to the onset of the suffix, with a 200 ms pre-stimulus period and 1400 ms post-stimulus period. Artefact rejection was performed semi-automatically. Segments of the signal exceeding a z-value of 7 were highlighted automatically. Then, we rejected muscle and jump artifacts manually. To correct ocular artifacts, we used an independent component analysis (ICA). For this, we used the method "runica" as implemented in the FieldTrip toolbox (Oostenveld et al., 2011). We decomposed the data from all channels except the bipolar EOG channels into 26 ICA components. Using the topographies and time representation of ICA components, we rejected components corresponding to artefacts.

We computed separate repeated measures analysis of variance (rm-ANOVA) for lateral electrodes (lateral rm-ANOVA) and midline electrodes (central rm-ANOVA). The lateral, four-way rm-ANOVA, included the within-subject factors condition (correct, incorrect), region (frontal, central, parietal), hemisphere (left, right), and time (0-200 ms, 200-400 ms, 400-600 ms, 600-800 ms, 800-1000 ms, 1000-1200 ms, 1200-1400 ms). Single electrode positions were assigned to the factors region and hemisphere in the following way: frontal region: F7, F3, FC3, FC4, F4, F7; central region: T7, CP5, C3, C4, CP6, T8; posterior region: O1, P7, P3, P4, P8, O2; left hemisphere: F7, F3, FC3, T7, CP5, C3, O1, P3, P7; and right hemipshere: F8, F4, FC4, T8, CP6, C4, O2, P4, P8. The midline, three-way rm-ANOVA included the factors condition (correct, incorrect) x region (frontal, central, parietal) x time (0-200 ms, 200-400 ms, 400-600 ms, 600-800 ms, 800-1000 ms, 1000-1200 ms, 1200-1400 ms). Fz, Cz and Pz were assigned to the frontal, central, and posterior region, respectively. In the result section, we only report statistically significant interactions and main effects that include the factor condition.

2.3 Results

We found no statistically significant main effects or interactions including the factor condition, in neither the lateral nor the central rm-ANOVA (all Fs < 2.1, all ps > 0.1; see Supplementary Table 2.1). That is, there was no evidence that infants processed NAD violations (incorrect condition) significantly differently than familiarized NADs (correct condition). For a visualization of the ERP waves, see Figure 2.3.

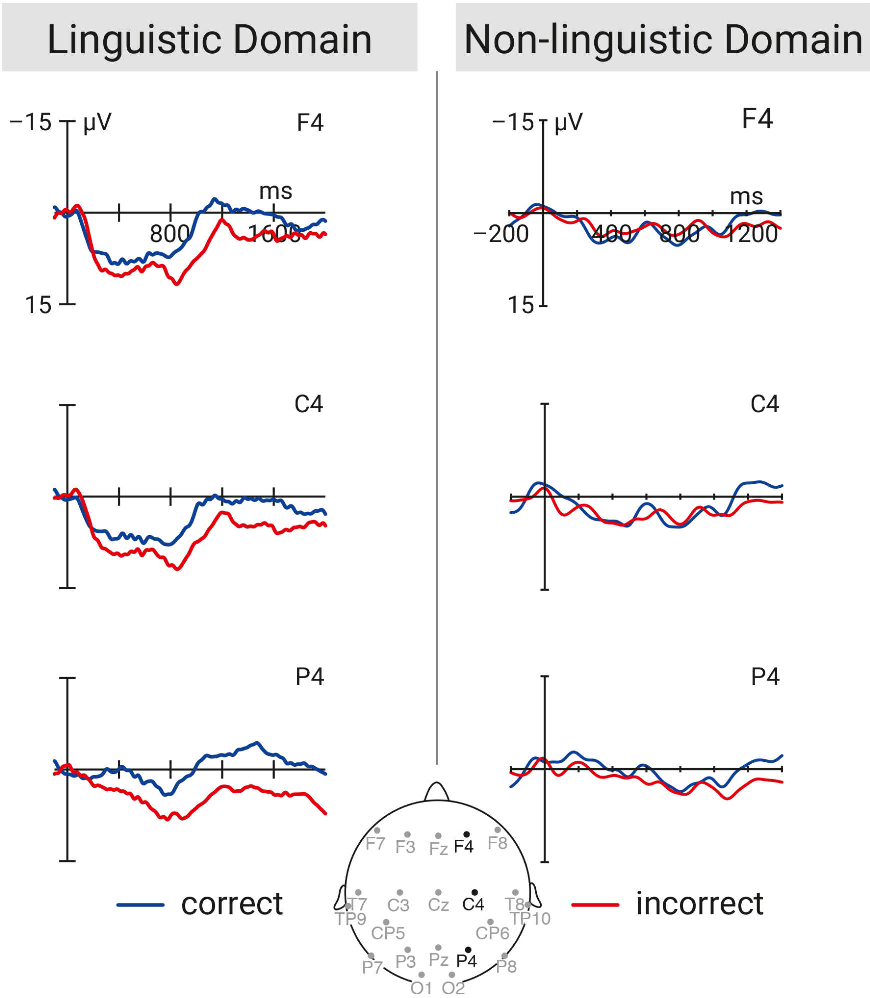

FIGURE 2.3: Grand-averaged event-related potentials in response to NAD violations and familiarized NADs. Left panel: Data from the linguistic domain (N = 34, adapted from Friederici et al., 2011). Right panel: Preliminary data from the non-linguistic domain (N = 20, present study). ERPs are timelocked to the onset of the verb stem (linguistic domain) and the onset of the sixth tone (non-linguistic domain). Familiarized (correct) NADs are shown in blue, NAD violations (incorrect) are shown in red.

2.4 Discussion

In the current study, we aimed to investigate whether 4-month-old infants are able to learn NADs from non-linguistic tone sequences. Infants were exposed to tone sequences containing NADs and subsequently tested with a mixture of tone sequences containing familiarized NADs (correct items) and sequences containing NAD violations (incorrect items). Due to COVID-19-related restrictions, the present paper presents preliminary results from a sample of 20 infants. Our preliminary results do not provide evidence that infants at 4 months of age detected NAD violations. If these results remain unchanged with a larger sample, this will indicate that very young infants cannot yet learn NADs from tone sequences, at least under the present experimental conditions, that is, under passive listening conditions and after approximately 13 minutes of exposure. This would put the onset of NAD learning in the non-linguistic auditory domain later in development, likely between 2 and 3 years of age (van der Kant et al., 2020).

Our findings provide a first indication that early development of NAD learning differs between the linguistic and non-linguistic auditory domain. Our study was designed to be directly comparable to a previous study testing infants' NAD learning in the linguistic domain (Friederici et al., 2011). This study demonstrated that 4-month-old infants were able to detect linguistic NADs embedded in sentences (Friederici et al., 2011). Despite the paradigm being directly comparable and the stimuli being matched on several dimensions, there was evidence for learning in the linguistic domain (Friederici et al., 2011), but not the non-linguistic domain (based on the present study). While a more direct, statistical comparison between these two studies will need to be conducted on the final sample, the present results provide first, preliminary evidence that NAD learning in its earliest stages may be specific to language.

The possible domain-specific nature of NAD learning during early development fits with recent findings that young children fail to learn NADs in the non-linguistic domain, while learning them in the linguistic domain. In particular, a recent fNIRS study demonstrated that even at 2 years, children struggle to learn NADs from tone sequences, whereas they readily learned NADs from linguistic material (van der Kant et al., 2020). Only at 3 years of age did this study find evidence for successful non-linguistic NAD learning. Together, our studies indicate that the developmental trajectory of NAD learning differs between the linguistic and the non-linguistic auditory domain and that these differences are already present during the earliest stages of development. To the best of our knowledge, there are currently no other direct comparisons between NAD learning in the linguistic and non-linguistic auditory domain. However, studies investigating NAD learning in the linguistic and the non-linguistic domain separately find NAD learning in both domains for adults and even with similar limitations on learning between the domains. For example, learning was only found when perceptual cues eased learning (e.g., Creel et al., 2004; Gebhart et al., 2009; Onnis et al., 2005). It is therefore possible that the differences between the linguistic and non-linguistic auditory domain diminish later in development, but more direct comparisons between the domains are needed to test this claim. Based on the available evidence, NAD learning seems to be specific to language at least during infancy early childhood (van der Kant et al., 2020).

The possible domain-specific nature of early NAD learning is in contrast with other forms of SL. For adjacent dependencies, there is evidence that humans possess the ability to track transitional probabilities across age and across domains: newborns can learn adjacent dependencies in the linguistic auditory (Teinonen et al., 2009) and the non-linguistic visual domain (Bulf et al., 2011); infants at 8 months of age can learn adjacent dependencies both in the linguistic (Saffran, Aslin, et al., 1996; Aslin et al., 1998; Black, 2017) and in the non-linguistic auditory domain (Saffran et al., 1999); and adults have also been shown to learn adjacent dependencies in the linguistic (Saffran, Newport, et al., 1996) and non-linguistic auditory domain (Saffran et al., 1999), as well as in the visual (Conway and Christiansen, 2009) and the haptic domain (Conway and Christiansen, 2005). Non-adjacent repetiion-based dependencies can be learned at 4-5 months in the non-linguistic domain (Dawson and Gerken, 2009), even from more complex, nested dependencies (Winkler et al., 2018). However, the dependent elements in these studies were identical, which likely eases learning compared to the non-identical NADs in our study (see Wilson et al., 2018). Taken together, the domain-specificity for language observed in early NAD learning stands in contrast to other types of statistical learning, which can be learned across domains, both in infancy and later in life.

Seeming differences in domains for learning repetiion-based dependencies (Marcus et al., 2007; Dawson and Gerken, 2009) were recently shown to be explained by the meaningfulness of stimuli rather than domain-specificity. Previous studies had reported differences in domains, with 7-month-old infants being able to learn repetiion-based dependencies in the linguistic auditory domain, but not other domains (Marcus et al., 1999; Marcus et al., 2007). However, other studies reported learning in the visual domain when stimuli were pictures of animals (Saffran et al., 2007). A recent meta-analysis suggested that these findings could be reconciled by considering whether the stimuli were meaningful rather than in which domain they were presented (Rabagliati et al., 2019). Indeed, in a follow-up experiment, the authors demonstrated that infants could learn repetiion-based dependencies from gestures only when they were perceived as meaningful but not when they were perceived as meaningless (Rabagliati et al., 2019). Here, we cannot account for whether the reported differences between the linguistic and non-linguistic domain are due to meaningfulness of the stimuli. Further studies will need to investigate whether the domain-differences observed in NAD learning can be explained by the meaningfulness of stimuli.

In conclusion, we provide first, preliminary evidence that there are domain-specific differences in the onset of NAD learning between the linguistic and non-linguistic auditory domain. We did not find evidence for NAD learning from tone sequences by 4-month-old infants, who had previously been shown to be able to learn NADs from linguistic material. Based on our findings and previous studies, there seems to be an advantage for linguistic compared to non-linguistic NAD learning during infancy and early childhood.

Supplementary Materials

TABLE 2.1: Overview of results of the lateral and central repeated measures ANOVA. Only main effects and interactions including the factor condition are shown.

	lateral ANOVA		central ANOVA	
	F-value	p-value	F-value	p-value
cond	2.047	0.169	1.887	0.186
cond * regi	0.713	0.497	0.957	0.393
cond * hemi	0.909	0.352	NA	NA
cond * time	0.067	0.999	0.373	0.895
cond * regi * hemi	0.420	0.660	NA	NA
cond * regi * time	0.338	0.981	0.574	0.862
cond * hemi * time	1.556	0.166	NA	NA
cond * regi * hemi * time	0.831	0.619	NA	NA

Note: The central ANOVA only included midline electrodes and thus did not include the factor hemisphere. cond - condition; regi - region; hemi - hemisphere.

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Chapter 3

Experiment 2: Developmental trajectory of linguistic NAD learning

Gradual development of non-adjacent dependency learning during early childhood

Mariella Paul[1,2,3], Claudia Männel[1,4], Anne van der Kant[5], Jutta L. Mueller[6,7], Barbara Höhle[5], Isabell Wartenburger[2,5], and Angela D. Friederici[1,2]

[1] Department of Neuropsychology, Max Planck Institute for Human Cognitive and Brain Sciences
[2] Berlin School of Mind and Brain, Humboldt-Universität zu Berlin
[3] Psychology of Language Research Group, University of Göttingen
[4] Clinic of Audiology and Phoniatrics, Charité – Universitätsmedizin Berlin
[5] Cognitive Sciences, Dept. Linguistics, University of Potsdam
[6] Institute of Cognitive Science, Osnabrück University
[7] Institute of Linguistics, University of Vienna

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Abstract

In order to become proficient native speakers, children have to learn the morpho-syntactic relations between distant elements in a sentence, so-called non-adjacent dependencies (NADs). Previous research suggests that NAD learning in children comprises different developmental stages, where until 2 years of age children are able to learn NADs associatively under passive listening conditions, while starting around the age of 3 to 4 years children fail to learn NADs during passive listening. To test whether the transition between these developmental stages occurs gradually, we tested children's NAD learning in a foreign language using event-related potentials (ERPs). We found ERP evidence of NAD learning across the ages of 1, 2 and 3 years. The amplitude of the ERP effect indexing NAD learning, however, decreased with age. These findings might indicate a gradual transition in children's ability to learn NADs associatively. Cognitively, this transition might be driven by children's increasing knowledge of their native language, hindering NAD learning in novel contexts. Neuroanatomically, maturation of the prefrontal cortex might play a crucial role, promoting top-down learning, affecting bottom-up, associative learning. In sum, our study suggests that NAD learning under passive listening conditions undergoes a gradual transition between different developmental stages during early childhood.

Keywords: development, language acquisition, statistical learning, artificial language learning, non-adjacent dependencies, event-related potentials

3.1 Introduction

In order to successfully communicate with their environment, infants must not only learn the words of their native language(s) but also the relations that define how these words combine into phrases and sentences. These relations can hold for neighboring elements in a sentence (e.g., *Mary is happy*) or non-neighboring elements (e.g., *The sister is singing*). These latter relations, so-called non-adjacent dependencies (NADs), require the learner to track dependent elements (is and -ing in these examples) across one or more intervening elements (here: *sing-*). NADs are a crucial aspect of natural languages and are present, for example, in subject-verb agreement and English tense marking. Nevertheless, NADs are relatively difficult to learn and behavioral evidence indicates that, during both natural language acquisition and artificial language learning, children learn NADs only in their second year of life, around 14-15 months of age, depending on the acquired language (Culbertson et al., 2016; Gómez and Maye, 2005; Höhle et al., 2006; Santelmann, 1998).

The learning of NADs during early childhood has been shown to undergo different developmental stages, both in terms of behavioral and neurophysiological learning measures (Culbertson et al., 2016; Mueller et al., 2019; van der Kant et al., 2020). For example, Culbertson et al. (2016) investigated French infants' learning of NADs in subject-verb agreement in French stimuli and observed two stages of different behavioral responses in a head-turn preference procedure. Across age, children displayed two cycles of a shift from a familiarity preference for encountered NADs to a novelty preference. The authors proposed that the processes related to the first stage, from 14 to 18 months of age, reflect initial surface-level representations based on phonological features of the NADs. In contrast, the processes related to the second stage, from 21 to 24 months of age, were interpreted as higher-level representations of the morphological features (Culbertson et al., 2016). The current paper aims to investigate the transition between these developmental stages in NAD learning more closely by looking at the development of surface-level phonological NAD learning in non-native speech stimuli throughout early childhood using event-related potentials (ERPs).

Previous studies using ERPs have provided evidence for the existence of different developmental stages of NAD learning. Friederici et al. (2011) tested German 4-month-old infants' NAD learning in a passive listening familiarization-test paradigm using a non-native language (Italian) containing NADs (e.g., *La sorella sta cantando*; *The sister is singing*). By means of ERPs, the authors showed that even at the early age of 4 months, infants succeeded at NAD learning. Learning was indexed by a late positive ERP effect, which was interpreted as associative learning of NADs based on phonological cues (Friederici et al., 2011). NAD learning in this miniature version of Italian and in similarly structured syllable sequences was shown to display different developmental stages during early childhood, with an initial stage up to the age of 2 to 3 years, during which young children can learn NADs through passive listening, which likely triggers associative learning (Friederici et al., 2011; Mueller et al., 2019; van der Kant et al., 2020). This is followed by a stage starting at around 3 to 4 years, during which children and adults struggle to learn NADs under passive listening (without additional cues marking the NADs), but succeed in learning under active listening conditions, that is, when a task, administered during the whole experiment or during testing only, guides their attention towards the NADs (Friederici et al., 2013; Lammertink et al., 2019; Mueller et al., 2012; Mueller et al., 2019; see also Pacton et al., 2015; Pacton and Perruchet, 2008). Notably, adults' neural signature of NAD learning under active listening conditions differed from infants' neural signature under passive listening: Adults under active task conditions showed an N400-like, negative ERP component and a P3, which were interpreted as indicating lexicalization of the NADs and attention-driven processing respectively (Mueller et al., 2009). This is in contrast to infants' associative learning triggered by passive listening, which was based on phonological information processing, indexed by a late positive ERP component (Friederici et al., 2011; Friederici et al., 2013). This difference in ERP responses between adults and infants was proposed to partly be driven by the maturation of the prefrontal cortex which supports top-down processes in contrast to the temporal cortex subserving bottom-up associative processes (Skeide and Friederici, 2016). This proposal is in line with the results of a study that tested adults' NAD learning while top-down processing was suppressed (by inhibiting the prefrontal cortex with transcranial direct current stimulation; Friederici et al., 2013). Under these conditions, adults showed a late positive ERP component in response to NAD violations, comparable to the ERP response found in infants using the same paradigm. This ERP response was interpreted to indicate associative

NAD learning, comparable to infants' learning (Friederici et al., 2013). Thus, ERP research on NAD learning further corroborates the observation of different developmental stages, as the neural signature of NAD learning seems to change with age, and is dependent on the presence or absence of a task. However, it is less clear exactly when or how the transition between these developmental stages occurs, and whether the transition occurs abruptly or more gradually across preschool age.

Investigating the nature of the transition between the different developmental stages of NAD learning can improve our understanding of children's acquisition of grammatical rules and language learning in general. A rich body of literature has demonstrated that the ability for language learning, and in particular learning grammatical rules, has its peak in infancy and decreases over development (e.g., Hartshorne et al., 2018; Johnson and Newport, 1989; Senghas et al., 2004; Singleton, 2005). It has been suggested that this time course is driven by a sensitive period for language learning under passive listening conditions influenced by brain plasticity (e.g., Knudsen, 2004; Kuhl, 2004; Kuhl, 2010; see also Skeide and Friederici, 2016). Crucially, first language learning occurs under passive listening conditions. That is, infants learn NADs in their first language by simply listening to their environment, without being taught explicit rules (see Perruchet and Pacton, 2006). If NAD learning under passive listening conditions indeed undergoes a sensitive period, defined by a gradual closing of the period (Knudsen, 2004), we would expect to see a gradual transition between the developmental stages of NAD learning. Based on the studies reviewed above, we would expect to observe surface-based learning of phonological associations during this potential sensitive period.

In the present study, we aimed to confirm the presence of different developmental stages of NAD learning found in previous studies (Culbertson et al., 2016; Mueller et al., 2019; van der Kant et al., 2020) and, for the first time, systematically investigate the nature of the transition between the different developmental stages of NAD learning under passive listening conditions. In particular, we aimed to investigate whether this transition occurs in a gradual manner, which may point towards a sensitive period of NAD learning under passive listening conditions. To investigate this, we used the same familiarization-test paradigm with Italian sentences as previous ERP studies that provided evidence for different developmental stages of NAD learning (Friederici et al., 2011; Friederici et al., 2013; Mueller et al., 2009; van der Kant et al., 2020). Using a set of non-native sentences allows for combining the advantages of artificial grammars, by controlling for children's exposure to the language, and those of natural language, by being more naturalistic than artificial grammars. Based on previous findings with the same paradigm and artificial grammar paradigms, we propose that a transition between different developmental stages of NAD learning takes place between 2 and 4 years of age (Mueller et al., 2019; van der Kant et al., 2020). To investigate whether this transition occurs in a gradual manner, that is, whether we can observe a linear decline in NAD learning under passive listening conditions during early childhood, we exposed 1- to 3-year-old children to Italian sentences under passive listening conditions in a familiarization-test paradigm while recording ERPs. ERPs offer the advantage that they can be measured throughout the age range tested here, because they do not require children to give explicit responses or to exhibit any kind of behavior (as in the head-turn preference procedure). ERPs also allow us to make inferences based on both the strength (amplitude) and the timing (latency) of children's ERP responses. Based on previous infant and adult ERP studies using the same familiarization-test paradigm (Friederici et al., 2011; Friederici et al., 2013), we expected passive listening to trigger associative learning. In these previous studies, detection of NAD violations was indexed by a late positive ERP effect in response to incorrect sentences (containing NAD violations) compared to correct sentences (containing familiarized NADs) during test phases. If the transition between the different stages of NAD learning indeed occurs in a gradual manner, we would expect to see a linear decrease in the amplitude of this ERP effect of NAD learning between the age of 1 and 3 years. If the transition instead occurs more abruptly, we would not expect to see a linear decrease in ERP amplitude between the ages of 1 and 3 years; in this case we would expect the amplitude of the ERP effect to be either unchanged across the ages tested here or to show evidence for learning in the younger, but not in the older children. More specifically, we hypothesize a significant difference in ERP responses to NAD violations compared to familiarized NADs under passive listening conditions for 1-year-old children, who have been shown to successfully learn NADs in an associative manner (Culbertson et al., 2016). For 2-year-olds, we expect successful NAD learning under passive listening conditions (Mueller et al., 2019; van der Kant et al., 2020), although the strength of associative learning under passive listening conditions may have started to decrease (Culbertson et al., 2016). Finally, for 3-year-old children, we expect a further decline of the strength of NAD learning under passive listening conditions, based on a previous ERP study that found that only a subgroup of 4-year-old children learned NADs under passive listening (Mueller et al., 2019, but see van der Kant et al., 2020 for no evidence for NAD learning under passive listening conditions at 3 years of age using functional near-infrared spectroscopy (fNIRS).

In previous ERP studies on NAD learning, the detection of NAD violations was indexed by different ERP responses, depending on the specifics of the experimental design and stimuli as well as the studied participant sample. In particular, in the studies using the same Italian sentence material as we use here, the ERP polarity differed depending on participants' age and whether participants were tested under passive listening conditions or performed a violation detection task (Friederici et al., 2011; Friederici et al., 2013; Mueller et al., 2009). Moreover, ERP polarity was shown to change with the discrimination difficulty of the chosen stimuli (Schaadt & Männel, 2019), infants' sex (Mueller et al., 2012), and whether school-age children were tested immediately after NAD learning or following a retention period involving sleep (Schaadt et al., 2020). Similarly, the polarity of infants' ERP effects was found to be associated with later language outcomes in studies testing lexical segmentation and phoneme discrimination (Kooijman et al., 2013; Schaadt et al., 2015). Based on the polarity differences in these studies, we do not make a priori predictions about the polarity of the measured ERP effects, but investigate whether it plays a role in the developmental stages of NAD learning and the transition between them. We included ERP polarity in an exploratory analysis and investigated whether the ERP effect's polarity was associated with children's age, sex or behaviorally tested language development (comprehension and production), as it was in previous ERP studies (Friederici et al., 2011; Friederici et al., 2013; Kooijman et al., 2013; Mueller et al., 2012; Schaadt et al., 2015).

