The cognitive basis of the child advantage in language learning: A memory-based approach

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Eleonore Smalle

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Faculté de psychologie et des sciences de l'éducation
Université catholique de Louvain

Promoteurs

Prof. Arnaud Szmalec (UCL/PSP)
Prof. Martin Edwards (UCL/PSP)

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Every single word in this thesis is dedicated to Mannie, who gave me memories, and to my parents, who gave me language

ABSTRACT

Why do children appear to learn languages more easily than adults? This lingering question, better known as the sensitive period hypothesis, has generated much research interest. A central aspect of language development is the acquisition of new words. During novel word acquisition, learners need to discover novel lexical units from fluent speech, associate them with a meaning, and memorize them for the long-term. It is still not fully understood whether and how word-learning differs between children and adults. Due to a neurologically based maturational change at the level of the frontal and medial-temporal circuit, adults have access to a different set of learning and memory processes than children, which make them more explicit/attention-driven learners. Children in contrast have only limited memory and attention capacities. It forces them to focus on smaller linguistic units that constitute the formal properties of language (i.e., phonemes or syllables). These are potentially more stable for representation and retention in long-term memory. Children also have a well-developed implicit or procedural memory system. Implicit learning is important for many aspects of languages, also for learning novel word-forms. Here, we postulate that learning certain aspects of language can be hindered by cognitive abilities, such as executive functions or attentional control, and aided by implicit learning mechanisms. The observations in the present work support this idea at the level of word-learning and offer a promising memory framework to investigate language learning across life.

RÉSUMÉ

Pourquoi les enfants semblent-ils apprendre les langues plus facilement que les adultes ? Cette question persistante, mieux connue en tant qu'hypothèse sur la période sensible a généré beaucoup d'intérêt dans la recherche. Un aspect central du développement du langage est l'acquisition de nouveaux mots. Lors de l'apprentissage de nouveaux mots, les apprenants doivent découvrir de nouvelles unités lexicales du discours fluide, les associer à une signification et les mémoriser à long terme. Il n'est toujours pas entièrement compris si et comment l'apprentissage de mots diffère entre les enfants et les adultes. Grâce à un changement de maturation neurologique au niveau des circuits frontaux et médio-temporaux, les adultes ont accès à des procédures d'apprentissage et de mémorisation différentes des enfants, ce qui fait d'eux des apprenants plutôt explicites/guidés par l'attention. Les enfants, au contraire, ont seulement des capacités de mémoire et d'attention limitées ce qui les force à se concentrer sur des plus petites unités linguistiques qui constituent les propriétés formelles du langage (c.-à-d., phonèmes ou syllabes). Elles sont potentiellement plus stables pour la représentation et la rétention en mémoire à long terme. Les enfants ont également un système de mémoire implicite ou procédurale bien développé. L'apprentissage implicite est important dans de nombreux aspects des langues, notamment pour apprendre de nouvelles formes de mots. Ici, nous postulons qu'apprendre certains aspects du langage peut être entravé par des habilités cognitives, comme les fonctions exécutives ou le contrôle attentionnel, et aidé par des mécanismes d'apprentissage implicites. Les observations du présent travail supportent cette idée au niveau de l'apprentissage des mots et offrent un cadre mnésique prometteur pour investiguer l'apprentissage des langues au cours de la vie.

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ACKNOWLEDGMENTS

There we are, after getting the so-called writer's block many times, barring losing confidence just as many times, computers crashing, administration failures, re-writing, re-revising and re-submitting, moments of pure frustration as well as moments of pure conviction, I finally finished my doctoral project. This of course would not have been possible without the time, support and dedication of the people around me.

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Finally, I would like to dedicate my thesis to my godmother, who would have been so proud.

And last but not least, every single word in this thesis is written to my most loving parents, who gave me language (and so much more).