Investigating the nature of the transition between the different developmental stages of NAD learning can improve our understanding of children's acquisition of grammatical rules and language learning in general. A rich body of literature has demonstrated that the ability for language learning, and in particular learning grammatical rules, has its peak in infancy and decreases over development (e.g., Hartshorne et al., 2018; Johnson and Newport, 1989; Senghas et al., 2004;

Singleton, 2005). It has been suggested that this time course is driven by a sensitive period for language learning under passive listening conditions influenced by brain plasticity (e.g., Knudsen, 2004; Kuhl, 2004; Kuhl, 2010; see also Skeide and Friederici, 2016). Crucially, first language learning occurs under passive listening conditions. That is, infants learn NADs in their first language by simply listening to their environment, without being taught explicit rules (see Perruchet and Pacton, 2006). If NAD learning under passive listening conditions indeed undergoes a sensitive period, defined by a gradual closing of the period (Knudsen, 2004), we would expect to see a gradual transition between the developmental stages of NAD learning. Based on the studies reviewed above, we would expect to observe surface-based learning of phonological associations during this potential sensitive period.

In the present study, we aimed to confirm the presence of different developmental stages of NAD learning found in previous studies (Culbertson et al., 2016; Mueller et al., 2019; van der Kant et al., 2020) and, for the first time, systematically investigate the nature of the transition between the different developmental stages of NAD learning under passive listening conditions. In particular, we aimed to investigate whether this transition occurs in a gradual manner, which may point towards a sensitive period of NAD learning under passive listening conditions. To investigate this, we used the same familiarization-test paradigm with Italian sentences as previous ERP studies that provided evidence for different developmental stages of NAD learning (Friederici et al., 2011; Friederici et al., 2013; Mueller et al., 2009; van der Kant et al., 2020). Using a set of non-native sentences allows for combining the advantages of artificial grammars, by controlling for children's exposure to the language, and those of natural language, by being more naturalistic than artificial grammars. Based on previous findings with the same paradigm and artificial grammar paradigms, we propose that a transition between different developmental stages of NAD learning takes place between 2 and 4 years of age (Mueller et al., 2019; van der Kant et al., 2020). To investigate whether this transition occurs in a gradual manner, that is, whether we can observe a linear decline in NAD learning under passive listening conditions during early childhood, we exposed 1- to 3-year-old children to Italian sentences under passive listening conditions in a familiarization-test paradigm while recording ERPs. ERPs offer the advantage that they can be measured throughout the age range tested here, because they do not require children to give explicit responses or to exhibit any kind of behavior (as in the head-turn preference procedure). ERPs also allow us to make inferences based on both the strength (amplitude) and the timing (latency) of children's ERP responses. Based on previous infant and adult ERP studies using the same familiarization-test paradigm (Friederici et al., 2011; Friederici et al., 2013), we expected passive listening to trigger associative learning. In these previous studies, detection of NAD violations was indexed by a late positive ERP effect in response to incorrect sentences (containing NAD violations) compared to correct sentences (containing familiarized NADs) during test phases. If the transition between the different stages of NAD learning indeed occurs in a gradual manner, we would expect to see a linear decrease in the amplitude of this ERP effect of NAD learning between the age of 1 and 3 years. If the transition instead occurs more abruptly, we would not expect to see a linear decrease in ERP amplitude between the ages of 1 and 3 years; in this case we would expect the amplitude of the ERP effect to be either unchanged across the ages tested here or to show evidence for learning in the younger, but not in the older children. More specifically, we hypothesize a significant difference in ERP responses to NAD violations compared to familiarized NADs under passive listening conditions for 1-year-old children, who have been shown to successfully learn NADs in an associative manner (Culbertson et al., 2016). For 2-year-olds, we expect successful NAD learning under passive listening conditions (Mueller et al., 2019; van der Kant et al., 2020), although the strength of associative learning under passive listening conditions may have started to decrease (Culbertson et al., 2016). Finally, for 3-year-old children, we expect a further decline of the strength of NAD learning under passive listening conditions, based on a previous ERP study that found that only a subgroup of 4-year-old children learned NADs under passive listening (Mueller et al., 2019; but see van der Kant et al., 2020 for no evidence for NAD learning under passive listening conditions at 3 years of age using fNIRS.

In previous ERP studies on NAD learning, the detection of NAD violations was indexed by different ERP responses, depending on the specifics of the experimental design and stimuli as well as the studied participant sample. In particular, in the studies using the same Italian sentence material as we use here, the ERP polarity differed depending on participants' age and whether participants were tested under passive listening conditions or performed a violation detection task (Friederici et al., 2011; Friederici et al., 2013; Mueller et al., 2009). Moreover, ERP polarity was shown to change with the discrimination difficulty of the chosen stimuli (Schaadt and Männel, 2019), infants' sex (Mueller et al., 2012), and whether school-age children were tested immediately after NAD learning or following a retention period involving sleep (Schaadt et al., 2020). Similarly, the polarity of infants' ERP effects was found to be associated with later language outcomes in studies testing lexical segmentation and phoneme discrimination (Kooijman et al., 2013; Schaadt et al., 2015). Based on the polarity differences in these studies, we do not make a priori predictions about the polarity of the measured ERP effects, but investigate whether it plays a role in the developmental stages of NAD learning and the transition between them. We included ERP polarity in an exploratory analysis and investigated whether the ERP effect's polarity was associated with children's age, sex or behaviorally tested language development (comprehension and production), as it was in previous ERP studies (Friederici et al., 2011; Friederici et al., 2013; Kooijman et al., 2013; Mueller et al., 2012; Schaadt et al., 2015).

3.2 Materials and methods

3.2.1 Participants

115 healthy children growing up in monolingual German families participated in this study. Of these, 40 were 1 year old (mean age: 12.80 months, SD: 0.54; 20 girls), 40 were 2 years old (mean age: 25.08 months, SD: 0.88; 16 girls) and 35 were 3 years old (mean age: 37.10, SD: 0.60; 18 girls). Children were orally informed about the experimental procedure and caregivers were informed both in written and oral form. Caregivers gave written informed consent for their children's participation in the study. Ethical approval was obtained from the Medical Faculty of the University of Leipzig. Forty-nine additional children had to be excluded from data analysis, either due to non-compliance during the experimental procedure (22 children) or because they contributed less than 10 artefact-free EEG trials per condition across all test phases and/or no trials in at least one test phase (27 children). For additional information on EEG trial numbers see Table 3.1.

TABLE 3.1: Overview of participants and trials. “Additional participants” refers to children that were tested, but excluded based on either non-compliance or insufficient number of artefact-free EEG trials. Correct and incorrect trials refer to the average number of included trials in the correct and incorrect condition during test phases. The difference in trial numbers between the correct and incorrect conditions was not significant for any age group (all p>0.1).

	1 year	2 years	3 years
Participants (N)	40	40	35
Mean age (months)	12.80 (SD: 0.54)	25.08 (SD: 0.88)	37.10 (SD: 0.60)
Sex	20 girls	16 girls	18 girls
Additional participants (N)	28	15	6
Correct Trials (N)	21.90 (SD: 4.24)	24.25 (SD: 4.47)	26.77 (SD: 4.15)
Incorrect Trials (N)	22.53 (SD: 3.85)	23.93 (SD: 4.70)	27.26 (SD: 3.59)

3.2.2 Stimuli

EEG experiment

The stimuli for the EEG experiment were adapted from Mueller et al. (2009). Participants listened to Italian sentences (see Figure 3.1) spoken by a female native speaker of Italian. The sentences consisted of a determiner phrase (*La sorella (The sister)* or *Il fratello (The brother)*), followed by a verb phrase consisting of an auxiliary (*sta (is)* or a modal verb *puo (can)*), a verb stem (32 different verbs, e.g., *cant- (sing-)*), and a suffix (*-ando (-ing)* or *-are* (-∅)). In grammatical sentences, *sta (is)* is followed by a verb stem and *-ando (-ing)*, while *puo (can)* is followed by a verb stem and *-are* (-∅). In ungrammatical sentences, the verb suffixes did not match the auxiliary, namely *sta (is)* was followed by a verb stem and *-are* (-∅), while *puo (can)* was followed by a verb stem and *-ando (-ing)*. Crucially, to avoid introducing acoustic cues regarding the grammaticality of the sentence as well as potential acoustic differences between the two conditions, the speaker produced only grammatical sentences and both correct and incorrect sentences underwent a cross-splicing procedure (Adobe Audition), in which the verb was exchanged with the verb from a different sentence (see Friederici et al., 2011).

Sentences had a mean length of 2.43 s (SD: 0.12). Because we counterbalanced whether participants were familiarized with grammatical or ungrammatical Italian sentences, we will refer to the NADs presented in the familiarization phases as correct (i.e., regardless of grammaticality in Italian).

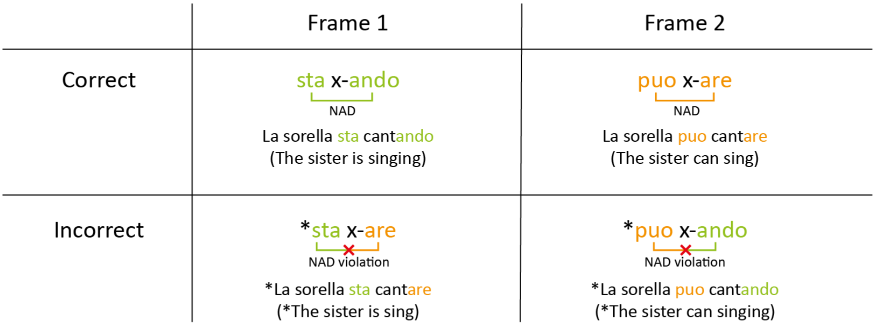

FIGURE 3.1: Visualization of the stimuli for the EEG experiment with examples, adapted from Friederici et al. (2011). Ungrammatical sentences and frames are marked with an asterisk. Unicolored brackets visualize non-adjacent dependencies (NADs). Bicolored brackets and red crosses indicate NAD violations.

Tests of language development

For all three age groups, we behaviorally assessed language abilities via standardized tests. For 1-year-old children, we used the German version of the Bayley Scales of Infant and Toddler Development Screening Test (Bayley, 2015). For the language comprehension measure, we used the subscale receptive language of the Screening Test and for the language production measure, we used the subscale productive language. Both of these subscales assess children's vocabulary in a playful interactive manner. For 2- and 3-year-old children, we used the Sprachentwicklungstest für zweijährige Kinder (SETK-2; Grimm et al., 2016) and Sprachentwicklungstest für drei- bis fünfjährige Kinder (SETK 3-5; Grimm, 2015), respectively. For 2-year-old children's language scores, we used the averaged word and sentence comprehension and production subscales. For 3-year-old children's language scores, we used the sentence comprehension and production measures. Because the Bayley Screening Test only offers raw scores, we used z-transformed raw scores of all tests to allow for comparisons across age groups.

3.2.3 Procedure

During the EEG experiment, participants were seated on their caregiver's lap in a soundproof booth. The experiment consisted of four familiarization phases alternating with four test phases. Familiarization phases (3.3 minutes each) consisted of 64 correct sentences each (overall 256 sentences). Each familiarization phase was followed by a test phase (1.3 minutes each), consisting of 8 correct and 8 incorrect sentences each (overall 32 sentences per condition; see Figure 2). Note that the sentences that participants heard in the test phases were not repeated in any of the familiarization phases. Furthermore, verb stems were divided into two sets, such that they were not presented in the familiarization phase immediately preceding a given test phase, but only occurred in earlier or later familiarization phases. The inter-stimulus-intervals (ISI) were 580 ms in the familiarization phases and 1380 ms in the test phases. Between familiarization and test phases, there was a pause of 2780 ms. Overall, the EEG experiment took approximately 20 min, during which participants watched a silent children's movie (*Peppa Pig*, *Bummi*, or *Alles Trick 9*) in order to increase compliance. The EEG experiment and the standardized language tests were either administered during the same session or in two separate sessions (mean time between sessions: 13.35 days, SD: 14.78).

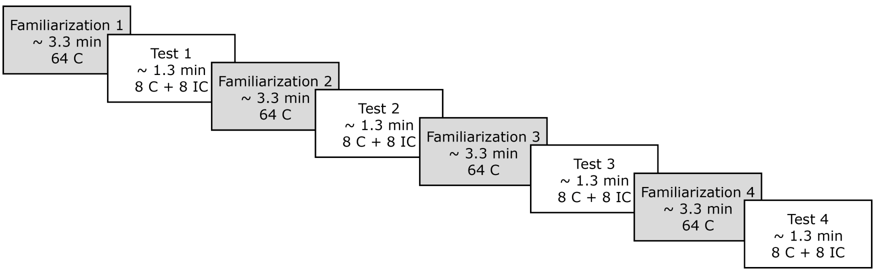

FIGURE 3.2: Experimental procedure: alternating familiarization and test phases. Participants listened to four familiarization phases (64 correct trials each) alternated with four test phases (eight correct and eight incorrect trials each). C: correct, IC: incorrect. Figure adapted from Friederici et al. (2011).

3.2.4 Data recording

EEG data were recorded from 24 Ag/AgCl electrodes (Fp1, F7, F3, Fz, F4, F8, FC3, FC4, T7, C3, Cz, C4, T8, CP5, CP6, P7, P3, Pz, P4, P8, O1, O2, M1, and M2) placed according to the International 10-20 System of Electrode Placement and secured in an elastic electrode cap (Easycap GmbH, Herrsching, Germany). Cz served as an online reference during recording. Electrooculograms (EOG) were recorded from 4 additional electrodes, placed supraorbitally (Fp2) and infraorbitally (V-) to the right eye to capture vertical eye movements, as well as laterally to the left (F9) and right eye (F10), for horizontal eye-movements. The signal was digitized with a sampling rate of 500 Hz.

The EEG data were analyzed using the Fieldtrip toolbox (Oostenveld et al., 2011) implemented in Matlab (MATLAB, 2017). Scripts for both preprocessing and analysis can be found on the Open Science Framework (https://osf.io/43t9q). The signal was re-referenced offline to the linked mastoids (the algebraic average of M1 and M2) and down-sampled to 250 Hz. We applied a kaiser-windowed finite-impulse response high-pass filter with half-amplitude cutoff (-6 dB) of 0.3 Hz and a transition width of 0.3 Hz. We also applied a kaiser-windowed finite-impulse response low-pass filter with a half-amplitude cutoff (-6dB) of 30 Hz and a transition width of 5 Hz. Data were segmented and time-locked to the onset of the suffix, with a 600 ms pre-stimulus period (to include the onset of the verb stem) and 1300 ms post-suffix-onset period. Artefact rejection was performed semi-automatically. Segments of the signal exceeding a z-value of 7 were highlighted automatically and screened manually to reject muscle and coarse-movement artefacts. To correct ocular artefacts, we used an independent component analysis (ICA) ("runica", implemented in the FieldTrip toolbox; Oostenveld et al., 2011), decomposed the data from all channels into 26 ICA components, and rejected components corresponding to blinks and saccades. Afterward, we shortened the baseline period to 400 ms pre-suffix onset for plotting and averaging.

3.2.5 Statistical Analysis

For the main statistical analysis, we used linear models (LMs; see Frömer et al., 2018 for use of LMs and linear mixed models with EEG data), as implemented in the lme4 package (Bates et al., 2015) in R (R Core Team, 2017). LMs offer a reliable way to analyze all three age groups in one statistical model. The time window of interest was defined as 600-1000 ms relative to the onset of the suffix (-are, -ando) and the spatial region of interest included the electrode positions F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, based on a previous ERP study with the same paradigm in infants (Friederici et al., 2011). Thus, we computed mean amplitudes across the defined time window and region of interest for each subject.

Predictors of ERP polarity

Fifty-seven percent of the participants (N=66) showed a positive-going ERP effect (correct vs. incorrect) in the time window and region of interest, while the other 43% (N=49) showed a negative-going ERP effect. We here used a logistic regression to investigate whether children's ERP polarity (positive vs. negative) could be significantly predicted by their age (1 year, 2 years, 3 years; using linear contrast coding; see Schad et al., 2020) for further information on contrast coding), sex (male, female; using sum contrast coding), or language comprehension or language production abilities (z-transformed raw scores of the language tests). This analysis was performed in R (R Core Team, 2017).

Age effects of NAD learning

Using the time window and region of interest defined above, we set up an LM in R (R Core Team, 2017) to test for the effect of age on children's ERP effect (correct vs. incorrect), as an indicator for NAD learning. As the dependent variable, we used the amplitude of the absolute (based on the results of the linear regression, see section 3.1) ERP difference wave (incorrect – correct; see Figure 3) averaged over the time window and region of interest, further averaged over trials in order to increase the signal-to-noise ratio for the LM, resulting in one ERP amplitude value per participant. When considering the ERP amplitude values entered into the LM, there was still considerable variability (mean: 0.059; SD = 6.73; min = -31.06, max = 15.69). Therefore, we excluded outliers, defined as 2.5 times the median absolute cutoff (Leys et al., 2013). This procedure resulted in the exclusion of the datasets of 6 additional children. The results of the linear model were the same regardless of outlier exclusion. The results reported in the main text do not include outliers; for the same analyses including outliers, see Supplementary

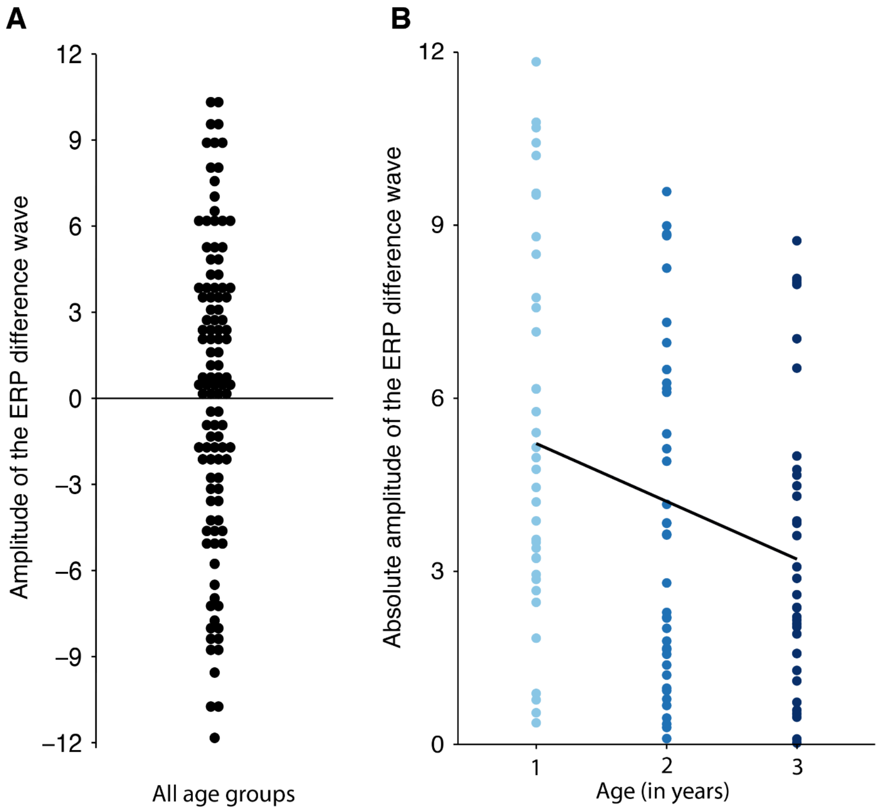

FIGURE 3.3: A. Amplitude of the ERP difference wave (incorrect - correct) across all age groups. B. Absolute amplitude of the ERP difference wave (incorrect - correct) plotted by age. Absolute ERP amplitude is significantly predicted by age.

Table 3.4. We entered age (1 year, 2 years, 3 years; using linear contrast coding) as a fixed effect (independent variable) into the model. We further added weights to the model, accounting for the number of trials of each average.

Exploratory analysis of ERP latency

To explore whether the onset and duration of the ERP effect differed between age groups we did an additional analysis on the latency of the ERP effect. This analysis was conducted in SPSS v.26 (IBM SPSS Statistics, 2019) and Matlab (MATLAB, 2017). We conducted a repeated-measures ANOVA with 2 factors: age (1, 2, and 3 years) and time (13 100-ms time windows from 0-1300 ms).

3.3 Results

3.3.1 Predictors of ERP polarity

The logistic regression analysis revealed that none of the tested variables (age, sex, language comprehension, and language production) significantly predicted whether children showed a positive or negative ERP effect polarity (all $p>0.05$; Table 3.2). Therefore, we used the absolute amplitude as the dependent measure in the LM.

TABLE 3.2: Summary of the logistic regression to predict children's ERP effect polarity.

Predictors	*Odds Ratios*	*CI*	*p*
(Intercept)	0.71	0.19 - 2.71	0.619
age	1.03	0.52 – 2.05	0.922
sex	1.44	0.63 – 3.38	0.390
lang. comp.	1.16	0.71 - 1.92	0.565
lang. prod.	1.09	0.68 - 1.77	0.713
Observations	99		
R^2 Tjur	0.014		

Note: lang. comp. – language comprehension. lang. prod. – language production

3.3.2 Age effects of NAD learning

A likelihood-ratio test revealed that the LM including the fixed effect age explained significantly more variance than a restricted model with the factor age omitted (F = 6.11 p = 0.015). There was a significant main effect of age (*beta* = -1.20, p = 0.013; **??**), indicating that the absolute amplitude of the ERP effect significantly decreased with increasing age (Figure 3b; Figure 4).

TABLE 3.3: Summary of the LM predicting children's ERP amplitudes. Statistically significant p-values are highlighted in bold.

Predictors	*Estimates*	*CI*	*p*
(Intercept)	4.10	3.55 – 4.65	**<0.001**
age	-1.20	-2.17 – -0.24	**0.015**
sex	1.44	0.63 – 3.38	0.390
lang. comp.	1.16	0.71 - 1.92	0.565
lang. prod.	1.09	0.68 - 1.77	0.713
Observations	109		
R^2 / R^2 adjusted	0.054 / 0.045		

We followed up on this significant effect of age with separate LMs for each age group. These LMs are equivalent to one-sample t-tests, but include weights for the number of trials that constituted each average. These one-sample t-tests revealed that for all three age groups, the absolute amplitude of the difference wave was significantly different from 0 (1 year: *beta* = 5.23, p < 0.001; 2 years: *beta* = 3.62, p < 0.001; *beta* = 3.48, p < 0.001).

3.3.3 Exploratory analysis of ERP latency

The repeated-measures ANOVA with factors age (1, 2, and 3 years) and time (13 time windows of 100 ms each, ranging from 0-1300 ms) revealed a significant main effect of age (F= 4.85, p = 0.01), a significant main effect of time (F = 8.68, p < 0.001), and a marginally significant age*time interaction (F = 1.46, p = 0.063). We followed up on this interaction with individual t-tests per age group (Bonferroni-corrected for multiple testing within each age group). These t-tests revealed that for the 1-year-old children, the latency of the ERP effect was 200-1100 ms, for the 2-year-old children, it was 500-1100 ms, and for the 3-year-old children, it was 600-1000 ms. For a table of all t-values and p-values of the individual t-tests, please see Supplementary Table 3.5. These results indicate that increasing age is associated with a later onset as well as a shorter duration of the ERP effect.