With love,

Eleonore

CHAPTER 1

GENERAL INTRODUCTION

« Language ability is an instinctive tendency to acquire an art »

- Charles Darwin

General Introduction

« *As you are reading these words, you are taking part in one of the wonders* of the natural world. For you and I belong to a species with a remarkable ability: we can shape events in each other's brains with exquisite precision […] an ability that is uncontroversially present in every one of us. That ability is *language* » (Pinker, 1994). But why is it that children seem to acquire novel linguistic representations so easily, whether it be in the first or a second language, and yet we adults struggle much more with reaching a high proficiency in linguistic acquisition? To extend the point, children are not only better at language learning, but appear also to be more rapid acquirers of other skills such as playing a novel sport or a new musical instrument. Adult learners by contrast, even with the best of intentions, seldom become true champions or talented musicians. This feels rather counterintuitive as we adults, compared to children, are very strong on most tests of cognitive abilities such as factual learning, attentional control, working memory and many other intellectual abilities (Craik & Bialystok, 2006). Perhaps not surprisingly, many of these cognitive abilities involve aspects of the cognitive system that recruit regions within the prefrontal lobe; a brain structure that matures rather late in adolescence (Thompson-Schill, Ramscar, & Chrysikou, 2009). Yet, we seem to fail in learning languages with the ease that children do. This suggests that children's superiority in learning various new skills, such as language, must be based on another, perhaps implicit or unconscious, learning mechanism that matures early in life.

The aim of the present thesis is to gain better understanding of the different learning and memory processes that children versus adults use when learning novel linguistic representations. We are particularly interested in the acquisition of novel words, as this a component of language that is still poorly understood with respect to child-adult differences. In this general introduction, we will review the literature relevant for this thesis. In section 1, we start with the literature on critical periods in the development of brain and behavior in relation to processes such as human language development. We will set out evidence that there are several components of language that have different critical periods, and we will describe the explanations that have been put forward. In section 2, we will attempt to explain into more detail the process of what it means to learn a novel word. We will illustrate the complexity of word-learning and will propose a memory framework to best approach this complex task. Finally, in section 3, we will review evidence for developmental differences in a skill other than language; namely motor skill learning. We will try to argue how this field of research has important implications for studying child-adult differences in language learning. In section 4, we conclude by providing a summary of the main objectives and the studies that were developed as part of this thesis.

1. Critical periods

Given that adults perform better on a wide range of learning tasks, the observation that children still seem to be stronger at learning such a complex skill as language, is puzzling. In the literature, this phenomenon of children's apparent flawless language learning skills is also known as the *critical period* hypothesis (Lenneberg, 1967). The term "critical period" has a long history, and was first described in relation to the phenomenon of filial imprinting in young animals (Lorenz, 1937). Immediately after birth, animals learn to recognize and attach with their parents. Since the young animal cannot know the identity of its parent a priori, it imprints on the first stimulus nearby that best satisfies the innate expectations of a parent. Lorenz described a short and sharply defined period in the life cycle during which the brain is open to learn. This learning is irreversible in the face of later experience. Later, the idea of a critical window of opportunity to learn was applied to a wide arrange of other phenomena in the development of brain and behavior (Knudsen, 2004). For instance in their groundbreaking studies with cats, Wiesel and Hubel (1963) observed a physiological shift in the responsiveness of neurons in the visual cortex to light stimulation when one eye was deprived of vision early in life. The plasticity with which the other eye adapted diminished once the cats became older. This showed that a change in the external environment (e.g., vision deprivation) could alter preexisting neuronal connections during a limited period in development. Other evidence for critical periods comes from work with songbirds. When birds such as the chaffinch are not exposed to the song of their species until 15 days after birth, they will never be able to acquire the song normally (Thorpe, 1961). This is thought to be due to a time-dependent specialization of the hemisphere that controls singing (Demers, 1988).

1.1 Language development

Extensive research has investigated whether a critical change also exists for human language development (Lenneberg, 1967; Michel & Tyler, 2005). In his book, *Biological Foundations of Language*, Eric Lenneberg (1967) hypothesized that language acquisition was an example of biologically constrained learning in humans that occurs during a critical period. This period, as he hypothesized, begins early in life, and ends at puberty when the brain has fully established cortical lateralization of its functions. Lenneberg's assumptions were based on a few observations of crossed aphasia where damage to the right hemisphere leads to language deficits, which appeared to occur more often in young children than in adults; and the observation that younger children with left-hemispheric damage had the best chances for language recovery (Harley, 2013). Other important evidence for the critical-period hypothesis comes from case studies of individual feral or abused children who were isolated from exposure to their first language until after puberty. A famous case was a girl named Genie who was released from her plight at the age