3.4 Discussion

Previous studies have demonstrated that NAD learning undergoes different developmental stages during early childhood (Culbertson et al., 2016; Mueller et al., 2019; van der Kant et al., 2020). The aim of the present study was to investigate whether the transition between these stages occurs in a gradual or more abrupt manner. To this end, we exposed 1- to 3-year-old children to Italian sentences containing NADs and measured children's ERP responses to incorrect sentences (containing NAD violations) compared to correct sentences (containing familiarized NADs). Independent of the tested age, children's ERP responses suggested that they were able to distinguish correct from incorrect sentences, and had thus learned the NADs, indexed by an ERP component between 600 and 1000 ms (relative to suffix onset) with a positive polarity in 57% of all children and a negative polarity in 43%. Previous studies found an association of children's ERP polarity and later language outcomes (Kooijman et al., 2013; Schaadt et al., 2015) as well as infants' sex (Mueller et al., 2012). In addition, when the current paradigm was used in previous studies, ERP polarity had been related to participants' age and/or the presence or absence of a task (Friederici et al., 2011; Friederici et al., 2013; Mueller et al., 2009). Yet, neither children's age, sex, nor their behaviorally tested language abilities did predict a given child's ERP polarity in our study. Importantly, regardless of ERP polarity, the amplitude of the ERP effect of NAD learning decreased linearly with age, which we suggest indicates a gradual decrease in strength of NAD learning. In previous studies, ERP amplitude has been shown to be indicative of both strength of learning (Boll-Avetisyan et al., 2018) and tone and phoneme discrimination abilities (Garcia-Sierra et al., 2011; Kujala et al., 2001). A previous infant ERP study using the same paradigm as the current study found that 4-month-old infants' NADs learning was indicated by a late positive ERP component (640-1040 ms relative to suffix onset; Friederici et al., 2011). This ERP component was interpreted to reflect associative learning, that is, infants learned associations between surface-level phonological features of the dependent elements (Friederici et al., 2011). In line with Friederici et al. (2011)'s interpretation, we propose that children in our study learned the NADs in an associative manner, via surface-level phonological features, based on the passive listening design and the findings that at least 1-year-old children are not yet able to learn the grammatical rules underlying NADs (Culbertson et al., 2016; Legendre et al., 2010). Our findings would then imply that at 1 to 3 years of age, children are in principle capable of learning NADs associatively from passive listening, but that this ability gradually decreases with increasing age. This interpretation is supported by an exploratory analysis of the latency of the ERP effect, which showed that the ERP effect starts earlier and lasts longer in younger children, indicating the effect is more robust in younger children than in older children. In line with the proposal of an age-related decrease, German adults have been shown to struggle to learn NADs from Italian sentences through passive listening (Friederici et al., 2013), but to successfully learn the NADs under active conditions, that is, in the presence of a task (Mueller et al., 2009; see also Pacton and Perruchet, 2008; Pacton et al., 2015). Together, these findings imply that during development, there is an initial stage of NAD learning, during which young children are able to learn NADs associatively, and a later stage, during which older children and adults need additional cues (e.g., Gómez, 2002; Grama and Wijnen, 2018; Newport and Aslin, 2004; for a review, see Wilson et al., 2018) or a task (Mueller et al., 2012; Pacton and Perruchet, 2008; Pacton et al., 2015) to guide their attention to successfully learn NADs. Our current findings contribute to this notion and, moreover, provide evidence that the transition between these developmental stages of NAD learning occurs in the form of a gradual decrease of associative learning during early childhood.

These findings raise the question of which processes underlie the developmental stages of NAD learning, including their transition. A behavioral study by Culbertson et al. (2016) proposed that an initial developmental stage of NAD learning (around 1 to 1.5 years of age) is characterized by associative learning of phonological features, while a later stage (around 2 years of age) is characterized by higher-level morphological learning. Our findings suggest that 2-year-old and even 3-year-old children are still able to learn NADs associatively from passive listening, but also indicate that children show smaller and less robust effects for associative learning with increasing age. Considering Culbertson et al. (2016)'s behavioral findings using the headturn-preference procedure, it is possible that the ability to learn not only the surface-level phonological features, but also the higher-level morphological features of the NADs is slowly developing between 1 and 3 years, but this learning strategy was not triggered by our passive listening task. Similarly, it is possible that different measures, such as the head-turn preference procedure compared to ERPs and different NAD learning paradigms, tap into different learning processes. This difference in measures might also explain the differences between our study and a recent study using a similar paradigm with fNIRS, in which we found NAD learning from the same Italian sentences in 2-year-old, but not 3-year-old children (van der Kant et al., 2020). While fNIRS informs us about the brain areas underlying NAD learning during early childhood, EEG may be more sensitive to detect children's decreased responses to NAD violations at 3 years of age. Our results of a gradual decrease of associative NAD learning are therefore not necessarily at odds with previous studies reporting different developmental stages of NAD learning even before 3 years of age (Culbertson et al., 2016; van der Kant et al., 2020), but electrophysiological measures might be more sensitive to the associative processes triggered by our passive listening design.

In the following, we discuss two potential explanations for the observed gradual decrease of associative NAD learning during early childhood in the present study: (1) entrenchment of children's knowledge of their native language, and (2) maturational brain changes during early childhood. Regarding the former, children's early established (or entrenched) learning may influence expectations during later stages of learning (see Thiessen et al., 2016). These expectations facilitate subsequent learning of similar items, but hinder learning of new, dissimilar items. In line with this idea, entrenchment has been shown to occur and hinder learning of new items in infants' use of lexical stress cues in word segmentation (Jusczyk et al., 1999) and in learning to read (Zevin and Seidenberg, 2002; Zevin and Seidenberg, 2004). Similarly, it is plausible that through the course of early childhood, children's knowledge of the NADs in their native language becomes entrenched. Indeed, evidence from natural language studies show that native-language NAD learning slowly develops between 1 and 3 years of age. For example, French-learning infants can detect NAD violations in their native language starting around 14 months to 18 months, depending on the exact NADs tested (Culbertson et al., 2016; Nazzi et al., 2011; van Heugten and Shi, 2010). English-learning infants are able to detect NAD violations in 'is -ing' constructions in their native language at 18 months, but not 15 months, and only when the NADs have no more than 3 intervening syllables (Santelmann, 1998; see also Höhle et al., 2006 for evidence from German-learning infants). However, detecting violations does not necessarily mean that children learn the higher-level morphological rule and comprehend the meaning of the NADs. These abilities seem to develop later, between 21 and 30 months (Culbertson et al., 2016; Legendre et al., 2010). It is conceivable that this increasing knowledge of children's native language NADs makes learning NADs in a foreign language (or an artificial language, such as our miniature version of Italian) more difficult with increasing age. Indeed, infants' NAD learning in an artificial language has been linked to processing NADs in their native language (Lany and Shoaib, 2019). This effect of entrenchment on learning novel NADs would explain why children's ability to learn NADs associatively decreased with age in our study. Taken together, children's knowledge of the NADs of their native language builds up over the first three years of life, possibly making learning of NADs in another language (such as our miniature version of Italian) more difficult for older children.

The second explanation of the gradual decrease in associative NAD learning refers to the maturation of the developing brain (Ramscar and Gitcho, 2007). Associative NAD learning has been proposed to demand an interplay between posterior temporal brain areas and the premotor cortex (Friederici, 2012; Gervain et al., 2008; Gervain et al., 2011; see Skeide and Friederici, 2016). These regions are involved in language comprehension and production more generally (Bruderer et al., 2015; Möttönen and Watkins, 2009; Rodd et al., 2015) and functionally connected through ventral and dorsal fiber pathways (Dubois et al., 2016; Perani et al., 2011). The ventral pathway is already well myelinated at birth (Perani et al., 2011) and available to infants for learning NADs at a very young age, likely providing the neurobiological basis of infants' ability to learn NADs associatively through surface-level phonological features (see Friederici et al., 2011; Skeide and Friederici, 2016). In contrast, the development of higher-level learning of morpho-syntactic NADs is likely linked to the maturation of the prefrontal cortex and the arcuate fasciculus as the dorsal pathway, connecting the posterior temporal cortex and the pars opercularis (part of the inferior frontal gyrus), which has been shown to be specifically involved in syntactic processing in adults (Rodd et al., 2015; Vigneau et al., 2006). The arcuate fasciculus, unlike the dorsal pathway which connects to the premotor cortex, shows continuous maturation until early adulthood, and has been linked to the development of syntactic processing (Skeide et al., 2016). Specifically, in young children, syntactic information triggers activation in the left temporal cortex, but not the left inferior frontal cortex; at 3 years of age, at the latest, both regions are activated during syntactic processing (Dehaene-Lambertz et al., 2002; Dehaene-Lambertz et al., 2006; Skeide et al., 2016). In summary of these results, Skeide and Friederici (2016) proposed a transition from associative, bottom-up learning mainly based on the temporal cortex to higher-level, top-down learning around the age of 3 years involving the left inferior frontal cortex. Further studies need to evaluate whether the decrease of associative learning of phonological features is accompanied by a comparable gradual increase of higher-level morphological NAD learning during the same developmental period. The interplay between a decrease in bottom-up learning and an increase in top-down learning, driven by the continuous maturation of the arcuate fasciculus, most likely provides the neurobiological basis for the gradual decrease of associative learning of NADs during early childhood, as observed in the current study.

Overall, our results are in line with previous studies arguing for different developmental stages of NAD learning (Culbertson et al., 2016) and add a new aspect: the notion of a gradual transition between these stages, supported by a reduction in amplitude and duration of the reported ERP effect. This gradual transition may point towards a sensitive period for associative NAD learning during early childhood. Under this view, younger children would have an advantage of learning NADs under passive listening conditions (Friederici et al., 2011; Mueller et al., 2019; van der Kant et al., 2020) compared to older children and adults (Friederici et al., 2013; Mueller et al., 2012; Mueller et al., 2019). This advantage would decrease gradually with age, as indicated by the linear decrease in our study. Older children and adults may still be able to learn NADs under passive listening in the presence of facilitating factors, such as additional acoustic cues (Frost and Monaghan, 2016; Gómez, 2002).

3.5 Limitations

As discussed in the introduction, previous studies have found different polarities of the ERP effect evoked in the present and similar NAD learning paradigms, that were related to different external variables, such as age (Friederici et al., 2011; Mueller et al., 2009), sex (Mueller et al., 2012), and children's language development (Kooijman et al., 2013; Schaadt et al., 2015). Like these studies, we here found different ERP polarities of the NAD-related effect; however, none of the external variables we assessed (i.e., age, sex, language comprehension and language production) significantly explained this polarity difference. It is therefore not certain whether the two ERP responses (with positive and negative polarity) can be equated and the present results should be interpreted with caution in this regard. However, independent of whether the positive and negative ERP response indicate the same underlying process, we still consider the fact that both ERP amplitudes decrease with age informative, interpreted as an age-related decrease of the strength of NAD learning.

Moreover, our study is the first to find a gradual decrease of NAD learning under passive listening with age. While some form of age-dependent decrease of NAD learning under passive listening is well documented in the literature (Friederici et al., 2011; Mueller et al., 2009; Mueller et al., 2019; van der Kant et al., 2020), more studies will be needed to confirm the gradual nature of this decrease. Here, we sampled NAD learning at three time points during early childhood, 1 year (13 months), 2 years (25 months), and 3 years (37 months) of age. Future studies will need to sample age more continuously to confirm the gradual decrease of NAD learning under passive listening conditions.

3.6 Conclusion

Our findings suggest a gradual decrease of associative NAD learning under passive listening during early childhood. Children at 1 to 3 years of age showed neurophysiological evidence of associative NAD learning under passive listening conditions, but the amplitude of this ERP effect linearly decreased with age. We propose that this linear decrease may be driven by entrenchment of children's knowledge of their native language NADs, which may hinder NAD learning in a foreign language. In addition, brain maturation during early childhood likely contributes to children's increasing ability to utilize higher-level, morphological features of the input through top-down learning, and to their decreasing ability to learn NADs associatively under passive listening conditions. Our study provides first evidence that the transition between different developmental stages of NAD learning may occur in a gradual manner, pointing toward a sensitive period for NAD learning during early childhood.

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Supplementary Materials

Analysis including outliers

We excluded outliers from our dataset, following two approaches. First, we applied exclusion criteria based on the quality of children's EEG data (see main text, section 2.1) and based on the absolute ERP amplitude, for which outliers were defined as 2.5 times the median absolute cutoff (see main text, section 2.5.2). This procedure resulted in the exclusion of the datasets of 6 additional children. Here, we report the results of the linear mixed model before outlier exclusion. These results were similar to the linear mixed model after outlier exclusion, that is, all effects were on the same side of the significance threshold ($p<0.05$). In particular, the LM with outliers showed a significant effect of age (β = -2.07, p = 0.003; table S1). The follow-up LMs (equivalent to a one-sample t-tests including weights for the number of trials that constituted each average) for each age group revealed that, for all age groups, the ERP absolute ERP amplitude was significantly different from 0 (1 year: β = 6.42; p < 0.001; 2 years: β = 4.32; p < 0.001; 3 years: β = 3.48).

TABLE 3.4: Summary of the linear mixed model of children's ERP amplitudes including outliers

Predictors	*Estimates*	*CI*	*p*
(Intercept)	4.73	3.95 – 5.51	**<0.001**
age	-2.07	-3.43 – -0.70	**0.003**
Observations	115		
R^2 / R^2 adjusted	0.074 / 0.066		

Latency analysis

	12-mo		24-mo		36-mo	
TW	pvalues_corr	t-values	pvalues_corr	t-values	pvalues_corr	t-values
0-100	0.415462099	2.25714278	11.5190394	0.22547323	8.78346043	0.48984426
100-200	0.096927608	2.85147127	0.52797723	2.15121386	4.30313885	1.03632111
200-300	**0.006786692**	3.80744477	2.75533704	1.31314011	0.1995691	2.58343966
300-400	**0.000976224**	4.45014352	7.10113973	0.66933647	0.09820444	2.86981968
400-500	**8.98924E-06**	5.93279956	0.12489933	2.75288089	0.05959546	3.0638681
500-600	**4.98525E-06**	6.11711461	**0.00144405**	4.32267004	0.11996529	2.79039979
600-700	**4.2748E-07**	6.88811719	**1.9465E-05**	5.69120888	**0.0047398**	3.98446818
700-800	**1.09123E-06**	6.59304843	**0.00334204**	4.04584517	**0.000193**	5.07368389
800-900	**3.47828E-06**	6.2297063	**0.00067773**	4.56815689	**0.00019114**	5.07693106
900-1000	**0.000762352**	4.53018788	**0.00095585**	4.45698491	**0.00028085**	4.9479835
1000-1100	**0.010751435**	3.64977139	**0.06759137**	2.98881329	0.51867163	2.17047061
1100-1200	0.512261213	2.16472839	0.43825973	2.233774	5.39744968	0.87907366
1200-1300	0.364661166	2.31364385	0.6995757	2.02297211	1.78442298	1.56238318
1300-1400	0.42438982	2.24785824	0.69391544	2.02673752	3.53795693	1.16354015

TABLE 3.5: Full table of the results of the follow-up t-tests on the latency of the ERP effect for each age group. P-values

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Chapter 4

Experiment 3: Overnight change of representations of learned NADs

Seven-year-olds recall non-adjacent dependencies after overnight retention

Gesa Schaadt[a,b,*], Mariella Paul[a,c,*], R. Muralikrishnan[d], Claudia Männel[a,b,e], Angela D. Friederici[a]

[a] Department of Neuropsychology, Max Planck Institute for Human Cognitive and Brain Sciences, Stephanstr. 1a, 04103 Leipzig, Germany
[b] Department of Neurology, Max Planck Institute for Human Cognitive and Brain Sciences, Stephanstr. 1a, 04103 Leipzig and Clinic for Cognitive Neurology, Medical
Faculty, Leipzig University, Liebigstr. 16, 04103 Leipzig, Germany [c] Berlin School of Mind and Brain, Humboldt-Universität zu Berlin, Luisenstraße 56, 10117 Berlin, Germany
[d] Max Planck Institute for Empirical Aesthetics, Grüneburgweg 14, 60322 Frankfurt am Main, Germany

[e] Clinic of Audiology and Phoniatrics, Charité – Universitätsmedizin Berlin, Germany
[*] These authors contributed equally

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Abstract

Becoming a successful speaker depends on acquiring and learning grammatical dependencies between neighboring and non-neighboring linguistic elements (non-adjacent dependencies; NADs). Previous studies have demonstrated children's and adults' ability to distinguish NADs from NAD violations right after familiarization. However, demonstrating NAD recall after retention is crucial to demonstrate a lasting effect of NAD learning. We tested 7-year-olds' NAD learning in a natural, non-native language on one day and NAD recall on the next day by means of event-related potentials (ERPs). Our results revealed ERPs with a more positive amplitude to NAD violations than correct NADs after familiarization on day one, but ERPs with a more negative amplitude to NAD violations on day two. This change from more positive to more negative ERPs to NAD violations possibly indicates that children's representations of NADs changed during an overnight retention period, potentially associated with children's NAD learning. Indeed, our descriptive analyses showed that both ERP patterns (i.e., day one: positive, day two: negative) were related to stronger behavioral improvement (i.e., more correct answers on day two compared to day one) in a grammaticality judgment task from day one to day two. We suggest these findings to indicate that children successfully built associative representations of NADs on day one and then strengthened these associations during overnight retention, revealing NAD recall on day two. The present results suggest that 7-year-olds readily track NADs in a natural, non-native language and are able to recall NADs after a retention period involving sleep, providing evidence of a lasting effect of NAD learning.

Keywords: non-adjacent dependencies, ERPs, recall, children, development

4.1 Introduction

Language is made up of different building blocks, combined together to form sentences. The grammar of a given language defines the rules for these combinations. For example, grammatical rules define that determiners can be combined with nouns (The girl), but not with verbs (*The give). Grammatical dependencies can be formed not only between neighboring elements, but also between non-neighboring elements of a sentence. For example, in the sentence The girl$_{Sg}$ smile$_{Sg}$, girl$_{Sg}$ and -s$_{Sg}$ form a grammatical dependency (i.e., number agreement) that spans one element (smile). In theory, these dependencies can span an arbitrary number of elements, as demonstrated in the following example: The girlSg who visited us yesterday smilesSg. These types of dependencies, called non-adjacent dependencies (NADs), are important grammatical rules of a language, such that becoming a proficient speaker and listener of languages highly depends on acquiring these rules (see Wilson et al., 2018).

Adults have been shown to be able to process and learn NADs in a number of behavioral studies (e.g., Frost and Monaghan, 2016; Gómez, 2002; Newport and Aslin, 2004; Peña, 2002). For example, Gómez (2002) exposed adults to an artificial language containing NADs in the form of three-syllable strings. In this study, the artificial language learning task consisted of NADs that were realized as AXC structures, with A and C being the dependent elements and X being variable elements. After familiarization to these strings, participants were shown a mixture of strings, either containing familiarized NADs or NAD violations; they were asked to indicate whether a given string followed the rules of the familiarized artificial language. The results showed that adults are in principle able to learn NADs (Gómez, 2002). However, adults' NAD learning has been shown to be somewhat restricted, as several studies demonstrated that adults only successfully learned NADs when phonological cues between dependent elements were provided (Mueller et al., 2008; Newport and Aslin, 2004; Peña, 2002). Taken together, behavioral studies demonstrated that adults are able to learn NADs in an artificial language. Becoming a successful speaker, however, already starts in early infancy; and even infants have been shown to be able to learn NADs (Gómez and Maye, 2005; Lany and Gómez, 2008). For example, Gómez and Maye, 2005 exposed infants to AXC grammars using the Head Turn Preference Procedure (Kemler Nelson et al., 1995), with which they measured infants' looking time towards an auditory stream played on either side of the infant. Specifically, they first familiarized infants with the AXC grammar (i.e., NADs), which was then followed by the presentation of correct or incorrect (i.e., containing a violation) NADs. Fifteen-month-old infants oriented more towards the familiarized stimuli (i.e., correct NADs) than to violations (i.e., incorrect NADs), indicating that 15-month-olds learned the AXC grammar (Gómez and Maye, 2005). However, infants' NAD learning underlies some restrictions depending on how the NADs are presented (e.g., Höhle et al., 2006; Santelmann, 1998). For example, 18- to 19-month-old infants can only learn NADs when the intervening elements consist of three syllables or less. If there are more intervening elements, NAD learning breaks down (Höhle et al., 2006; Santelmann, 1998). Taken together, both adults and infants are able to learn NADs in principle. However, the processes underlying NAD learning cannot be fully understood by using offline behavioral methods alone, but should be supplemented by online methods, such as the serial reaction time task or the click detection task (Gómez et al., 2011; Misyak et al., 2010). In addition, event-related potentials (ERPs) have been used as an online method to investigate NAD learning. Such online methods allow the more direct examination of the time course of learning and the possible change of underlying learning mechanisms.

Mueller et al. (2009) used ERPs to investigate the learning of NADs that were embedded in natural speech in a foreign language (Italian). During familiarization, they exposed German native speakers, without prior knowledge of Italian, to Italian sentences containing NADs (e.g., "La sorella sta cantando"; the sister is singing). In testing phases, participants heard a mixture of correct sentences and incorrect sentences containing NAD violations (e.g., "La sorella sta cantare"; the sister is sing∅). By comparing ERPs to incorrect sentences with ERPs to correct sentences during testing phases, a series of studies could show that both infants (under passive listening conditions, i.e., without a task; Friederici et al., 2011) and adults (under active conditions, i.e., with a task; Mueller et al., 2009) are able to learn these NADs embedded in a miniature version of Italian. Infants showed a more positive ERP response to incorrect compared to correct NADs, while adults showed a more negative ERP response. Interestingly, when adults' prefrontal cortex (PFC) was inhibited using transcranial direct current stimulation (tDCS), adults' ERP response to incorrect compared to correct NADs changed from a negative ERP to a late positive ERP, which was interpreted to indicate different underlying processes (Friederici et al., 2013). The late positive ERP found in adults whose PFC was inhibited was similar to infants' positive ERP responses to NAD violations (Friederici et al., 2011), whose PFC is not yet fully developed (Huttenlocher, 1990). Thus, the polarity difference of the ERP responses to NAD violations seems to be not only due maturational changes between infancy and adulthood, but moreover due to an underlying difference in learning mechanisms. Similarly, studies of language development in early childhood have demonstrated that the polarity of an ERP effect and a developmental change of the ERP effect polarity can be meaningful in terms of later behavior and indicative of different underlying processes (Kooijman et al., 2013; Schaadt et al., 2015; see also Eimer et al., 2003 and Penney et al., 2001, for evidence of a reversal of polarity that is indicative of behavior in adults).

As indicated by a difference in ERP polarity of components elicited by NAD violations, infants and adults might use different learning mechanisms and develop different representations of the NADs. Specifically, it has been suggested that infants learn NADs more automatically than adults do, also reflected in infants' ability to learn under passive listening, which adults struggle to do (Mueller et al., 2012). Interestingly, Mueller et al. (2018) showed that children up to the age of 2 years are able to learn NADs under passive listening conditions, while 4-year-olds, similar to adults (Mueller et al., 2012) struggle to do so and may need active task conditions. It has been suggested that the specific need for an active task is associated with a switch in learning mechanisms from associative, bottom-up learning (allowing learning under passive listening conditions) to controlled, top-down learning (hindering learning under passive listening conditions, but facilitating learning under active task conditions; see Skeide and Friederici, 2016). This switch may be associated with PFC maturation (Skeide and Friederici, 2016), which reaches near adult-like maturity around the age of 7 years (Huttenlocher, 1990). While this claim has not been tested longitudinally, there is some evidence for this from the tDCS (Friederici et al., 2013) and the cross-sectional study (Mueller et al., 2018) described above. Taken together, NAD learning mechanisms change during development, which may possibly be linked to PFC development.

Although previous studies (Friederici et al., 2011; Mueller et al., 2009; Mueller et al., 2012) convincingly demonstrated that individuals can differentiate familiarized NADs from NAD violations, NAD learning was always tested on the day of the familiarization itself, either on the same items as during familiarization (e.g., Friederici et al., 2011; Mueller et al., 2009) or on novel items (i.e., items that share the same structure as familiarized items, but use different tokens; e.g., Gómez et al., 2006). This testing procedure provides a measure of whether participants have formed a representation of the familiarized items, which can then be compared to test items. Test items perceived as similar to familiarization items would then be interpreted as adhering to the (possibly unknown) rule. On the other hand, test items judged as dissimilar would be interpreted as not adhering to the underlying rule (similarity-based learning; see Opitz and Hofmann, 2015). While testing NAD learning on the same day of familiarization is certainly informative, it is a matter of discussion whether this should be interpreted as evidence that the underlying rules have been learned, rather than some surface-based features of the NADs. This is because the knowledge of the underlying rules that characterize the (artificial) grammar only builds up over time (Opitz and Hofmann, 2015) and might not be fully present immediately after a relatively brief familiarization. Thus, it is important to retest NAD learning after a period of time in order to investigate whether NAD learning had a lasting effect and to show that learned NADs are not simply forgotten again shortly after familiarization. In order to investigate whether participants have really learned the underlying rules and could recall them after a period of time, several studies have investigated recall of grammatical rules after a retention period. For example, Fischer et al. (2006) investigated the effect of a retention period on artificial grammar learning in adults. The authors showed that before sleep there was no evidence for above-chance level performance in adults in a generation task, during which participants had to predict the next letter in a string based on the artificial grammar. However, after a retention period involving sleep, participants could solve the task successfully, which was not the case after a retention period without sleep. A number of studies has demonstrated that this benefit of a retention period involving sleep is linked to a change in representations (see Diekelmann and Born, 2010; Ellenbogen et al., 2007; Fischer et al., 2006; Wagner et al., 2004). Davis and Gaskell (2009) suggested that a model of memory consolidation, the complementary learning systems model, could also apply to the linguistic domain, specifically word learning. Under this model, new knowledge, such as a newly encountered word, is initially stored in episodic memory, where it is not yet integrated into the lexicon. New words are then consolidated into lexical memory over time, facilitated by sleep (Henderson et al., 2012; Smith et al., 2018; Tamminen et al., 2010). Especially infants and children were shown to benefit from a retention period (particularly when retention involved sleep; Backhaus et al., 2008; Henderson et al., 2012; Hupbach et al., 2009; Smith et al., 2018) and for generalizing learned information to new input (Gómez et al., 2006). A study by Friedrich et al. (2017) linked a change in representations of learned associations during the course of a retention period to particular ERPs. In this study, infants were exposed to object-word pairs followed by a retention period that either involved a long nap, a short nap, or no sleep. Before retention, there was no evidence for learning of the object-word pairs and neither did the group without sleep show any sign of learning after retention. In contrast, infants who had a short retention period (30 minutes on average) involving sleep showed consolidation of the object-word pairs. However, the ERPs only revealed a late negativity, which was interpreted to be indicative of a phonological association between the word and object, but not for a lexical-semantic representation of the object-word pairs in long-term memory. Only those children who had a longer consolidation period (50 minutes on average) involving sleep also showed ERP evidence of lexical-semantic representations of word meaning in long-term memory in form of an N400 (i.e., earlier negativity; Friedrich et al., 2017). Thus, this study demonstrates that children benefit from a retention period involving sleep, which most likely leads to the ERP effects of successful recall of learned associations after the retention period. Given these promising findings showing a beneficial effect of a retention period involving sleep on long-term memory consolidation, we aimed at investigating the effect of retention involving sleep on the recall of NADs as important grammatical rules of language.

Thus, in the present ERP study, we investigated 7-year-old children's recall of NADs embedded in a miniature version of a foreign language (i.e., Italian), using the same paradigm as Mueller et al. (2009), including a grammaticality judgment task. We invited our participants on two consecutive days, ensuring a retention period involving sleep to test recall of NADs. If we can show recall of NADs on day two, we provide evidence that children learned the NADs and that this learning had lasting effects beyond the familiarization day, which goes over and above showing processing differences between correct and incorrect NADs on the same day when familiarization took place. We tested 7-year-olds because they have been shown to be able to successfully perform offline behavioral tasks assessing statistical learning (Raviv and Arnon, 2018; Shufaniya and Arnon, 2018), most likely associated with 7-year-olds' advanced PFC maturation (Huttenlocher, 1990), playing a crucial role in NAD learning (Friederici et al., 2013).

A number of recent studies have raised concerns that group-level offline tasks, which assess statistical learning, may not provide reliable measures of individual differences (Siegelman, Bogaerts, and Frost, 2017; West et al., 2018), particularly in children (Arnon, 2019). Siegelman, Bogaerts, and Frost (2017) suggest that online measures may circumvent some of the problems seen in the reliability of offline tasks. Here, we use ERPs as an online test of NAD learning both at the group level and the individual level, as ERPs have been shown to be a reliable measure of interindividual differences in a variety of paradigms (Cassidy et al., 2012).

In accordance with the procedure of Mueller et al. (2009) in adults, children listened to only correct stimuli (i.e., Italian sentences) during the four learning phases on the first testing day. Each learning phase was followed by a testing phase, during which children listened to incorrect stimuli containing NAD violations intermixed with correct stimuli following the familiarized NAD rule. During the testing phases, children were required to behaviorally indicate whether or not a given stimulus belonged to the language they were familiarized with in the learning phases (i.e., grammaticality judgment task). On the following day, we tested recall of NADs by asking children to perform only the four testing phases, again including the grammaticality judgment task. To capture consolidation and recall of NADs on the next day, we specifically focused on the change in behavior from day one to day two. Successful recall of NADs will be reflected in behavioral improvement from day one to day two (i.e., more correct grammaticality judgments on day two compared to day one). If children learn the NADs on day one and recall them on day two, we expect that children's ERP responses on both days are associated with their improvement in the number of correct grammaticality judgments from day one to day two. While we will treat this correlational analysis as an exploratory analysis due to reliability concerns (see Siegelman, Bogaerts, and Frost, 2017), linking ERPs to the behavioral outcome may strengthen the interpretability of our results.

4.2 Materials and methods

4.2.1 Participants

For the present experiment, 49 children were invited. The datasets of 36 children (20 boys) with a mean age of 7.22 years [Standard Deviation (SD) = 0.36] entered the final analyses (i.e., the datasets of 13 children were excluded due to movement and perspiration artifacts in the EEG). Children visited the first and second school grade. All participants were German monolinguals and none of the children had any known hearing deficits or neurological problems. In order to ensure that the Italian sentences used for the present study were foreign to the children and thus, functioned as an "artificial" language, we asked the parents about the child's experience with foreign languages and specifically with the Italian language. One of the 36 children visited a bilingual French-German kindergarten and at school, 11 of the 36 children learned a second language, with two children learning French and nine children learning English. Thus, none of the children had any specific experience with the Italian or Spanish (Spanish and Italian consist of the same NADs) language.

The study followed American Psychological Association (APA) standards in accordance with the declaration of Helsinki from 1964 (World Medical Association, 2013) and was approved by the ethics committee of the University Leipzig. Parental written consent was obtained after children and parents had been informed about the procedure and agreed to participation.

4.2.2 Stimulus material

Mueller et al. (2009) provided the stimuli for the present study. They consisted of simple Italian sentences, containing an NAD between an auxiliary and a main verb's suffix. Sentences were made up of one of two noun phrases (il fratello, the brother; la sorella, the sister), one of two auxiliaries (può, to be able to, first person singular; sta, to be, first person singular), and one of 32 verbs. Verbs could either occur in infinitive (e.g., arrivare) or in gerund form (e.g., arrivando). Between the auxiliary and the verb suffix was a non-adjacent grammatical dependency, such that the auxiliary sta required the gerund form -ando and the auxiliary può required the infinitive form -are. In total, 128 correct sentences were generated. All correct sentences were spoken by a female native Italian speaker and digitally recorded.

Subsequently, the auditory material was segmented and normalized using the ReZound software. Incorrect sentences were produced by combining auxiliaries with the incorrectly suffixed verbs from a different, correct sentence. This was done by a cross-splicing procedure at the beginning of each verb. In each sentence, the verb was thus exchanged with a verb from a different sentence. To control for splicing effects across conditions, correct sentences were spliced in the same manner.

4.2.3 Experimental procedure

Participants were invited for two consecutive days. On the first testing day, participating children and their parents were verbally informed about the procedure. Children were asked to provide consent to participate and parents gave written informed consent on behalf of their children. Participating children were read a cover story about an explorer hearing sentences in a foreign language and who needs help deciding whether the words in the sentences fit together. Children were not explicitly told that they were supposed to learn an underlying rule, but to carefully listen to the sentences and decide whether the words in the sentence fit together (for further details, see the exact instructions at https://osf.io/b3e5a/). Further, children were informed that they would be re-invited for the next day, but not that they would be tested on the same grammar again. Our experiment on the first day comprised four alternating learning and testing phases. In each learning phase, participants were presented with 64 correct sentences (256 in total across all learning phases). After a learning phase, a testing phase followed where participants were presented with correct sentences and incorrect versions of the sentences containing NAD violations. Each testing phase consisted of 8 correct and 8 incorrect sentences (64 sentences across all four testing phases). Please note that each testing phase contained different auxiliary-verb-suffix-triplets compared to the preceding learning phase to ensure that participants learned NADs (and not auxiliary-verb-suffix triplets).

For the ERP experiment, participants sat in a sound-attenuated booth in front of a computer screen and stimuli were presented via loudspeaker using Presentation® software Version 14 (Neurobehavioral Systems Inc., Berkely CA, USA). Children were instructed by using a cover story, where they were asked to support an adventurer, needing help to decide whether the sentences in a foreign language are correct or incorrect. Further, they were told that it is important to listen carefully, because otherwise the adventurer would not be able to continue his journey around the world. After the instruction, the experiment started with the first learning phase, in which participants passively listened to the correct NAD sentences. A fixation cross was continuously presented in the middle of the screen to reduce extreme eye-movements. Sentences were presented in a pseudo-randomized order, such that each sentence beginning (i.e., il fratello sta, la sorella sta, il fratello può, la sorella può) was not presented more than three-times in a row; and such that a verb could only be repeated every third sentence. From the beginning of each sentence to the beginning of the following sentence, there was an inter-stimulus-interval (ISI) of 3000 ms. Each learning phase (in total 4 learning phases) was followed by a grammaticality judgment task to test for learning effects, with pseudo-randomized presentation following the above mentioned criteria for pseudo-randomization and pseudo-randomized presentation of incorrect and correct sentences, such that correct or incorrect sentences could only be presented twice in a row. Children were required to give grammaticality judgments on each stimulus (i.e., correct vs. incorrect) by using a button-press response device. The trials started with a fixation cross that was presented for 1000 ms, before one of the correct or incorrect sentences was presented. After an ISI of 3000 ms, the simultaneous display of a happy (indicating correct) and a sad face (indicating incorrect) prompted participants to judge the grammatical correctness of the sentence via the provided response keys. The response key assignment (right / left) to the answer type (correct / incorrect) during the testing phases was counterbalanced across participants. Each learning phase lasted for about 3.5 min and each testing phase lasted for about 10 min (i.e., depending on the child's response times), summing up to a total experimental time of around 60 min.

For the second testing day, our experiment only comprised four testing phases (i.e., grammaticality judgment task as described above), but no learning phases, to investigate NAD learning after a retention period including sleep. Stimuli used for the second testing day were not identical to those used on the first testing day (i.e., sentence beginnings and verbs forming correct and incorrect sentences were combined differently on day two compared to day one; for a list, see https://osf.io/b3e5a/). As participants were not presented with the learning phases on the second testing day, the total experimental time was reduced (i.e., around 40 min). EEG was recorded during the whole experiment on both testing days. Behavioral data (i.e., error rates; response times) were recorded for each participant during testing phases on testing day one and testing day two.

4.2.4 EEG recording and analysis

Continuous EEG was recorded with an EGI (Electrical Geodesics, 1998) 128-electrode array (see Figures 1, 2, and 3 for schematic illustration). The vertex (recording site Cz) was chosen as online reference. For the EGI high input impedance amplifier, impedances were kept below 75 kΩ. The sampling rate was 500 Hz and all channels were pre-processed online by means of 0.01 – 200-Hz band-pass filter. In addition, vertical and horizontal eye movements were monitored with a subset of the 128 electrodes.

For offline EEG analysis, we used the Fieldtrip toolbox for EEG/MEG analysis (Oostenveld et al., 2011) and the MATLAB® version R2017b (The MathWorks, 2017). Before preprocessing, EEG data was manually scanned for electrodes with bad or missing signal. Those electrodes were excluded from the respective data set. Note, however, that the number of excluded electrodes never exceeded 6 out of 128 (i.e., < 5%) and that excluded electrodes differed across participants. Thereafter, data were offline re-referenced to the average of all EEG electrodes. Before data were filtered, the sampling rate was reduced to 250 Hz. We then applied a digital low-pass filter of 30 Hz (Kaiser-windowed finite-impulse response low-pass filter, half-amplitude cutoff (-6 dB) of 30 Hz, transition width of 5 Hz) to remove muscle artifacts and a high-pass filter of 0.3 Hz (Kaiser-windowed finite-impulse response high-pass filter, half-amplitude cutoff (-6 dB) of 0.3 Hz, transition width of 0.3 Hz), to remove very slow drifts. In a next step, we extracted trials of -200 to 2000 ms time-locked to the onset of the critical verb (i.e., containing either the correct or incorrect suffix). Across all remaining trials, we identified muscle artifacts with a distribution-based identification approach. We set the rejection threshold to z = 7.0. Trials were visually scanned and, if applicable, further trials with severe artifacts were manually marked and removed. To remove eye-movement artifacts, an independent-component analysis (ICA; Makeig et al., 1996) was performed. ICA components were visually scanned and eye movement-related components removed. Before individual averages were computed (baseline corrected from -200 to 0 ms relative to verb-onset), the removed electrodes with bad or missing signal were interpolated by using spherical spline interpolation (Perrin et al., 1989). In a second step, grand averages were computed in relation to the suffix onset for the learning phases (separately for the first and second halves of the experiment) and for the testing phases on day one and day two, separately for verbs containing correct suffixes (i.e., NAD was not violated) and verbs with incorrect suffixes (i.e., NAD was violated).

4.2.5 Statistical analysis

For statistical analyses, we used the Statistical Package for the Social Sciences (SPSS) Software Version 24 (IBM; Walldorf, Germany).

Behavioral data

For each testing day, statistical means of response times (RTs) in ms and correct answers in percent were calculated for each participant. To analyze whether RTs and correct answers differed between day one and day two, we calculated dependent t-Tests. In a next step, we performed binomial tests for each child to determine whether performance (i.e., correct answers in percent) was above chance level in the grammaticality judgment task.[1] According to the performed binomial test, the threshold indicating above chance-level performance was 58.2 or more correct answers in percent ($p < .05$), which we used to classify each child's grammaticality judgment task performance. Finally, we obtained a score indicating whether children's task performance changed (i.e., number of correctly answered trials) from day one to day two by calculating the difference between correct answers on day two and the correct answers on day one.

[1] In order to do so, we used the formula $z = \frac{X-p}{\sqrt{(\frac{pq}{n})}} + p$ (see Tuomainen, n.d.). In this formula, X refers to the child's observed score, p refers to the probability of chance, q refers to the reciprocal of the probability of chance, and n to the total number of observations. We then set z to a critical value of ≥ 1.64 (i.e., the observed score is significantly different from chance at level $p < .05$, one-sided) and solved the equation to $X = z\sqrt{\frac{pq}{n}} + p$, in order to find the threshold indicating above chance-level performance.

EEG data

To statistically analyze the ERP data, we defined two frontal regions of interest (ROIs), two central ROIs, and two parietal ROIs for each hemisphere (i.e., left and right; see Figures 1, 2, 3 and Luu and Ferree, 2005). Further, we defined ROIs for the midline (see Figures 1, 2, 3 and Luu and Ferree, 2005). ERP analyses were performed on six time windows (TW) of 200 ms each. The suffix-onset (-are and -ando) served as criterion for TW definition, as it is the earliest point at which a correct sentence can be distinguished from an incorrect sentence. On average, suffix onset occurred at 267 ms (range: 138 – 408 ms) relative to the onset of the verb stem, such that we defined the first TW of interest to start 300 ms after verb onset.

To identify significant ERP effects of learning across the experiment on day one, we contrasted ERPs in response to the critical suffixes during the first and second halves of the experiment. In order to do so, we calculated a three-factorial repeated measures analyses of variance (ANOVA) with the within-subject factors learning phase (first half, second half), region (left frontal, centro frontal, right frontal, left central, centro central, right central, left parietal, centro parietal, right parietal), and TW (300–500 ms, 500–700 ms, 700–900 ms, 900–1100 ms, 1100–1300 ms, 1300–1500 ms). If effects involving the factor learning phase reached significance ($p < .05$), post-hoc pairwise comparisons were computed, p-values were Bonferroni-corrected and reported p-values are adjusted for multiple testing.

To identify significant ERP differences between the processing of correct and incorrect suffixes during testing phases and whether these potential ERP differences change from day one to day two, we calculated a four-factorial ANOVA with the within-subject factors testing day (day one, day two), condition (correct, incorrect), region (left frontal, centro frontal, right frontal, left central, centro central, right central, left parietal, centro parietal, right parietal), and TW (300–500 ms, 500–700 ms, 700–900 ms, 900–1100 ms, 1100–1300 ms, 1300–1500 ms). Two hundred-ms time windows were chosen to enable comparability to previous studies using the same stimuli (specifically Friederici et al., 2011, who used 200-ms analysis time windows)[2]. If effects involving the factor condition reached significance ($p < .05$), post-hoc pairwise comparisons were computed, p-values were Bonferroni-corrected and reported p-values are adjusted for multiple testing.

In a further step, we analyzed whether significant ERP effects could predict the change in task performance from day one to day two. First, we calculated the ERP difference waves between those contrasts, for which the above-described ANOVAs revealed statistically significant effects (e.g., ERP to incorrect suffixes – ERP to correct suffixes). By calculating such ERP difference waves, we were able to determine the quantity (i.e., difference in amplitude) and quality (i.e., polarity) of potential processing differences, which might be associated differently with task performance. both the amplitude and polarity of the difference wave are indicative of the underlying processes involved in stimulus processing (Luck, 2004) and might thus influence task performance differently. For example, Kooijman and colleagues (2013) showed that infants' polarity of ERP components elicited during a word segmentation task was predictive of later vocabulary. Second, we then calculated a correlational analysis between the ERP difference waves (i.e., for those contrasts that revealed statistically significant effects on day one and on day two) and the change in task performance from day one to day two (correct answers day two – correct answers day one).

4.3 Results

4.3.1 Behavioral results

Correct answers in percent on day one (mean = 48.65%; SD = 5.90) did not differ significantly from correct answers on day two (mean = 50.73%; SD = 6.18; $t(35) = -1.49$; $p = .15$). RTs were significantly shorter on day two (mean = 7489.13 ms; SD = 3843.89) compared to day one (mean = 11552.69 ms; SD = 4847.99; $t(35) = 5.77$; $p < .001$). When using the criterion of the binomial test (i.e., when z was set to 1.64, resulting in a above-chance level threshold of 58.2% correct answers in percent), we could identify three children performing above chance level on

[2]Please note that other studies using the same stimuli (Citron et al., 2011; Friederici et al., 2013; Mueller et al., 2009) used visual inspection to identify relevant time windows, which we wanted to refrain from here, due to concerns of inflating the probability of type I errors.

day one and three children on day two (only partially overlapping; i.e., one child). Further, the mean change in behavior was 2.09% (SD = 8.41; min = -15.65; max = 17.15), indicating that some children showed more correct answers on day two compared to day one (i.e., positive values) and some children showed less correct answers on day two compared to day one (i.e., negative values).

4.3.2 EEG results

Learning phases day one

Neither the main effect of learning phase [F (1, 35) = 0.41; p = .53], nor any interaction involving the factor learning phase [learning phase * TW: F (5, 175) = 0.63; p = .59, learning phase * region: F (8, 280) = 0.71; p = .55, learning phase * TW * region: F (40, 1400) = 0.92; p = .48] reached significance (see Figure 4.1). Thus, ERPs in response to the critical suffixes during the first half of the experiment did not differ significantly from the ERPs in response to the critical suffixes during the second half of the experiment.

Testing phases day one and day two

We found a significant interaction between the factors testing day and condition [F (1, 35) = 4.19; p = .049; η^2 = .11], which could be explained by a more positive ERP response to incorrect suffixes compared to correct suffixes on day one (p = .026). Further, we found a significant interaction between the factors testing day, condition, TW, and region [F (40, 1400) = 2.03; p = .03; η^2 = .06], which could be explained by a more positive ERP response to incorrect suffixes compared to correct suffixes on day one for the TW 1100-1300 ms at the centro frontal region (p = .02), the left frontal region (p = .004), and the left central region (p = .04) (see Figure 4.2); and by a more negative ERP response to incorrect suffixes compared to correct suffixes on day two for the TW 900-1100 ms at the left frontal region (p = .05) and at the left central region (p = .01); and for the TW 1100-1300 ms at the left frontal region (p = .02) (see Figure 4.3).

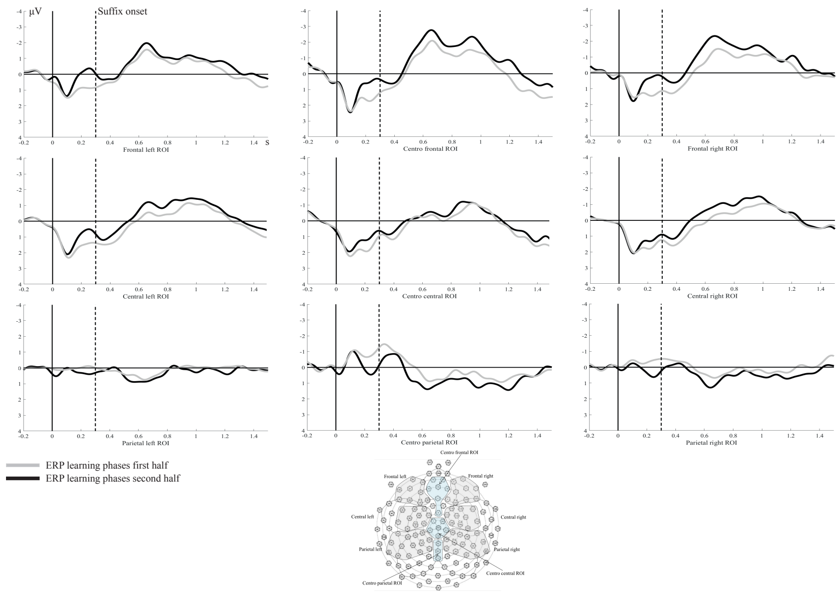

FIGURE 4.1: Event-related potentials (ERPs) of the learning phases on day one. Illustrated are the mean ERPs in response to the correct suffixes during the first half of the learning phases (grey line) and to the correct suffixes during the second half of the learning phases (black line) averaged for left, middle, and right frontal, central, and parietal regions of interest (ROIs; see schematic head for details on electrodes).

Thus, we found a more positive ERP response to incorrect compared to correct suffixes between 1100 and 1300 ms, that is, between 800 and 1000 ms after suffix onset on day one and a more negative ERP response to incorrect compared to correct suffixes between 900 and 1300 ms, that is, between 600 and 1000 ms after suffix onset on day two.

4.3.3 Descriptive analyses of behavioral changes in relation to ERPs

Because task performance was not above-chance at the group level and only very few children performed above-chance on an individual level (see Section 4.3.1), we will only analyze the association between behavioral changes and ERPs descriptively, and will refrain from performing inference statistics for this analysis. We calculated Pearson's bivariate correlation coefficient to analyze the association

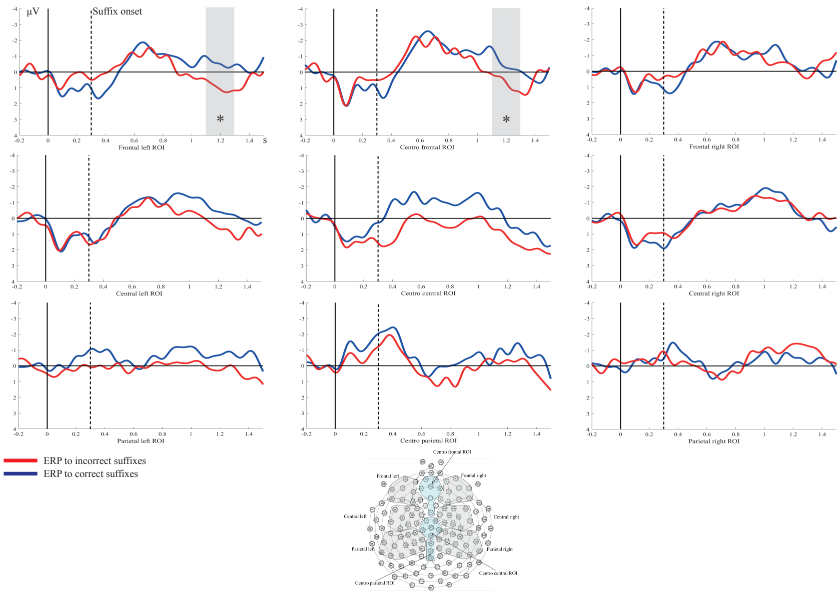

FIGURE 4.2: Event-related potentials (ERPs) of the testing phases on day one. Illustrated are the mean ERPs in response to the correct suffixes containing the nonadjacent dependency (blue line) and to the incorrect suffixes violating the nonadjacent dependency rule (red line) averaged for left, middle, and right frontal, central, and parietal regions of interest (ROIs; see schematic head for details on electrodes). Grey bars and asterisk indicate time windows and regions with significant differences between the ERPs of the two conditions (* $p < .05$).

between ERP difference waves (ERP to incorrect suffixes – ERP to correct suffixes) of those contrasts that revealed statistically significant effects on day one and on day two and the change in task performance from day one to day two (correct answers day two – correct answers day one).

The results showed that the ERP effect between 1100 and 1300 ms on day one (i.e., positivity) was positively associated with the change in task performance from day one to day two ($r = .21$), while the ERP effect between 900 and 1300 ms on day two (i.e., negativity) was negatively associated with the change in task performance from day one to day two ($r = -.45$) (see Figure **??**).

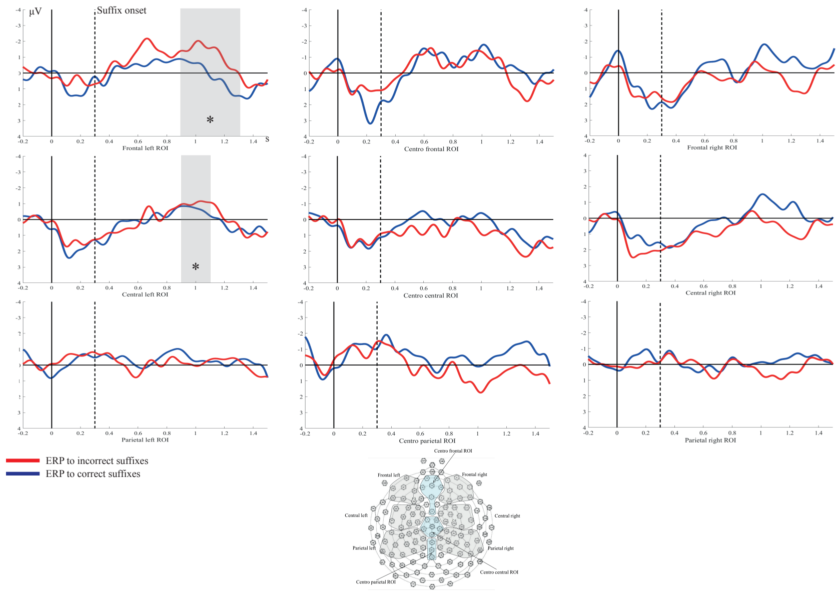

FIGURE 4.3: Event-related potentials (ERPs) of the testing phases on day two. Illustrated are the mean ERPs in response to the correct suffixes containing the nonadjacent dependency (blue line) and to the incorrect suffixes violating the nonadjacent dependency rule (red line) averaged for left, middle, and right frontal, central, and parietal regions of interest (ROIs; see schematic head for details on electrodes). Grey bars and asterisk indicate time windows and regions with significant differences between the ERPs of the two conditions (* p < .05).

Further, we calculated the difference between the positivity on day one and the negativity on day two, according to the procedure of calculating the change in task performance as described above. A negative value would indicate a stronger change from positivity on day one to negativity on day two. We again calculated Pearson's bivariate correlation coefficient to now analyze the association between the changes in ERP polarity from day one to day two and the change in task performance from day one to day two.

The results showed a negative correlation between the individual change in ERP polarity from day one to day two and the individual change in task performance from day one to day two (r = - .52) (see Figure 4.4).

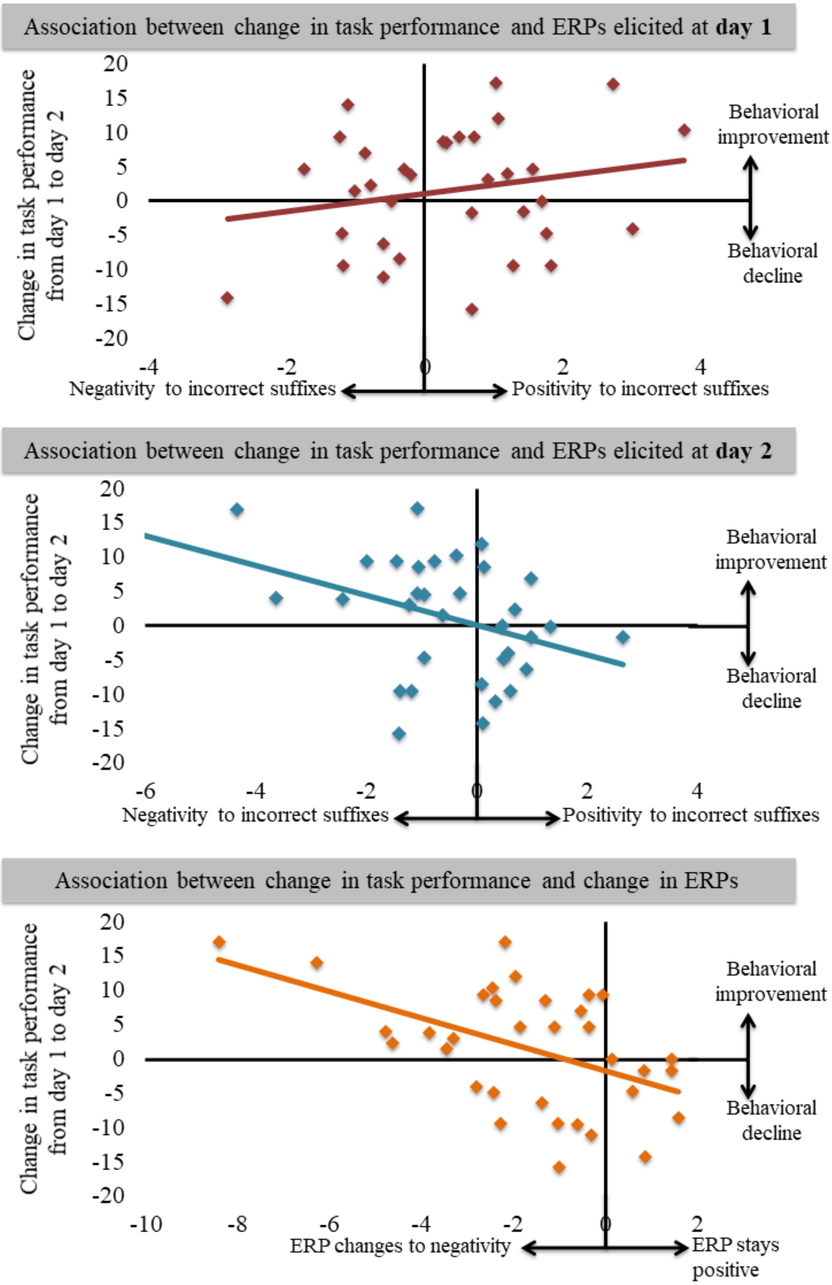
Association between change in task performance and ERPs elicited at **day 1**
Change in task performance from day 1 to day 2
20
15
10
5
0
-5
-10
-15
-20
-4
-2
0
2
4
Behavioral improvement
Behavioral decline
Negativity to incorrect suffixes
Positivity to incorrect suffixes
Association between change in task performance and ERPs elicited at **day 2**
Change in task performance from day 1 to day 2
20
15
10
5
0
-5
-10
-15
-20
-6
-4
-2
0
2
4
Behavioral improvement
Behavioral decline
Negativity to incorrect suffixes
Positivity to incorrect suffixes
Association between change in task performance and change in ERPs
Change in task performance from day 1 to day 2
20
15
10
5
0
-5
-10
-15
-20
-10
-8
-6
-4
-2
0
2
Behavioral improvement
Behavioral decline
ERP changes to negativity
ERP stays positive

FIGURE 4.4: Association between change in task performance and event-related potentials (ERPs). The upper panel of the figure illustrates how the ERP in response to incorrect suffixes (i.e., ERP incorrect suffix – ERP correct suffix) on day one is related to the individual change in task performance (i.e., correctly answered trials in percent) from day one to day two (r = .28). The middle panel illustrates how the ERP to incorrect suffixes (i.e., ERP incorrect suffix – ERP correct suffix) on day two is related to the individual change in task performance (i.e., correctly answered trials in percent) from day one to day two (r = – .45). Children showing a more positive ERP to incorrect suffixes on day one are more likely to improve behaviorally compared to children showing a less positive ERP on day one. Similarly, children who showed a more negative ERP to incorrect suffixes on day two more strongly improved behaviorally from day one to day two compared to children who less strongly improved behaviorally. The lower panel illustrates how the change from a positive ERP on day one to a more negative ERP on day two is related to the individual change in task performance (r = – .52). Children showing a stronger change from positivity on day one to negativity on day two improved more strongly behaviorally from day one to day two.

4.4 Discussion

The aim of the present ERP study was to investigate NAD learning by means of NAD violation recall using a miniature version of a natural language in 7-year-olds. Specifically, we not only tested NAD processing directly after learning, but also after a retention period involving sleep (i.e., at the next day). On the first day, German-speaking children were exposed to Italian sentences containing NADs (e.g., *La sorella sta cantando*; *the sister is singing*). Learning phases were followed by testing phases in which participants heard a mixture of correct sentences containing the same NADs as during learning phases, as well as incorrect sentences containing NAD violations (e.g., La sorella sta cantare; the sister is sing∅; see Friederici et al., 2011; Mueller et al., 2009), while they performed a grammaticality judgment task. To then test recall of NADs, participants were re-invited the following day, on which they were presented with testing phases only, while again their EEG data and grammaticality judgments were acquired.

The grammaticality judgment task at either day did not reveal any NAD learning at the behavioral level (above-chance performance) in our group of 7-year-old children. This result was unexpected, given findings by Raviv and Arnon, 2018, who showed that 7-year-olds had successfully learned an artificial grammar on a behavioral level. This discrepancy in results could have one of the following reasons: (1) Our natural language stimuli were more complex than the artificial language involving syllable triplets in Raviv and Arnon (2018)'s study and may thus be more difficult to learn. (2) Our grammaticality judgment task was more difficult than the two-alternative forced choice (2-AFC) task used by Raviv and Arnon (2018), in which children were presented with two stimuli, one of which conformed to a familiarized language and one did not. It is conceivable that having the direct comparison between a correct and an incorrect example in the 2-AFC task, including the knowledge that one sentence is correct and one incorrect, facilitates learning compared to the grammaticality judgment task used in the present study. Thus, it might be concluded that the present grammaticality judgment task is still too difficult for 7-year-old children (see also Lammertink et al., 2019) such that they cannot successfully show the same behavior as adults (i.e., above chance level, see Mueller et al., 2009). Based on these results, it might be concluded that our group of 7-year-old children did not learn the NADs explicitly. However, when looking at behavioral changes in performance (i.e., correct responses) from day one to day two, we found behavioral changes in the positive direction for some children (i.e., more correct answers on day two compared to day one), possibly indicating NAD learning at least for some of the 7-year-olds after a retention period involving sleep.

In the following, we will first discuss the ERP findings of NAD processing at the group level, before elaborating on our descriptive analysis of the association between behavioral and neurophysiological responses at the individual level. At the neural level, we found a more positive ERP response to NAD violations (i.e., 800 to 1000 ms after suffix onset) during testing phases on day one. In contrast, we found a more negative ERP response to NAD violations (i.e., 600 to 1000 ms after suffix onset) during testing phases on day two.

Regarding the latencies of the observed ERP components, the positivity on day one occurred slightly later than the negativity on day two. Since shorter latencies are typically interpreted as reflecting faster, more automatic processing (e.g., Friederici et al., 2003), it is possible that the detection of NAD violations was still somewhat slower on day one and became faster and possibly more automatic after children had time to consolidate the learned NADs during sleep. Regarding the change in polarity of the ERP effects following overnight-retention, we suggest a change in representation as interpretation. In previous studies using this paradigm, positive ERPs in response to NAD violations have been reported for infants (Friederici et al., 2011) and adults when their PFC was inhibited by tDCS (Friederici et al., 2013). It has been suggested that infants employ associative learning strategies and that with increased PFC development, learning mechanisms change to controlled top-down learning (Skeide and Friederici, 2016). Because both infants, whose PFC is not yet fully developed (Huttenlocher, 1990), and adults with a temporarily inhibited PFC, showed a positive ERP response to NAD violations, more positive ERPs have been interpreted to indicate associative learning of NADs (Friederici et al., 2011; Friederici et al., 2013). In our study, the positivity on day one may thus indicate that children have formed associative representations of the NADs before retention. In contrast, we found a negative ERP to NAD violations on day two. Negative ERP responses to NAD violations in this paradigm have been reported for adults under standard conditions, that is, when their PFC was not inhibited (Friederici et al., 2013; Mueller et al., 2009; Citron et al., 2011). This negativity (occurring approx. 340 to 540 ms after suffix onset with a centro-parietal distribution) was interpreted to reflect an N400, indicating lexical access, based on perceptual features (Mueller et al., 2009; Kutas and Federmeier, 2000). Children's negativity found in the present study on day two occurred slightly later (i.e., 600 to 1000 ms after suffix onset) and more frontally, most likely reflecting an immature N400 (see Hahne et al., 2004; Henderson et al., 2011), indicating a lexical strategy (Mueller et al., 2009) on testing day two. We speculate that children's NAD representation may have initially been a phonological association stored in episodic memory. These associative representations were then most likely transferred to long-term memory overnight (comparable to how new words are learned and consolidated over night; see Davis and Gaskell, 2009; Henderson et al., 2012; Tamminen et al., 2010), which children then tried to access during testing phases on day two. Consequently, NAD violations would then have led to a larger negative ERP component due to retrieval difficulties. It is possible that these long-term representations of NADs were lexicalized, as in adults (Mueller et al., 2009), perhaps as whole phrases. Under this view, children would have attempted to store the dependent elements of the NADs as lexicalized phrases in lexical long-term memory, as indicated by an immature N400-like response. While it is likely a more efficient way to learn and store the NADs in an associative way, like infants do (Friederici et al., 2011), a lexical strategy has been proposed as the mechanism adults use to learn NADs (Mueller et al., 2009). Based on the similarity of ERP components in our study compared to adults' ERPs (see Mueller et al., 2009), we propose that 7-year-olds employed this strategy on the second day. Further, it is likely that children employed an implicit rather than an explicit strategy, as we found significant ERP effects on both testing days, but no significant behavioral effects. Taken together, we suggest the positivity in the ERP on day one to indicate associative NAD learning and the negativity in the ERP on day two to indicate a lexical processing strategy, where both mechanisms might be beneficial for NAD learning in 7-year-old children.

ERPs have previously been used to study children's NAD learning during infancy (Friederici et al., 2011) and early childhood (Mueller et al., 2018) and have been shown to have a strong test-retest reliability (Cassidy et al., 2012). In contrast, behavioral measures of individual differences in statistical learning, such as grammaticality judgments and 2-AFC tasks, have recently been criticized for being unreliable at the individual level (Siegelman, Bogaerts, and Frost, 2017; West et al., 2018). Specifically, when tests that were developed for group-level inferences are used to study individual differences, they often do not have enough statistical power at the individual level. This can be due to several factors, such as 1) a low number of trials, 2) all trials having the same difficulty, and 3) group-level performance often being at chance-level (Siegelman, Bogaerts, and Frost, 2017). In light of these concerns, we will discuss individual differences in ERPs in relation to mean change in behavior in the grammaticality judgment task from day one to day two in terms of a descriptive analysis in the following.

Both the positivity on day one, as well as the negativity on day two, were associated with children's behavioral changes in performance from day one to day two. Specifically, children who showed a more positive ERP response to NAD violations on day one and children who showed a more negative ERP response to NAD violations on day two showed a stronger behavioral change towards more correct answers on day two compared to day one. These results possibly indicate that 7-year-olds show NAD recall after a retention period involving sleep and that their representations of NADs change over this retention period (the ERP polarity change might indicate a representation change). Further, we showed that an individual's stronger change from a positive ERP effect on day one to a negative ERP effect on day two was correlated with stronger positive behavioral changes (i.e., more correct answers on day two compared to day one). These results have to be interpreted with caution because individual differences in statistical learning show questionable reliability (Arnon, 2019; Siegelman et al., 2017a, 2017b; West et al., 2018) and the behavioral performance was not above chance at the group level. However, our results at the individual level are in line with our results at the group level. Both analyses lend support to the interpretation of a change of NAD representation during a retention period enabling 7-year-olds' recall of NADs on the second testing day.

A study by Friedrich et al. (2017) offers insight into a possible mechanism underlying this change of representations during a retention period. Specifically, this study demonstrates an effect of sleep on the representation of learned associations between object-word pairs in infants. Object-word pairs were learned through mere phonological associations by infants who had a short nap after familiarization, while infants who had a longer nap built up semantic long-term memory representations of the object-word pairs. Infants who did not sleep between familiarization and test, however, did not show any evidence for learning the object-word pairs. Similarly, it is possible that in our study some children built up an associative representation of NADs on day one (indexed by a stronger positivity), possibly in episodic memory. The retention period between day one and day two then may have allowed those children to consolidate their associations and transfer them to long-term memory (in line with system consolidations theory, see e.g., Davis and Gaskell, 2009). This consolidation may have enabled children to build more robust representations (indexed by a stronger negativity) of the NADs, enabling these children to recall the NADs on day two, as indicated by more correct answers on day two. Our results are in line with previous studies reporting a beneficial effect of a consolidation period involving sleep for artificial grammar learning in infants (Gómez et al., 2006; Hupbach et al., 2009) and for word learning in older children (Backhaus et al., 2008; Henderson et al., 2012; Smith et al., 2018). More specifically, the idea that successful performance in an artificial grammar-learning task is only achieved after consolidation involving sleep is in line with a study by Fischer et al. (2006). Crucially, only after a consolidation period that involved sleep, but not a consolidation period without sleep, did participants perform significantly above chance in the artificial grammar-learning task (Fischer et al., 2006). Our study provides further support for the beneficial effect of sleep on NAD learning.

It has recently been debated whether (artificial) grammar learning is governed by similarity-based or rule-based learning mechanisms (see Hahn and Chater, 1998). Similarity-based learning occurs when (chunks of) familiarized items are memorized and these memorized representations are then compared to test items during testing phases. During rule-based learning, on the other hand, abstract statistical regularities underlying the items are implicitly extracted and tested against the incoming test items. This would then result in stored rule-based mental representations. Opitz and Hofmann (2015) provided evidence that both mechanisms play a role in artificial grammar learning, with similarity-based learning being especially prominent in initial stages of learning, while rule-based learning builds up over time. These different learning stages are supported by different brain structures with similarity-learning being sub-served by the hippocampus and rule-based learning by the PFC (Opitz and Friederici, 2003; Opitz, 2004). In our study, it would be possible that on day one, children used similarity-based learning to associate the elements of the NADs on day one and that rule-based learning took place over the retention period allowing children to recall the NADs on day two. These different processing mechanisms would then account for the observed change from positivity to negativity in the ERPs. Because the change from positivity to negativity correlates with change in behavior from day one to day two, this might mean that only those children, who learned similarity-based on day one were able to transform their knowledge to rule-based representations on day two. However, in the present study, we cannot directly test whether children relied on similarity-based or rule-based representations at a given day and future studies will have to test this claim, for example by manipulating the instructions the participants receive. Specifically, with more explicit instructions regarding the underlying rules, participants could be nudged into employing rule-based rather than similarity-based mechanisms early on in learning.

4.4.1 Limitations

We examined the correlation of two measures of individual differences in NAD learning, one offline measure (change in behavior from day one to day two) and one online measure (ERPs). Since these measures were acquired in the same task, their correlation should not be over-interpreted. Recently, several concerns have been raised about the reliability of offline measures of individual differences in statistical learning (Siegelman, Bogaerts, and Frost, 2017; Siegelman, Bogaerts, Christiansen, et al., 2017; West et al., 2018; Arnon, 2019). In the present study, we address some of these concerns, as we used a relatively high number of trials (32 trials test phase trials per condition, which should allow for a relatively good discrimination between subjects' NAD learning abilities; see Siegelman, Bogaerts, and Frost, 2017). Moreover, we used ERPs, which have been shown to be strongly reliable (Cassidy et al., 2012). In addition, we found significant ERP effects at the group-level, supporting our interpretation of the identified individual differences (see also Siegelman, Bogaerts, and Frost, 2017). However, we cannot account for all reliability issues raised in the literature. For example, there was no significant above-chance performance at the group level for the behavioral task, with most of the children performing at chance level on both days, making individual differences more difficult to interpret (see Siegelman, Bogaerts, and Frost, 2017). The mean change in behavior from day one to day two was small, further making the interpretation of the mean change in behavior difficult. However, we believe that the association we found between ERPs and behavior supports the meaningfulness of change of behavior from day one to day two as a measure.[3]

Another possible limitation of the present study is that we did not manipulate children's sleep duration between day one and day two. Therefore, we cannot make claims about whether the change in NAD representations is specifically due to sleep or due to a more general effect occurring over the course of a consolidation period. Similarly, we did not manipulate whether or not children underwent testing phases on day one. Thus, we cannot clearly infer whether the differences between ERPs on day two (negativity) compared to day one (positivity) were due to repetition effects (i.e., testing phases on both days) or whether we would still find a negativity on day two if day one did not include a testing phase. Future studies will have to investigate whether the representational change also occurs in a sleep-wake design and when testing conditions are manipulated.

[3]Please note that our group-level analyses, on the other hand, are not affected by these concerns (see Arnon, 2019).

4.5 Conclusion

Taken together, the present study indicates that, even though 7-year-old children do not show above-chance level performance in our NAD grammaticality judgment task yet, NAD representations changed after a retention period including sleep, as indicated by ERP responses to NAD violations compared to familiarized NADs. At the group level, we found a more positive ERP response to NAD violations before retention, which could indicate associative representations of NADs and/or similarity-based learning. In contrast, after a retention period involving sleep, we found a more negative ERP response to NAD violations, indicating that representations had been stored in long-term memory and thus demonstrating recall of NADs. In a descriptive analysis of individual differences, a stronger change from a more positive ERP response on day one to a more negative ERP response on day two was associated with stronger positive changes in behavior (i.e., more correct answers on day two compared to day one). This could possibly indicate that only those children who had built associative representations of the dependencies on day one were able to consolidate these representations and show recall of NADs on day two, as indicated by a positive change in behavior (i.e., more correct answers on day two compared to day one). These results are the first to show children's implicit recall of NADs embedded in a natural, foreign language after a retention period involving sleep.

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Chapter 5

General discussion

In this thesis, I explored NAD learning as a special case of statistical learning using the ERP technique. I aimed to investigate 1) the development of NAD learning throughout childhood and whether the early development of NAD learning differs across domains, and 2) how children recall learned NADs after a retention period. The results of studies 1 and 2 point towards a sensitive period of NAD learning under passive listening conditions that is specific for language. The use of ERPs offers a sensitive measure to detect NAD learning under passive listening conditions and can help us draw inferences about the possible processes underlying NAD learning. Similarly, ERPs allowed us to make inferences about a change in underlying representations of the learned NADs in study 3. The first part of this discussion will therefore focus on the development of NAD learning in the linguistic and non-linguistic auditory domain, considering the possibility of a sensitive period for NAD learning, while the second part will discuss how mental representations of NADs are formed, stored, and retrieved.

5.1 Summary study 1: Domain-specific NAD learning during early development

Study 1 explored the earliest stages of NAD learning and investigated whether infants' remarkable ability to learn phonological associations between non-adjacent elements extended from the linguistic to the non-linguistic domain. Friederici et al. (2011) demonstrated that infants as young as 4 months were able to track NADs between an auxiliary and a suffix in sentences in a non-native language.

When tested with NAD violations, infants showed a late positive ERP response that was taken to indicate associative learning of the phonological forms of the NADs. Chapter 2 (Paul et al., in prep.) replicated these results with directly comparable non-linguistic stimuli. Four-month-old infants were exposed to sequences of pure tones containing NADs and tested with sequences that either contained familiarized NADs or NAD violations. Based on preliminary data, we did not find evidence that infants at 4 months of age learned NADs from tone sequences.

These findings confirm that the developmental trajectory of NAD learning differs between the linguistic and the non-linguistic domain and puts the onset of these differences in very early infancy. This is in line with our previous study reporting NAD learning for the linguistic, but not the non-linguistic auditory domain for 2-year-old children (van der Kant et al., 2020). Only at 3 years of age did this study find evidence for NAD learning in the non-linguistic domain. One possible explanation for these findings is that young children's NAD learning is specific to the linguistic domain, and that this domain-specificity fades during later development.

5.2 Summary study 2: Developmental trajectory of linguistic NAD learning

Chapter 3 (Paul et al., 2021) more closely investigated NAD learning in the linguistic domain through the course of early childhood. Previous studies had identified two different developmental stages of NAD learning: a first stage where children up to the age of 2 years learn the phonological features of NADs through associative learning and during which learning under passive listening is possible, and a second stage, during which older children and adults learn the morphological features of NADs, but struggle to learn under passive listening conditions (Culbertson et al., 2016; Friederici et al., 2011; Mueller et al., 2019). Here, we investigated how the transition between these two developmental stages of NAD learning occurs. Using the same stimuli and paradigm as a previous study with infants (Friederici et al., 2011), children between 1 and 3 years were familiarized with foreign language sentences containing NADs under passive listening conditions and then tested with both familiarized NADs and NAD violations. We found evidence that children tracked the NADs and detected violations throughout the tested age range. Based on the passive listening design, it is likely that children learned the NADs in an associative manner.

Importantly, the strength of associative NAD learning decreased linearly with age. This provides first evidence that the transition between the two developmental stages of NAD learning may occur in a gradual fashion. This gradualness is one of the defining features of a sensitive period and our findings may thus point towards a sensitive period of NAD learning under passive listening conditions.

5.3 Development and domain differences of NAD learning

In this section, I will discuss both the development and domain-specific differences of NAD learning. To put this into context, I will also compare the findings on NAD learning to other types of statistical learning. In order to be able to make this comparison, I will first briefly summarize findings about the domain-generality of ADs and repetition-based dependencies. As discussed in chapter 1, there are some differences in the strength and facilitating factors of AD learning across domains (Conway and Christiansen, 2005; Conway and Christiansen, 2009). However, the ability to learn ADs is present across domains, including the visual domain (e.g., Conway and Christiansen, 2009; Kirkham et al., 2002), and the linguistic (e.g., Saffran, Newport, and Aslin, 1996; Pelucchi et al., 2009) and non-linguistic auditory domain (Saffran et al., 1999). This holds not only for adults, but also infants (e.g., Bulf et al., 2011; Teinonen et al., 2009; Saffran et al., 1999). Similarly to ADs, infants can also learn repetition-based dependencies across the visual (e.g., Saffran et al., 2007; Rabagliati et al., 2019) and auditory domain (e.g.Marcus et al., 1999) as long as the stimuli have to be perceived to be meaningful (Rabagliati et al., 2019). Taken together, both ADs and repetition-based dependencies can be learned in both the visual and the auditory domain.

Next, I will briefly summarize the available literature on the development of AD and repetition-based dependency learning, with a focus on the linguistic and non-linguistic auditory domain. ADs can in principle be learned from birth (Teinonen et al., 2009), throughout infancy (Saffran, Aslin, et al., 1996; Saffran et al., 1999) and childhood (Raviv and Arnon, 2018; Shufaniya and Arnon, 2018), and up to adulthood (Saffran, Newport, and Aslin, 1996; Saffran et al., 1999). However, there seem to be some developmental differences between the linguistic and non-linguistic auditory domain during childhood. In particular, at least between 5 and 12 years of age, non-linguistic AD learning improves with age, whereas linguistic AD learning is age-invariant (Raviv and Arnon, 2018; Shufaniya and Arnon, 2018). For repetition-based dependencies, no reliable effect of age was found during infancy (4 - 15 months) regardless of domain, pointing towards age-invariance (Rabagliati et al., 2019). Taken together, learning ADs and repetition-based dependencies may be age-invariant, at least in the linguistic domain, whereas the picture is less clear for the non-linguistic auditory domain.

After reviewing the evidence about the development and domain-generality of ADs and repetition-based dependencies, I will discuss these factors for NAD learning. First, in chapter 2 (Paul et al., in prep.), we provided preliminary evidence that even at its earliest stages, NAD learning shows domain-specific differences, with 4-month-old infants being able to learn NADs in the linguistic domain (Friederici et al., 2011), but no evidence for learning in the non-linguistic auditory domain (chapter 2). These differences in the development of NAD learning in the linguistic compared to the non-linguistic auditory domain continue into early childhood, where 2-year-old children were shown to be able to learn NADs in the linguistic but not the non-linguistic auditory domain (van der Kant et al., 2020). Only at 3 years did this study find evidence for NAD learning in the non-linguistic auditory domain (van der Kant et al., 2020). This pattern clearly distinguishes NADs in the non-linguistic auditory domain from ADs, which can be learned by infants (e.g., Saffran et al., 1999) and children (e.g., Shufaniya and Arnon, 2018). This difference between AD and NAD learning decreases throughout development, such that adults can in principle learn both ADs and NADs in the linguistic as well as non-linguistic auditory domain (e.g., Saffran et al., 1999; Saffran, Newport, and Aslin, 1996; Mueller et al., 2009; Creel et al., 2004). However, some differences between AD and NAD learning remain even in adulthood; for example, adults process violations for ADs and NADs in distinct neural networks, indicating that processing NADs has different demands compared to ADs (Conway et al., 2020). Further investigation is needed to determine whether NAD learning resembles repetition-based learning in its domain-generality as long as stimuli are perceived to be meaningful (and whether it plays a role whether the repetition is between adjacent or non-adjacent elements). Taken together, NAD learning may differ from both AD and repetition-based dependency learning with respect to the interplay of development and domain-specificity.

Focusing on the linguistic domain, there also seem to be developmental differences for NADs compared to ADs and repetition-based dependencies. Both ADs and repetition-based dependencies seem to be age-invariant in the linguistic domain (Shufaniya and Arnon, 2018; Rabagliati et al., 2019); however, linguistic NAD learning changes throughout development. In particular, the ability to learn NADs under passive listening seems to decrease during development, with children up to 2 to 3 years of age being able to learn linguistic NADs under passive listening conditions (Friederici et al., 2011; Mueller et al., 2019; van der Kant et al., 2020), but older children and adults struggling to learn under passive listening conditions (Mueller et al., 2019; Mueller et al., 2012; van der Kant et al., 2020). However, older children and adults are able to learn NADs under active task conditions (Schaadt et al., 2020; Mueller et al., 2009; Mueller et al., 2012). As chapter 3 demonstrated, the ability to learn NADs under passive listening conditions gradually decreases during early childhood (see also Culbertson et al., 2016). This confirms that NAD learning, unlike other types of statistical learning in the linguistic domain, is not age-invariant and further shows that the decrease in NAD learning under passive listening conditions undergoes a gradual decrease during early childhood.

Based on this developmental trajectory, NAD learning under passive listening conditions may be undergoing a sensitive period. In the following I will discuss core features of sensitive period and argue that they also play a role in NAD learning. A sensitive period is defined by three major features (Knudsen, 2004): (1) a stage at which it is easier to learn a skill; (2) an effect of experience and plasticity; (3) a gradual closing of the sensitive period. The first feature, a stage at which it is easier to learn a skill, is present for NAD learning under passive listening conditions. As I have discussed above, several studies have shown that children up to the age of 2 years are able to learn NADs from linguistic material under passive listening conditions, whereas older children and adults struggle to do so (Friederici et al., 2011; Mueller et al., 2012; Mueller et al., 2019; van der Kant et al., 2020). Thus, the first two years of life may constitute a developmental period during which learning NADs under passive listening conditions is easier, fulfilling the first criterion for a sensitive period.

The second feature of sensitive periods, an effect of experience and plasticity on the learning of the skill, can also be observed in NAD learning under passive listening conditions. If there is an effect of (native language NAD) knowledge on NAD learning, one would expect to observe developmental changes in infants' processing of native language NADs during the proposed sensitive period. Indeed, knowledge of native language NADs strongly develops between the child's second and third year of life. Infants start being able to detect NAD violations in their native languages between 14 and 18 months, depending on the language and exact NADs tested (Culbertson et al., 2016; Höhle et al., 2006; Nazzi et al., 2011; Santelmann, 1998; van Heugten and Shi, 2010). Evidence for more mature knowledge of the grammatical rules and the meaning underlying NADs has been found to start around 21 to 30 months (Culbertson et al., 2016; Legendre et al., 2010). In particular, children start to be able to match sentences containing NADs to pictures in a sentence-picture matching task at 30 months (Legendre et al., 2010; see also Spit et al., 2020). Going beyond this observational evidence, there has been recent correlational evidence that infants' NAD learning from novel stimuli (i.e., from an artificial grammar) and processing of native language NADs is related to vocabulary size (Frost et al., 2020; Lany and Shoaib, 2019). More directly, NAD learning from novel stimuli has also been related to NAD processing in the infants' native language (although this relationship was only found in girls, not boys; Lany and Shoaib, 2019). Taken together, while the evidence is still sparse, there seems to be an effect of children's experience with their native language on NAD learning.

Similarly to experience, there is first evidence that plasticity plays a role in NAD learning under passive listening conditions. A recent model of the development of the language network (Skeide and Friederici, 2016) outlines how brain plasticity influences the way children learn and process linguistic structures, including NADs. In particular, the development of the prefrontal cortex, and with it, the cognitive control network, may play a role in the way children learn NADs (see Friederici et al., 2013; Skeide and Friederici, 2016; Ramscar and Gitcho, 2007). The development of the prefrontal cortex and the pathway connecting it to language regions is a crucial prerequisite for the development of higher-level learning, including top-down learning (Skeide and Friederici, 2016). The arcuate fascilus, connecting posterior language-related brain regions to the inferior frontal cortex, has not only been linked to syntactic processing in adults (Rodd et al., 2015; Vigneau et al., 2006), but its maturation has also been related to the development of syntactic processing (Dehaene-Lambertz et al., 2002; Skeide et al., 2016). The myelination of the prefrontal cortex progresses more slowly than that of other brain regions and still undergoes maturation during late childhood (Huttenlocher, 1990). This development of the prefrontal cortex has been hypothesized to drive the transition from associative NAD learning observed in infants to higher-level, morphological learning in adults (Friederici et al., 2013). This hypothesis is based on evidence from a transcranial direct current stimulation (tDCS) experiment. In the experimental group, tDCS was used to inhibit adult participants' prefrontal cortex while they were exposed to NADs embedded in sentences in a foreign language (i.e., the same stimuli as Friederici et al., 2011 and chapters 3 and 4) and subsequently tested with familiarized NADs and NAD violations. In the control group, participants received only a placebo stimulation, but were otherwise tested under the same experimental conditions. As expected from a previous study (Mueller et al., 2009), the control group, whose PFC was not inhibited, showed an N400 in response to NAD violations. However, those participants whose PFC was inhibited during familiarization, showed a different ERP response in response to NAD violations: a late positive ERP component that resembled the ERP component previously found for NAD violations in the same stimuli in infants (Friederici et al., 2011; Friederici et al., 2013). This was taken as first evidence that when adults do not have access to processes related to inhibition and cognitive control, they learn NADs in a more associative manner, like infants do (Friederici et al., 2013). Thus, while further evidence will be needed to confirm this, there is first evidence that both experience and plasticity play a role in NAD learning.

Lastly, the third feature of sensitive periods, a gradual closing of the sensitive period, plays a role in NAD learning, as I demonstrated in chapter 3 (Paul et al., 2021). Here, we provided empirical evidence that the strength of NAD learning under passive listening conditions decreases throughout early childhood. These findings are the first to show a gradual decrease of NAD learning under passive listening conditions across early childhood. However, the finding that NAD learning under passive listening conditions decreases is in line with previous studies showing successful NAD learning before 3 years of age (Friederici et al., 2011; Mueller et al., 2012; Mueller et al., 2019; van der Kant et al., 2020), but no evidence for learning under passive listening conditions (or only in partial groups) at or after the age of 3 (Mueller et al., 2012; Mueller et al., 2019; van der Kant et al., 2020). Taken together, linguistic NAD learning under passive listening conditions fulfills the core criteria of a sensitive period (Knudsen, 2004): a stage at which it easier to learn the skill in question, an influence of experience and plasticity, and a gradual closing of the sensitive period.

In contrast to the linguistic domain, NAD learning in the non-linguistic auditory domain does not seem to undergo a sensitive period. Up to 3 years of age, there is no evidence that children learn NADs in the non-linguistic domain (van der Kant et al., 2020 and chapter 2). Starting at 3 years, both children and adults seem to be able to learn NADs from tones (Creel et al., 2004; Gebhart et al., 2009; van der Kant et al., 2020). Looking also at other types of dependencies, statistical learning in the non-linguistic domain seems to improve with age, whereas statistical learning in the linguistic domain was found to be age-invariant between 5 and 12 years (Shufaniya and Arnon, 2018). Considering that the development of NAD learning differs from other types of statistical learning (as I have argued in this section), it is possible that NAD learning in the non-linguistic domain still undergoes a sensitive period, even if other types of statistical learning do not. However, to the best of my knowledge, there is no evidence that NAD learning in the non-linguistic domain undergoes a developmental period where learning is easier, shows an influence of experience and plasticity, or shows a gradual closing of that period. Indeed, it seems likely that if a sensitive period for NAD learning exists, it would apply only to the linguistic domain. After all, infants' brains seem to be uniquely wired to learn language, with one of the crucial pathways for language present and relative mature at birth (Perani et al., 2011). Infants are remarkable language learners and children have a good grasp of their native language before they have mastered many other skills. Further, even young infants show a preference for linguistic stimuli over matched non-linguistic stimuli (Colombo and Bundy, 1981; Glenn et al., 1981; Krentz and Corina, 2008; Vouloumanos and Werker, 2004). Finally, all typically developing children end up mastering their native language, whereas only some master non-linguistic domains, such as music. Taken together, if a sensitive period for NAD learning under passive listening conditions indeed exists, it seems to only apply to linguistic domain, reflecting the special role and importance of language learning during early childhood.

In the previous paragraph, I argued why a sensitive period for NAD learning might exist for the linguistic but not the non-linguistic domain; next, I will turn to the question why a sensitive period would exist specifically for NAD learning *under passive listening conditions*. Passive listening conditions, rather than a more active design featuring a task, most closely resemble the way infants learn language in a natural environment. Initial language learning occurs largely incidentally, without intention, and without awareness of what is known (see Perruchet and Pacton, 2006 and Saffran et al., 1997). This incidental, or bottom-up, learning may be the primary route available to infants, because higher-level top-down processes rely on the prefrontal cortex and, for language in particular, the arcuate fasciculus, both of which only mature later during development (Huttenlocher, 1990; Skeide et al., 2016; see Skeide and Friederici, 2016). It has been hypothesized that this more immature stage of associative learning (driven by bottom-up brain processes) actually facilitates infants' language learning compared to adults' top-down strategies (Ramscar and Gitcho, 2007). So then, if these associative learning processes are advantageous for language learning, why would older children and adults not also use them? Ramscar and Gitcho (2007) propose that a mature prefrontal cortex hinders these processes, but in turn allows to develop other skills, such as cognitive control, the selection and representation of active goals, and the maintenance of attention. Under this view, the developing brain has to strike a balance between language learning (which is facilitated by bottom-up processes and an immature prefrontal cortex) and executive functions (which are facilitated by top-down processes and a mature prefrontal cortex). This account would then also explain why the sensitive period of NAD learning under passive listening conditions closes: to open up the possibility to learn other skills through top-down processes.

5.4 Summary study 3: Overnight change of representations of learned NADs

While older children are hypothesized to struggle to learn NADs under passive listening conditions, they would be expected to learn under active task conditions. Chapter 4 investigated 7-year-old children's NAD learning under active task conditions. In addition, this study investigated whether children could detect NAD violations not only immediately after familiarization, but also after a delay of a day. As such, this study was the first to demonstrate school-age children's ability to recall NADs after a retention period involving sleep. Recall after a retention period is an important indicator that not only immediate associations of the dependent elements of the NAD were learned, but that the underlying morphological rule was learned and consolidated into long-term memory.

We found electrophysiological evidence of 7-year-old children's NAD learning both immediately after learning and after a retention period including sleep. This provides first evidence that school-age children can recall learned NADs after a day-long delay. Interestingly, we found different ERP responses on day 1 (i.e., immediately after test) compared to day 2 (i.e., after a retention period including sleep). This may indicate a change in children's mental representations of learned NADs during the retention period, possibly driven by sleep.

5.5 Mental representations of learned NADs

The results of chapter 4 are in line with previous evidence that children's mental representations of recently acquired knowledge change during sleep and that this change can be detected with ERPs. In a recent study, 6-months-old infants were familiarized with word-object pairs (Friedrich et al., 2017). Infants' generalization of the word-object pairs was then tested with correct items (i.e., the familiarized word with an object was similar to the object that was paired with this word during familiarization) and incorrect items (the familiarized word with an object that resembled *another* object than the one that was paired with the word during familiarization) after a retention period. During this retention period, one group of infants stayed awake (wake group), one group had a short nap (approx.

30 min; short nap group), and one group had a longer nap (approx. 50 min; long nap group). There was no evidence for learning (i.e., no significant difference between infants' ERP responses to correct and incorrect items) in the wake group. In contrast, both of the nap groups showed evidence of learning and generalizing the word-object pairs, but the two groups differed in their ERP responses. The short nap group had a late, more positive ERP response for incorrect compared to correct word-object pairs (the authors call this a late negative ERP response, because they compare correct to incorrect pairs). This response was interpreted to indicate perceptual-associative memory representations of the word-object pairs. The long nap group, on the other hand, had an N400-like response to incorrect compared to correct pairs. This N400-like response was interpreted to indicate higher-level lexico-semantic memory representations (Friedrich et al., 2017). Taken together, chapter 4 and the study discussed here provide evidence that children's mental representations of recently learned knowledge changes during a retention period involving sleep, and that this change can be detected using ERPs.

A change in children's mental representations of learned NADs during a retention period including sleep could be explained by several models. First, from the perspective of similiarity and rule-based learning (e.g., Hauser et al., 2012; Knowlton and Squire, 1996; Opitz and Hofmann, 2015), it would be plausible that children initially acquire similiarity-based knowledge that is available in an immediate test, but rule-based knowledge would take longer to build up and might only be available after a retention period. With regard to artificial grammar learning, similiarity-based learning refers to participants forming mental representations of features of the stimuli (which could include a subset or all of the available features) during familiarization. These mental representations in memory can then be compared to test items and a test item would be judged as adhering to the rule or not based on its similiarity to the feature representation in participants' memory. On the other hand, rule-based learning refers to the acquisition of the abstract rules underlying the stimuli in an artificial grammar. Rules, here, can be understood as complex combinations of mental representations of abstract statistical regularities underlying the familiarized stimuli (Opitz, 2010; Opitz and Hofmann, 2015; Sun, 1995). Similiarity-based and rule-based learning do not have to be mutually exclusive, but can operate jointly, with similiarity-based knowledge being available and prevalent immediately after learning, whereas rule-based knowledge only builds up over time (Opitz and Hofmann, 2015). This interplay between similarity-based learning and rule-based learning is supported by findings of an initial activation of the hippocampal system (indexing similarity-based) and the later involvement of Broca's area (indexing rule-based learning; Opitz and Friederici, 2003; Opitz, 2004). Rule-based knowledge may even be directly build upon previously learned similiarity-based knowledge in some cases (Opitz and Hofmann, 2015; see also Sun and Zhang, 2004; Sun et al., 2007; Sun et al., 2001). Thus, based on the results of chapter 4, it is plausible that children may initially learn NADs through similiarity-based learning, but the knowledge of the underlying rule only builds up over time and is only evident after a delay, resulting in different ERP results in a test immediately after familiarization compared to a test after a retention period involving sleep.

The role of sleep in this change in mental representations could be explained by the complementary learning systems model (McClelland et al., 1995). This model divides memory into two distinct systems: (1) one-of-a-kind episodic representations that are formed rapidly and are context-specific (processed in the hippocampus) and (2) subsequent representations in long-term memory that are generalized beyond a specific context and are learned more slowly (driven by the neocortex). Under this view, novel memories are processed by both systems. But whereas the first (hippocampal) system can store the memories immediately, the second (neocortical) system needs repetitions of the event in order to store the memory long-term. Interestingly, memories can be transferred from the rapid, hippocampal system to the slow, but long-term neocortical system via offline reinstatement of hippocampal memories, gradually reducing the memory strength in the hippocampus, but strengthening the long-term representation in the neocortical system. This process is likely facilitated by sleep, as was originally proposed by McClelland et al. (1995), which has been confirmed by empirical studies (e.g., Wilson and McNaughton, 1994; Cantero et al., 2003).

The complementary learning systems model (McClelland et al., 1995) has been proposed to extend to language acquisition, specifically word learning (Davis and Gaskell, 2009). According to this proposal, novel words are rapidly learned by the hippocampal system and lexicalized and stored in long-term memory by the neocortical system. Here again, sleep plays an important role in the transfer between memory systems. When both children and adults learned new words, they could recall these words during test on the same day, but the new words were not yet integrated into long-term lexico-semantic memory (or the mental lexicon). Newly learned words were only integrated into the mental lexicon after sleep (Henderson et al., 2012; Smith et al., 2018; Tamminen et al., 2010). Therefore, sleep has been shown to facilitate lexico-semantic memory of novel words for both children and adults.

Based on the results of chapter 4, that is, different ERP responses to NAD violations before and after a retention period involving sleep, one could hypothesize that similar processes also underlie NAD learning. Initial learning could take place via rapid, associative processes and through the hippocampal system, but long-term memories in the neocortical system might be slower to form. If this were true, one would expect that sleep facilitates NAD learning and specifically generalization of learned NADs to new stimuli. Indeed, one previous study (Gómez et al., 2006) showed that sleep can help children generalize learned NADs to novel items. In this study, 15-month-old infants were familiarized with NADs and tested with familiarized NADs and NAD violations using the headturn-preference procedure after a 4-hour retention period. One group of infants napped (nap condition) during this retention period, while another group stayed awake (no-nap condition). Infants in the no-nap condition showed a consistent preference for familiar over unfamiliar stimuli during test, that is, no evidence for generalization was found. However, infants in the nap-condition showed evidence of generalization and abstraction away from specific NADs. Preference for infants in the no-nap condition depended on the first test trial: when the first test trial was familiar, infants showed a preference for familiar items thereafter; when it was unfamiliar, infants showed a preference for unfamiliar items thereafter. The authors interpreted these findings as evidence that generalization only took place after sleep (Gómez et al., 2006). Looking beyond just NADs, sleep has also been shown to facilitate performance in artificial grammar learning tasks in adults (e.g., probabilistic sequence grammars; Fischer et al., 2006). Based on this study, it could be speculated that both the complementary learning systems model and the similarity vs. rule-based knowledge model go hand in hand: with the complementary learning systems driving the consolidation of similarity-based knowledge into rule-based knowledge. This is based on the finding that sleep selectively facilitates performance in explicit, but not implicit artificial grammar tasks (Fischer et al., 2006). In order to perform well in explicit artificial grammar tasks, participants may have to have a good grasp on the rules underlying the artificial grammar, whereas implicit tasks could be solved based on less in-depth knowledge of the rules, or similarity-based knowledge of the surface-features of the artificial grammar. However, this line of thinking is currently only speculative and future studies will need to further investigate the role of memory and sleep in NAD learning.

5.6 Limitations

In the following, I will discuss three limitations of the present thesis: (1) the generalizability from artificial grammar learning to real-world language acquisition, (2) some missing links in our knowledge of NAD learning that will need to be studied before we can make definite conclusions about a possible sensitive period of NAD learning, (3) the assumptions about ERPs underlying (some of) the interpretations, (4) the interpretation of null results in an incomplete sample, .

The first limitation lies in the nature of the artificial grammar experiments in all three of the studies in this thesis: the rapid exposure to many repetitions of the same NADs in a short time frame. Infants and children in all three studies (Paul et al., 2021; Schaadt et al., 2020; Paul et al., in prep.) were familiarized with auditory sequences (either Italian sentences or tone sequences) containing NADs for approximately 13 minutes. During this time, two NAD frames were presented, each approximately 128 times. Additionally, half of the test items also contained familiarized NADs, which gave infants and children further exposure to the NADs. While this or similiar setups are typical for an artificial grammar learning study, this is of course far removed from how children encounter NADs in their natural environment. Outside of the lab, children are not exposed to the same sentence structures over and over, but rather encounter different types of grammatical structures and different kinds of NADs all the time. It would be expected that, outside the lab, it would take a much longer time until infants have encountered enough instances of a specific NAD (or other grammatical structure) in order to detect violations. As discussed earlier, detection of NAD violations in the infants' native language starts around 14-18 months (e.g., Culbertson et al., 2016; Höhle et al., 2006; Santelmann, 1998), at which point infants have presumably heard these NADs for several months. Therefore, how we test NAD learning in the lab can only roughly be related to how infants learn NADs outside the lab. However, the age at which infants first start to be able to detect NAD violations behaviorally are similar for novel NADs learned in the lab as for NADs in their native language (e.g., Culbertson et al., 2016; Höhle et al., 2006; Santelmann, 1998; Gómez and Maye, 2005; Frost et al., 2020). Whether young children's NAD learning in artificial grammars and in natural language is subsumed by similar processes is currently unclear. However, there is evidence that adults' artificial grammar learning shares neural underpinnings with native language processing, including the recruitment of similar brain regions (e.g., Forkstam et al., 2006; Lieberman et al., 2004) and similar ERP responses (Christiansen et al., 2012). Whether similar processes underlie infants' grammar learning in general and NAD learning in particular in the lab setting and outside of the lab remains to be seen, but this seems to hold at least for adults' artificial grammar learning compared to language processing.

As a second limitation, I will discuss one missing link in the line of my argumentation for the existence of a sensitive period of NAD learning under passive listening conditions: if a sensitive period existed, we would expect older children to struggle with NAD learning under passive listening conditions. However, direct evidence for this is still missing. The interpretation of null results in a null hypothesis test is limited, because an absence of evidence is not evidence of absence (further discussed below). Taking this caveat into account, there are some studies reporting null results for NAD learning under passive listening in older children: van der Kant et al. (2020) find no evidence for NAD learning under passive listening conditions at 3 years. Mueller et al. (2019) reported null results for NAD learning under passive listening conditions for 4-year-old children at the group-level. However, a subgroup of these 4-year-old children still showed evidence of learning the NADs. For adults, there were also null results for NAD learning under passive listening conditions (Mueller et al., 2012; Friederici et al., 2011), but the same limitations apply. Therefore, more direct evidence is needed that older children and adults are not able to learn NADs under passive listening conditions in the same task setting that younger children learn successfully. This evidence would then point further toward a sensitive period of NAD learning.

Third, a further limitation of this thesis is that many of the interpretations rest on assumptions about infants' and children's ERP responses. Interpreting certain cognitive processes based on a given ERP response's properties (such as polarity, amplitude, latency, and topography) is subject to the fallacy of *reverse inference*.

Reverse inferences are backwards reasoning, in this case from the observed brain activity to a cognitive process that was not tested directly, drawing on previous research that has linked this ERP component to a particular cognitive process. This type of reasoning has been suggested to be problematic, because they are not deductively valid; however, they can still provide some information (Poldrack, 2006). In particular, reverse inference can still be informative when the inferences are limited to cognitive processes that are likely to be involved in the task at hand, thus reducing the amount of possible alternative explanations and, thereby, the risk of false interpretations (Hutzler, 2014). In this thesis, the conclusions about particular cognitive processes rely rather on the experimental manipulation and on the tested age groups than on the exact features of the reported ERP responses. For example, in chapter 3, the interpretation of an associative learning process relies on the passive listening design (which is expected to trigger associative processes, based on previous studies; Friederici et al., 2011; Friederici et al., 2013). Moreover, at least the younger children tested in this experiment are not expected to be able to learn the NADs using higher-level morphological processes (Culbertson et al., 2016). In chapter 4, the interpretation of a change in mental representations indeed relies on a statistical difference between the ERP responses during test phases immediately after familiarization and after a retention period of one day. However, whereas children's ERP responses might differ from adults', these changes would not be expected to occur within one day, and the ERP responses in chapter 4 differed on multiple features, including polarity and latency.

Finally, a further limitation is the interpretation of null results, particularly in chapter 2. The results of this chapter are preliminary and based on a partial dataset of 20 infants, because data collection was interrupted due to COVID-19 restrictions. A sample size of 34 infants was planned and preregistered (the preregistration is currently embargoed, but will be available here upon publication: https://osf.io/y2dfp/registrations) and data collection will continue when possible. Under these circumstances, and with only a partial sample, conclusions about the data should be taken with caution. This is especially true for null results in a null hypothesis testing framework, which do not necessarily indicate the absence of an effect (Lakens et al., 2020). Therefore, if we find a null effect also in the final sample, null hypothesis testing should be supplemented with equivalence tests or bayesian statistics in order to be able to make valid conclusions about the null results (Lakens et al., 2020). Until then, the results in chapter 2 should be seen as preliminary and any conclusions may need to be revised once the sample is complete.

5.7 Future Directions

In the following, I will discuss four possible avenues for future studies about NAD learning: (1) open research questions related to a possible sensitive period of NAD learning under passive listening, (2) establishing a more direct link between NAD learning and language development, (3) the role of sleep in NAD learning, and (4) differences and similarities for NAD learning in different domains.

First, to make strong conclusions about a sensitive period of NAD learning under passive listening conditions, some open questions need to be answered. Chapter 4 (Schaadt et al., 2020) provided ERP-evidence that 7-year-old children can learn NADs under active task conditions, but failed to provide behavioral evidence of learning, possibly due to task difficulty. However, to the best of my knowledge, younger chidren's ability to learn NADs under active task conditions has not been tested. Therefore, it is currently unclear at what age children begin to successfully learn NADs under active task conditions. Future studies could test this with a combination of methods. To test active learning, they would need a behavioral task, comparable to our design in chapter 4. However, because of possible problems with task difficulties in our study, future studies should consider using a task that is easier for children to complete than our grammaticality judgment task. This might include a two-alternative forced choice task or a more implicit measure, such as a serial reaction time task (e.g., Schvaneveldt and Gomez, 1998). The serial reaction time task has successfully been used with 4-year-old children (Thomas and Nelson, 2001), whereas children before the age of 6 still struggle with a two-alternative forced choice task in artificial grammar learning paradigms (Raviv and Arnon, 2018), making this implicit, online task possibly the better choice for younger children. Other online measures such as ERPs or eyetracking could of course be added to these behavioral measures to get a better grasp of the underlying learning processes.

Another missing link with regard to a possible sensitive period of NAD learning under passive listening conditions is a more direct link between the gradual decrease in the strength of NAD learning (chapter 3, Paul et al., 2021) and structural brain changes. A recent model has proposed that a shift from associative to higher-level language learning might be driven by the development of the prefrontal cortex and the arcuate fasciculus (Skeide and Friederici, 2016). While our recent fNIRS study localized children's NAD violation detection in inferior frontal, temporal, and parietal brain regions, it did not look at the familiarization phase, during which learning takes place. Future studies should investigate where in the brain children's NAD learning takes place and whether this changes during development. In particular, one could hypothesize that during the sensitive period of NAD learning under passive listening conditions, one would find activation of temporal brain areas during NAD learning under passive listening conditions (see Skeide and Friederici, 2016). On the other hand, older children under active task conditions might recruit prefrontal regions (as adults likely do; Friederici et al., 2013). Both of these research questions are currently being adressed within the DFG-funded project "Crossing the borders: the interplay of language, cognition, and the brain".

Second, if we want to make generalizations from artificial grammar learning (or miniature versions of a foreign language, as in this thesis) to real-world language acquisition, a more direct link between the two is needed. As discussed in section 5.6, artificial grammar learning has been shown to recruit similar brain areas and elicit similar ERPs as native language processing in adults (Forkstam et al., 2006; Lieberman et al., 2004; Christiansen et al., 2012). However, whether this also holds in children and in particular for NAD learning is currently still unclear. One recent study has correlated children's preference for familiar NADs compared to NAD violations in an artificial language NAD learning task (at 15 months of age) and a native language NAD processing task (at 18 months of age), and found no correlation at the group level (Lany and Shoaib, 2019). When looking at boys and girls separately, there was a significant correlation between the preferences in the two tasks for girls, but not boys. These results should be taken with caution, because the sample size for these correlations was very small and neither girls nor boys showed a preference for familiar NADs or NAD violations that was significantly different from zero (Lany and Shoaib, 2019).

More generally, more well-designed within-subject studies looking at individual differences in the development of NAD learning are needed to understand the factors influencing the opening and closing of the possible sensitive period of NAD learning, such as language and structural brain development. In designing future individual difference studies, special care should be taken to find tasks that yield reliable results at the individual level. Many of the tasks currently used to assess NAD learning and statistical learning more generally were originally designed to assess group-level differences and do not capture stable individual differences (Siegelman, Bogaerts, and Frost, 2017), a problem that is only amplified in developmental studies (Arnon, 2019a). Therefore, while it is an important future direction to consider individual differences in the development of NAD learning and statistical learning more generally (see also Siegelman, Bogaerts, Christiansen, et al., 2017), researchers need to think carefully how to adopt statistical learning tasks to measure individual rather than group-level performance.

Third, there are still many open questions remaining about the role of sleep in NAD learning. In chapter 4 (Schaadt et al., 2020), we provided evidence that 7-year-olds' mental representation of NADs learned in the lab change with sleep. As outlined in section 5.5, it is possible that NAD learning, similarly to word learning (Davis and Gaskell, 2009), is implemented via complementary memory systems (McClelland et al., 1995). Future studies could test this claim by investigating whether memory representations of NADs are initially (i.e., immediately after learning) stored in the hippocampus, and transferred to the neocortex after sleep. Another approach could be to test whether NADs learned in the lab interfere with participants' existing knowledge of their native language. This approach was used to demonstrate that word learning follows the complementary systems model: participants were familiarized with a novel pseudoword (e.g., cathedruke) that had some phonological overlap with a real word (cathedral) (Tamminen et al., 2010; Henderson et al., 2012). Pseudowords (cathedruke) interfered with (i.e., slowed down) recognition of phonologically similar familiar words (cathedral), indicating that the pseudowords had been integrating in the mental lexicon. However, this effect was only found after a retention period, not immediately after test.

This integration in the mental lexicon was associated with sleep spindle activity, indicating the importance of sleep in the transfer from one memory system (rapid hippocampal learning) to another (lexical long-term memory in the neocortical system; Tamminen et al., 2010; Henderson et al., 2012). A similar approach might be possible for NAD learning: participants could be familiarized with NADs that partially overlap with NADs in their native language (e.g., 'is' with a novel verb suffix instead of 'is -ing'). They could then be tested on their recognition speed of '-ing' in sentences containing 'is -ing' constructions. Following the approach of Tamminen et al. (2010), one would expect that the recognition of '-ing' would be slowed after a retention period, but not immediately after familiarization with the novel verb suffix. Taken together, future studies could further investigate how NAD learning interacts with memory, how NADs are stored and recalled, and the role of sleep in mental representations of NADs.

Finally, future studies should compare NAD learning in the linguistic and non-linguistic more directly. Our recent study (van der Kant et al., 2020) made an important step in this direction by comparing NAD learning in the linguistic and non-linguistic auditory domain in a within-subject design. With a within-subject design, brain responses to NAD violations could be compared directly. Previous studies have demonstrated quantitative and qualitative differences for different domains for statistical learning in general (Conway and Christiansen, 2005; Conway and Christiansen, 2009). However, it is not clear whether these domain differences also hold for NAD learning, because, to the best of my knowledge, NAD learning in different domains has not been compared directly with the exception of van der Kant et al. (2020). This study found learning in the linguistic domain at 2 years, but not 3 years and the reversed pattern for the non-linguistic auditory domain. However, adults and presumably older children are able to learn NADs in both domains with seemingly similar restrictions (e.g., Gebhart et al., 2009; Creel et al., 2004; Onnis et al., 2005). For example, several studies have shown that NAD learning is facilitated by perceptual similarity of the dependent elements and adults struggle to learn NADs when neither perceptual nor other cues are present (e.g., Creel et al., 2004; Gebhart et al., 2009; Onnis et al., 2005). However, because learning in different domains has not been compared directly, it is unclear whether the strength of learning is similar between domains or whether NAD learning in different domains is differently influenced by these cues. Future studies could therefore deploy within-subject designs with directly comparable stimuli in different domains to investigate possible domain differences in NAD learning for both children and adults.

5.8 Conclusion

The present thesis aimed to answer three main research questions about the development of NAD learning: (1) is NAD learning domain-specific for language or domain-general during the earliest stages of development? (2) Does NAD learning under passive listening conditions undergo a sensitive period? and (3) How are learned NADs stored in memory? What is the role of sleep for mental representations of NADs?

Regarding the first research question, chapter 2 provided preliminary evidence that infants' ability to learn NADs may be domain-specific for the linguistic domain at 4 months of age. While these findings will need to be confirmed with a bigger sample, they are in line with our previous study pointing to domain differences in NAD learning during early childhood (van der Kant et al., 2020). In contrast to infants, adults are able to learn NADs in both the linguistic and non-linguistic auditory domain (e.g., Creel et al., 2004; Gebhart et al., 2009; Newport and Aslin, 2004; Saffran, Newport, and Aslin, 1996). Domain-specificity and development may therefore be inexplicably related for NAD learning. This makes NAD learning a special case of statistical learning in so far that other types of statistical learning seem to be possible in both the linguistic and non-linguistic auditory domain across development (e.g., Bulf et al., 2011; Raviv and Arnon, 2018; Shufaniya and Arnon, 2018; Teinonen et al., 2009).

Regarding the second research question, chapter 3 (Paul et al., 2021) provided key evidence for the presence of a sensitive period in NAD learning under passive listening conditions. A sensitive period is defined by a developmental period during which a skill can be learned more easily than outside of that period (Knudsen, 2004). We confirmed that NAD learning under passive listening conditions undergoes such a developmental period during early childhood (Paul et al., 2021; see also Mueller et al., 2012; Mueller et al., 2019; van der Kant et al., 2020). We also provided first evidence that for a gradual closing of the sensitive period of NAD learning under passive listening conditions, a main feature of sensitive periods (Knudsen, 2004), by demonstrating that children's ability to learn NADs under passive listening conditions gradually decreases during early childhood (Paul et al., 2021). These results, along with others, suggest linguistic NAD learning under passive listening conditions might be undergoing a sensitive period, in contrast to other types of statistical learning and NAD learning in other domains.

Regarding the third research question, chapter 4 (Schaadt et al., 2020) demonstrated that 7-year-old children's mental representations of learned NADs change during an overnight retention, possibly through a consolidation process. Following the complementary systems account (McClelland et al., 1995; Davis and Gaskell, 2009), it is possible that NADs were initially learned rapidly through associative processes, driven by the hippocampal memory system. Through consolidation during sleep, NADs may then have been transferred to long-term memory in the neocortical system. While the observed change in ERP responses to NAD violations before and after sleep points in this direction, further studies will be needed to investigate whether mental represenations of learned NADs, similarly to word learning (Davis and Gaskell, 2009; Tamminen et al., 2010; Henderson et al., 2012), is indeed subject to this complementary systems account.

Methodologically, the present thesis further confirms that ERPs are a useful tool to study language acquisition in general and NAD learning in particular. With the help of ERPs, we could test even preverbal infants' NAD learning (chapter 2; Friederici et al., 2011), test young children's learning when they cannot yet perform an explicit task (chapter 3, Paul et al., 2021), and detect possible implicit learning in older children even when the chosen task is too difficult for them (chapter 4, Schaadt et al., 2020). While the problem of reverse inferences (see section 5.6) has to be taken into account, ERPs in principle allow us to make inferences about underlying cognitive processes, for example allowing us to detect a change in children's processing of NADs before and after a retention period (chapter 4, Schaadt et al., 2020). Further studies using ERPs will allow us to further our understanding of ERPs during development and allow for more precise inferences based on the polarity, latency, and topography of ERP components in the future.

Overall, these results have implications for the field of language learning more generally. A possible sensitive period of NAD learning under passive listening conditions implies that while young children can learn the grammar of a foreign language by simply listening to the language, older children and adults need more explicit instructions that help guide the learners' attention for at least some grammatical structures. This has implications for how grammar lessons should be structured. In addition, if sleep indeed helps children to consolidate their knowledge of grammatical structures, this has implications on how and when children should be tested on their newly learned linguistic knowledge in a classroom setting. Furthermore, if NAD learning is specific to language at least early during development, this implies that we should not expect transfer effects from NAD learning tasks to similar tasks in other domains.

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Summary of the thesis

Infants and young children possess the remarkable ability to learn language, in all its richness and complexity, with an apparent effortlessness. They do so simply by listening to the language produced in their environment, without receiving explicit instructions. In order to learn from the input provided by their caregivers and other people around them, children have to track regularities in the input and extract both meaning and grammatical dependencies between elements in the input. One key mechanism that allows children to achieve this feat is statistical learning, or the ability to discover and adapt to statistical regularities in the input.

These statistical regularities are ubiquitous in language and allow for children to discover, among other things, grammatical rules. For example, children may discover that articles (like the) are often followed by nouns (like sister). In order to learn other linguistic rules, children are required to track statistical regularities over the course of several elements in the input. For example, in order to learn the is verb-ing construction in English, children have to track the two dependent elements (is and -ing) across the verb stem (e.g., in the sentence The sister is singing) or even across several elements (e.g., in the sentence The sister is often singing). These dependencies between non-neighboring elements are referred to as non-adjacent dependencies (NADs). NADs are omnipresent in language, for example in subject-verb agreement (e.g., Mary walks) and tense-marking (e.g., Mary was walking) and learning them is therefore an important part of language acquisition.

Previous studies have demonstrated that children can in principle learn NADs (e.g. Gomez & Gerken, 1999; Höhle et al., 2006; Santelmann, 1998), but that the nature of the process by which they NADs changes during development. For example, children may be tracking phonological features of the dependent elements to learn NADs during the first one and a half years of life and only start to learn the underlying morphosyntactic rules during the end of their second year of life (Culbertson et al., 2016). In addition, there may be differences in NAD learning between the linguistic and non-linguistic auditory domain during early childhood (van der Kant et al., 2020).

The aim of this thesis was to further identify and understand the factors influencing the development of NAD learning during childhood. The first study investigated whether NAD learning is domain-specific for language or domain-general during the earliest stages of development by testing whether young infants can track NADs in tone sequences in a similar way as they do in sentences. The second study focused on the development of NAD learning in the linguistic domain and asked whether the transition between the two different processes of NAD learning during development, that is, initial phonological learning and later morphosyntactic learning, occurs in a gradual manner. The third study further tested how NADs are stored in memory and consolidated during sleep.

Specifically, the first study in this thesis built on our previous findings showing that NAD learning undergoes a different developmental trajectory in the linguistic compared to the non-linguistic auditory domain (van der Kant et al., 2020). This study suggested that NAD learning under passive listening conditions may be specific to language at 2 years of age. In the first empirical study of this thesis, we aimed to test whether this domain-specificity for language also held during early infancy, at 4 months of age, where a previous study reported NAD learning for the linguistic domain (Friederici et al., 2011). We familiarized 4-month-old children with tone sequences containing NADs and tested whether they were able to detect violations in these NADs using event-related potentials (ERPs). In a preliminary sample, we found no evidence that infants were able to detect the violations and therefore no evidence that 4-month-olds were able to learn NADs in the non-linguistic domain. This finding was in contrast with a comparable study in the linguistic domain, where 4-month-old infants successfully tracked NADs in sentences (Friederici et al., 2011), suggesting that NAD learning may be domain-specific to language during the earliest stages of development. These findings suggest that children only track NADs in stimuli that they perceive to be relevant for them to acquire language.

In the second study, we concentrated on the development of NAD learning in the linguistic domain. Regarding the linguistic domain, previous studies had suggested that NAD learning under passive listening conditions undergoes two developmental stages. During the first stage, up to around 2 years, children learn NADs associatively, via surface-level phonological features; during the second stage, starting at 2-3 years of age, children learn not only phonological features, but also the underlying morphosyntactic rules (Culbertson et al., 2016; Friederici et al., 2011; Mueller et al., 2019; van der Kant et al., 2020). The second study in this thesis set out to further understand the transition between these two developmental stages and asked whether the transition occurred in a gradual or more abrupt manner. In order to test question, we familiarized 1- to 3-year-old children with sentences in a foreign language containing NADs. We employed a passive listening paradigm in order to trigger associative learning processes (Friederici et al., 2011; Mueller et al., 2019). As in study 1, we used ERPs to test whether children were able to detect NAD violations. We found that children across the tested age range were able to detect NAD violations, providing evidence that they learned the NADs. Interestingly, however, the strength of learning linearly decreased with age, indicating a gradual transition between the two developmental stages of NAD learning. This gradual transition may point to a sensitive period of NAD learning under passive listening conditions. In other words, it is possible that there is a developmental period during early childhood where children can learn NADs by simply listening to language input, which may be much harder later during life.

The third study aimed to further investigate how newly learned NADs are mentally represented and whether learning had more lasting effects on children's memory. Few studies have considered whether newly learned NADs can only be recalled immediately after test or also after a retention period, which would be critical to demonstrate that learning had lasting effects. We employed an active learning version of the paradigm in study 2, familiarizing 7-year-old children with NADs embedded in foreign language sentences and testing them using a mixture of familiarized NADs and NAD violations, both immediately after familiarization (day one) and after a 24-hour retention period (day 2). Children were asked to perform a grammaticality judgment task while we measured ERPs. The grammaticality judgments revealed no significant evidence of NAD learning, which may be an indication that the task was too difficult for children to explicitly pick up on the NADs. However, the ERP responses for familiarized NADs and NAD violations significantly differed, indicated that children may have learned the NADs implicitly. Interestingly, we found a different pattern in the ERP responses on day one compared to day two. Specifically, we found a positive-going ERP response to violations compared to familiarized NADs on day one, but a negative-going ERP response with a relatively shorter latency on day two. The ERP amplitude correlated with children's performance on the grammaticality judgment task. We hypothesized that these differences in the ERP responses between day one and day two indicate a change in mental representations of the learned NADs through overnight consolidation. In particular, it is possible that children initially stored the newly learned NADs in short-term memory during familiarization and consolidated them into long-term memory during sleep.

Taken together, the three empirical studies presented in this thesis help advance our understanding the development of NAD learning as a window into language acquisition. The results of studies 1 and 2 provide further evidence that the developmental trajectory of NAD learning differs between the linguistic and the non-linguistic domain. Further, these studies point towards a possible sensitive period of NAD learning under passive listening conditions in the linguistic, but not the non-linguistic auditory domain.

The results of study 3 may offer a starting point to better understand how NADs, as an example of morphosyntactic rules, may be mentally represented, stored in memory, and recalled. The results of this study would fit with the complementary learning systems model (McClelland et al., 1995), under which there are two memory systems: the hippocampal system, where episodic, context-specific representations are rapidly formed and the neocortical system, where representations are generalized beyond a specific context and stored long-term. This model has previously been applied to word learning (Davis & Gaskell, 2009; Henderson et al., 2012; Smith et al., 2018) and future studies should investigate whether it can also apply to learning morphosyntactic rules, such as NADs.

Zusammenfassung der Dissertation

Säuglinge und Kleinkinder besitzen die bemerkenswerte Fähigkeit, Sprache, in all ihrem Reichtum und ihrer Komplexität, mit einer anscheinenden Leichtigkeit zu erlernen. Sie tun dies, indem sie einfach der Sprache zuhören, die in ihrer Umgebung produziert wird, ohne explizite Anweisungen zu erhalten. Um aus dem Input zu lernen, der von ihren Bezugspersonen und anderen Menschen in ihrer Umgebung geliefert wird, müssen Kinder Regelmäßigkeiten im Input aufspüren und sowohl Bedeutung als auch grammatikalische Abhängigkeiten zwischen Elementen im Input extrahieren. Ein Schlüsselmechanismus, der es Kindern ermöglicht, dieses Kunststück zu vollbringen, ist das statistische Lernen, das heißt, die Fähigkeit, statistische Regelmäßigkeiten im Input zu entdecken und sich daran anzupassen.

Diese statistischen Regelmäßigkeiten sind in der Sprache allgegenwärtig und ermöglichen es Kindern unter anderem, grammatikalische Regeln zu entdecken. Zum Beispiel können Kinder entdecken, dass auf einen Artikel (wie *die*) oft ein Substantiv (wie *Schwester*) folgt. Um andere sprachliche Regeln zu lernen, müssen Kinder statistische Regelmäßigkeiten über den Verlauf mehrerer Elemente im Input verfolgen. Um z.B. die kann Verb-en Konstruktion im Deutschen zu lernen, müssen Kinder die beiden abhängigen Elemente (*kann* und *-en*) über den Verbstamm (z.B. im Satz *Die Schwester kann singen*) oder sogar über mehrere Elemente (z.B. im Satz *Die Schwester kann schön singen*) verfolgen. Diese Abhängigkeiten zwischen nicht benachbarten Elementen werden als nicht benachbarte Abhängigkeiten (englisch: non-adjacent dependencies, nachfolgend NADs) bezeichnet. NADs sind in der Sprache allgegenwärtig, z. B. bei der Subjekt-Verb-Übereinstimmung (z.B. *Marie läuft*) und der Tempusmarkierung im Englischen (z.B. *Mary was walking*), und das Erlernen dieser Abhängigkeiten ist daher ein wichtiger Bestandteil des Spracherwerbs.

Frühere Studien haben gezeigt, dass Kinder NADs prinzipiell lernen können (z.B. Gomez & Gerken, 1999; Höhle et al., 2006; Santelmann, 1998), dass sich aber die Art des Prozesses, durch den sie NADs lernen, im Laufe der Entwicklung verändert. So kann es sein, dass Kinder in den ersten eineinhalb Lebensjahren phonologische Merkmale der abhängigen Elemente verfolgen, um NADs zu lernen, und erst gegen Ende des zweiten Lebensjahres beginnen, die zugrunde liegenden morphosyntaktischen Regeln zu lernen (Culbertson et al., 2016). Darüber hinaus kann es Unterschiede beim NAD-Lernen zwischen der sprachlichen und der nicht-sprachlichen auditiven Domäne in der frühen Kindheit geben (van der Kant et al., 2020).

Das Ziel dieser Arbeit war es, die Faktoren, die die Entwicklung des NAD-Lernens in der Kindheit beeinflussen, weiter zu identifizieren und zu verstehen. Die erste Studie untersuchte, ob das NAD-Lernen in den frühesten Entwicklungsstadien domänenspezifisch für Sprache oder domänenübergreifend ist, indem getestet wurde, ob junge Säuglinge NADs in Tonfolgen in ähnlicher Weise verfolgen können wie in Sätzen. Die zweite Studie konzentrierte sich auf die Entwicklung des NAD-Lernens in der sprachlichen Domäne und fragte, ob der Übergang zwischen den beiden unterschiedlichen Prozessen des NAD-Lernens während der Entwicklung, d.h. dem anfänglichen phonologischen Lernen und dem späteren morphosyntaktischen Lernen, in einer allmählichen, d.h. graduellen, Weise erfolgt. Die dritte Studie untersuchte weiter, wie NADs im Gedächtnis gespeichert und während des Schlafes konsolidiert werden.

Die erste Studie in dieser Arbeit baute auf unseren früheren Erkenntnissen auf, die zeigten, dass das NAD-Lernen in der sprachlichen im Vergleich zur nicht-sprachlichen auditorischen Domäne einen anderen Entwicklungsverlauf durchläuft (van der Kant et al., 2020). Diese Studie legte nahe, dass das NAD-Lernen durch passives Zuhören im Alter von 2 Jahren sprachspezifisch sein könnte. In der ersten empirischen Studie dieser Arbeit wollten wir testen, ob diese Domänenspezifität für Sprache auch im frühen Säuglingsalter, im Alter von 4 Monaten, besteht, für das eine frühere Studie NAD-Lernen für die sprachliche Domäne berichtete (Friederici et al., 2011). Wir machten 4 Monate alte Kinder mit Tonsequenzen vertraut, die NADs enthielten, und testeten mittels ereigniskorrelierter Potentiale (EKP), ob sie in der Lage waren, Verletzungen dieser NADs zu erkennen. In einer vorläufigen Stichprobe fanden wir keine Hinweise darauf, dass Säuglinge in der Lage waren, die Verletzungen zu erkennen und somit keine Hinweise darauf, dass 4 Monate alte Säuglinge in der Lage sind, NADs im nicht-sprachlichen Bereich zu lernen. Dieser Befund stand im Gegensatz zu einer vergleichbaren Studie in der sprachlichen Domäne, in der 4 Monate alte Säuglinge erfolgreich NADs in

Sätzen verfolgten (Friederici et al., 2011), was darauf hindeutet, dass das NAD-Lernen in den frühesten Entwicklungsstadien möglicherweise domänenspezifisch für Sprache ist. Diese Befunde legen nahe, dass Kinder NADs nur in Stimuli verfolgen, die sie als relevant für den Spracherwerb wahrnehmen.

In der zweiten Studie konzentrierten wir uns auf die Entwicklung des NAD-Lernens im sprachlichen Bereich. In Bezug auf die sprachliche Domäne hatten frühere Studien nahegelegt, dass das NAD-Lernen unter passiven Hörbedingungen zwei Entwicklungsstufen durchläuft. In der ersten Phase, bis etwa 2 Jahre, lernen Kinder NADs assoziativ über oberflächliche phonologische Merkmale; in der zweiten Phase, ab einem Alter von 2-3 Jahren, lernen Kinder nicht nur phonologische Merkmale, sondern auch die zugrunde liegenden morphosyntaktischen Regeln (Culbertson et al., 2016; Friederici et al., 2011; Mueller et al., 2019; van der Kant et al., 2020). Die zweite Studie in dieser Arbeit hatte zum Ziel, den Übergang zwischen diesen beiden Entwicklungsstufen besser zu verstehen und fragte, ob der Übergang allmählich oder eher abrupt erfolgt. Um diese Frage zu testen, machten wir 1- bis 3-jährige Kinder mit Sätzen in einer Fremdsprache vertraut, die NADs enthielten. Wir verwendeten ein passives Paradigma, um assoziative Lernprozesse auszulösen (Friederici et al., 2011; Mueller et al., 2019). Wie in Studie 1 verwendeten wir EKPs, um zu testen, ob die Kinder in der Lage waren, NAD-Verletzungen zu erkennen. Wir fanden heraus, dass Kinder über den getesteten Altersbereich hinweg in der Lage waren, NAD-Verletzungen zu erkennen, was ein Beleg dafür ist, dass sie die NADs gelernt haben. Interessanterweise nahm die Stärke des Lernens jedoch linear mit dem Alter ab, was auf einen allmählichen Übergang zwischen den beiden Entwicklungsstadien des NAD-Lernens hinweist. Dieser allmähliche Übergang könnte auf eine sensible Phase des NAD-Lernens für passives Zuhören hinweisen. Mit anderen Worten, es ist möglich, dass es eine Entwicklungsphase in der frühen Kindheit gibt, in der Kinder NADs durch einfaches Zuhören von Sprachinput lernen können, was später im Leben viel schwieriger sein kann.

Die dritte Studie zielte darauf ab, weiter zu untersuchen, wie neu gelernte NADs mental repräsentiert werden und ob das Lernen nachhaltigere Auswirkungen auf das Gedächtnis der Kinder hat. Nur wenige Studien haben berücksichtigt, ob neu gelernte NADs nur unmittelbar nach dem Test oder auch nach einer Retentionszeit (d.h. nach einer Pause) abgerufen werden können, was entscheidend wäre, um zu zeigen, dass das Lernen dauerhafte Effekte hat. In Studie 2 verwendeten wir eine aktive Version des oben beschriebenen Paradigmas. Hier machten wir 7-jährige Kinder mit NADs vertraut, die in fremdsprachliche Sätze eingebettet waren, und sie mit einer Mischung aus gelernten NADs und NAD-Verletzungen testeten, sowohl unmittelbar nach dem Familiarisieren (Tag 1) als auch nach einer 24-stündigen Retentionszeit (Tag 2). Die Kinder wurden gebeten, eine Aufgabe zur Beurteilung der Grammatikalität durchzuführen, während wir die EKPs maßen. Die Grammatikalitätsbeurteilungen ergaben keine signifikanten Hinweise auf NAD-Lernen, was darauf hindeuten könnte, dass die Aufgabe für die Kinder zu schwierig war, um die NADs explizit aufzugreifen. Allerdings unterschieden sich die EKP-Antworten für vertraute NADs und NAD-Verletzungen signifikant, was darauf hinweist, dass die Kinder die NADs möglicherweise implizit gelernt haben. Interessanterweise fanden wir ein anderes Muster in den EKP-Reaktionen am ersten Tag im Vergleich zum zweiten Tag. Speziell fanden wir eine positive EKP-Antwort auf Verletzungen in den NADs im Vergleich zu familiarisierten NADs am ersten Tag, aber eine negativ verlaufende EKP-Antwort mit einer relativ kürzeren Latenz am zweiten Tag. Die EKP-Amplitude korrelierte mit der Leistung der Kinder bei der Grammatikalitätsbeurteilungsaufgabe. Wir stellten die Hypothese auf, dass diese Unterschiede in den EKP-Antworten zwischen Tag eins und Tag zwei auf eine Veränderung der mentalen Repräsentationen der gelernten NADs durch die Konsolidierung über Nacht hinweisen. Insbesondere ist es möglich, dass die Kinder die neu gelernten NADs während des Familiarisierens zunächst im Kurzzeitgedächtnis gespeichert und während des Schlafes ins Langzeitgedächtnis konsolidiert haben.

Zusammengenommen tragen die drei in dieser Arbeit vorgestellten empirischen Studien dazu bei, unser Verständnis der Entwicklung des NAD-Lernens – als Fenster zum Spracherwerb – zu erweitern. Die Ergebnisse der ersten und zweiten Studien liefern weitere Hinweise darauf, dass sich der Entwicklungsverlauf des NAD-Lernens zwischen dem sprachlichen und dem nicht-sprachlichen Bereich unterscheidet. Außerdem weisen diese Studien auf eine mögliche sensible Phase des NAD-Lernens bei passivem Zuhören in der sprachlichen, aber nicht in der nicht-sprachlichen auditiven Domäne hin.

Die Ergebnisse der dritten Studie könnten einen Ansatzpunkt bieten, um besser zu verstehen, wie NADs, als Beispiel für morphosyntaktische Regeln, mental repräsentiert, im Gedächtnis gespeichert und abgerufen werden können. Die Ergebnisse dieser Studie würden zum Modell der komplementären Lernsysteme (complementary learning systems; McClelland et al., 1995) passen, nach dem es zwei Gedächtnissysteme gibt: das hippocampale System, in dem episodische, kontextspezifische Repräsentationen schnell gebildet werden, und das neokortikale System, in dem Repräsentationen über einen spezifischen Kontext hinaus generalisiert und langfristig gespeichert werden. Dieses Modell wurde bereits auf das Lernen von Wörtern angewandt (Davis & Gaskell, 2009; Henderson et al., 2012; Smith et al., 2018) und zukünftige Studien sollten untersuchen, ob es auch auf das Lernen von morphosyntaktischen Regeln, wie z. B. NADs, anwendbar ist.

Wissenschaftlicher Werdegang

Persönliche Daten

Name: Mariella Paul
Anschrift: Calsowstraße 66, 37085 Göttingen
E-Mail: mariella.n.paul@gmail.com

Ausbildung

2002-2011 Abitur, Städt. Geschwister-Scholl-Gymnasium, Düsseldorf

2011-2015 B.Sc. Cognitive Science, Universität Osnabrück

2015-2016 M.Sc. Experimental and Clinical Linguistics (mit Auszeichnung), Universität Potsdam

2016- Doktorandin in der Psychology, MPI für Kognitions- und Neurowissenschaften, Berlin School of Mind and Brain und Universität Leipzig

Arbeitserfahrung

2013-2014 Erasmus-Praktikum, Abteilung Sprache und Genetik, MPI für Psycholinguistik, Nijmegen, Niederlande

2014-2015 Studentische Hilfskraft, Forschungsgruppe (Computer-)Linguistik, Universität Osnabrück

2015-2016 Praktikum, Forschungsgruppe Neurokognition der Sprache, Universität Potsdam

2015–2016 Wissenschaftliche Hilfskraft BabyLab, Universität Potsdam

2020– Wissenschaftliche Mitarbeiterin, Forschungsgruppe Psychologie der Sprache, Universität Göttingen

Stipendien und Auszeichnungen

2016 Promotionsstipendium, Berlin School of Mind and Brain

2019 SIPS 2019 Travel award, Society for the Improvement of Psychological Science

2021 IGOR-Preis für offene und reproduzierbare Forschung 2021, Interessensgruppe für offene und reproduzierbare Forschung (IGOR) in der Fachgruppe Biologische Psychologie und Neuropsychologie der DGPs

Veröffentlichungen und Vorträge

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Junge, C., Boumeester, M., Mills, D.L., Paul, M., Cosper, S.H. (2021) Development of the N400 for Word Learning in the First 2 Years of Life: A Systematic Review. *Frontiers in psychology*. https://doi.org/10.3389/fpsyg.2021.689534

Ausgewählte Vorträge und Posterpräsentationen

Paul, M., Männel, C., Mueller, J.L., van der Kant, A., Wartenburger, I., Höhle, B., Friederici, A.D. (2017) *The sensitive period for associative learning of non-adjacent dependencies: ERP evidence from 24-month-olds*, Poster präsentiert auf der Konferenz Interdisciplinary Advances in Statistical Learning in Bilbao, Spanien, Juni 2017

Paul, M. & van der Kant, A. (2018) *Developmental shift in non-adjacent dependency learning*, Vortrag präsentiert auf dem International Congress of Infant Studies (ICIS), Philadelphia, USA, Juli 2018

van der Kant, A. & Paul, M. (2018) *Developmental shift in non-adjacent dependency learning*, Vortrag präsentiert auf der Crossing the Borders Konference, Potsdam, September 2018

Paul, M., Männel, C., Mueller, J.L., van der Kant, A., Wartenburger, I., Höhle, B., Friederici, A.D. (2018) *The sensitive period for associative learning of non-adjacent dependencies: ERP evidence*, Poster präsentiert auf dem 51. Kongress der DGPs in Frankfurt, September 2018

Paul, M. (2018) Non-adjacent dependency learning undergoes a developmental shift around the age of 2 years, Vortrag präsentiert auf der paEpsy-Tagung 2019, Leipzig, September 2019

Conry-Murray, C., Dietrich, B., Paul, M. (2019) *Open science in time-limited student projects*, Vortrag präsentiert auf der Society for the Improvement of Psychological Science (SIPS) 2019, Rotterdam, Niederlande, Juli 2019

Paul, M., Männel, C., van der Kant, A., Mueller, J.L., Wartenburger, I., Höhle, B., Friederici, A.D. (2020) *Gradual shift of non-adjacent dependency learning during early childhood*, Poster präsentiert auf der digitalen IMPRS Conference 2020 in Nijmegen, Niederlande, Juni 2020

Govaart, G.H. & Paul, M. (2021) *Preregistration: Increasing transparency in electrophysiological research*, Vortrag präsentiert auf der digitalen Psychologie und Gehirn 2021 in Tübingen, Juni 2021

Mariella Paul
Calsowstraße 66
37085 Göttingen
mariella.paul@uni-goettingen.de

Selbständigkeitserklärung gemäß §8 (2) der Promotionsordnung

Hiermit erkläre ich, Mariella Paul, das Folgende:

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III. Zudem standen mir andere wissenschaftliche und technische Mitarbeiter des Max-Planck-Instituts für Kognitions- und Neurowissenschaften bei der Diskussion inhaltlicher, methodischer und technischer Fragen und Probleme sowie bei der Datenerhebung hilfreich zur Seite.

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VI. Weiterhin erkenne ich hiermit die Promotionsordnung vom 30. September 2019 der Fakultät für Lebenswissenschaften der Universität Leipzig an.

Ort, Datum Mariella Paul

Nachweis über Anteile der Co-Autoren, Paul
Non-adjacent dependency learning: development, domain differences, and memory

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Nachweis über Anteile der Co-Autoren:

Titel:	Gradual development of non-adjacent dependency learning during early childhood
Journal:	Developmental Cognitive Neuroscience
Autoren:	Mariella Paul, Claudia Männel, Anne van der Kant, Jutta L Mueller, Barbara Höhle, Isabell Wartenburger, Angela D Friederici

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Anteil Mariella Paul (Erstautorin):

- Datenerhebung
- Datenanalyse und Dateninterpretation
- Schreiben der Publikation

Anteil Claudia Männel (Autorin 2):

- Konzeption
- Betreuung
- Beitrag zur Publikation

Anteil Anne van der Kant (Autorin 3):

- Beitrag zur Publikation

Anteil Jutta L Mueller (Autorin 4):

- Konzeption
- Beitrag zur Publikation

Anteil Barbara Höhle (Autorin 5):

- Konzeption
- Beitrag zur Publikation

Anteil Isabell Wartenburger (Autorin 6):

- Konzeption
- Beitrag zur Publikation

Anteil Angela D Friederici (Seniorautorin):

- Konzeption

– Beitrag zur Publikation

Doktorandin Mariella Paul	Senior-Autorin Angela D. Friederici

Nachweis über Anteile der Co-Autoren, Paul

Non-adjacent dependency learning: development, domain differences, and memory

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Nachweis über Anteile der Co-Autoren:

Titel: Seven-year-olds recall non-adjacent dependencies after overnight retention

Journal: Neurobiology of Learning and MemoryL

Autoren: Gesa Schaadt, Mariella Paul, R Muralikrishnan, Claudia Männel, Angela D Friederici

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Anteil Gesa Schaadt (geteilte Erstautorin):

- Datenanalyse und Dateninterpretation
- Schreiben der Publikation

Anteil Mariella Paul (geteilte Erstautorin):

- Schreiben der Publikation

Anteil R Muralikrishnan (Autor 2):

- Konzeption
- Datenerhebung
- Beitrag zur Publikation

Anteil Claudia Männel (Autorin 3):

- Betreuung
- Beitrag zur Publikation

Anteil Angela D Friederici (Seniorautorin):

- Konzeption
- Betreuung
- Beitrag zur Publikation

Doktorandin Mariella Paul

Senior-Autorin Angela D. Friederici