of thirteen (Curtiss, Fromkin, Krashen, Rigler, & Rigler, 1974). A team of researchers followed Genie closely during her placement in a normal linguistic environment to see whether she would ever be able to learn language, even though she had exceeded the hypothesized critical period. While Genie did successfully make progress in specific areas such as using social gestures and learning to dress herself, developmental progress in the language area remained poor. She acquired a few new words, but her phonology was abnormal, and her ability to make full sentences and to correctly use morphology was limited to only the simplest aspects of the language. This and further similar case studies provided initial evidence for the existence of a critical period in language. However skepticism rose about the lack of control for other important factors such as general physical and cognitive abilities that were also severely affected in children like Genie. Later work started focusing on larger populations. For instance, some interesting work was done with adults who were born deaf and started acquiring sign language as a primarily language later in life (Mayberry & Eichen, 1991). Yet other important evidence comes from immigrant populations (children and adults) who were exposed to a second language at different ages (Johnson & Newport, 1989; Krashen, Long, & Scarcella, 1979; Long, 1990). Based on these studies, it rapidly became evident that the opportunity to learn languages was not as sharply defined and irreversible as originally thought. Adults were still able to learn, though their learning was associated with more difficulties and with less proficiency in the long-term compared with that of child learners. This has led most researchers to adopt the alternative term "sensitive period", and to use this term to describe the general phenomenon that it seems easier to learn novel linguistic representations early in life, preferably before the age of twelve. We use the same term in the present thesis, and particularly focus on the ability to learn novel linguistic representations in one's native language.

In 2005, on the occasion of its 125th anniversary, the journal *Science* proposed the sensitive-period hypothesis for language development as one of the most fundamental issues that still lacks clear empirical evidence (Kennedy & Norman, 2005). When children and adults are directly compared under similar learning conditions in the laboratory, adults often outperform children rather than the other way around. This contradicts what we observe in daily life. To make things even more complicated regarding the sensitive-period hypothesis, not all aspects of language seem to exhibit the same age-related sensitivities (Newport, Bavelier, & Neville, 2001). Studies indicate, for example, that there are more sharp periods for phonology, in particular for the development of speech sounds (or phonetics), than for the ability to learn novel syntactic and morphological structures (Kuhl, 2010; Werker & Tees, 2005). For instance, Japanese 6 to 8-month babies are able to distinguish /l/ sounds from /r/ sounds, but lose this ability before the end of their first year (Houston, Horn, Qi, Ting, & Gao, 2007). Similarly, Kuhl and colleagues

showed in a laboratory setting that 9-month-old (but not 12-month-old) American infants are able to learn and discriminate specific phonetic elements of the Mandarin-Chinese language by brief exposure to that language (Kuhl, Tsao, & Liu, 2003). This suggests that there exists a sharp critical period of two to four months, already very early in development, for learning novel phonology that is important for attaining a native accent (phonetic development). There exists quite some inconsistency about the existence of critical periods in vocabulary learning (Neville, 2006; Newport et al., 2001). Although vocabulary development explodes from 18 months until school age, and reaches an asymptote in adulthood (Altman, 1997; Pinker, 1994), many people believe that one has actually the capacity to learn new words at any age. But is it the case that adults learn words in the same way, and at the same rate, as do children? Not many studies have investigated this question directly, and if they did, inconsistent findings have been obtained.

1.2 Different explanations

Various explanations have been put forward in an attempt to explain the age-sensitivities that are observed in language learning. The original biological approaches focused on brain plasticity such as the lateralization processes proposed in Lenneberg's work. According to the latest research in the field, brain plasticity occurs at the cellular level in which molecular changes eliminate the potential for further change (Knudsen, 2004; Werker & Hensch, 2015). The removal of neural plasticity "brakes" (for instance by using neuro-inhibitors) has the potential to re-open critical periods during learning (Bavelier, Levi, Li, Dan, & Hensch, 2010). This has for instance been shown in human pitch-learning, an ability that can only be acquired early in life (Gervain et al., 2013). In this pitch-learning study, adult participants who took a neuro-inhibitor (i.e., valproate, which is a histone deacetylase inhibitor) learned to identify pitch significantly better than those who took a placebo. This demonstrates that the removal of brakes on plasticity facilitates learning in the adult brain for abilities that normally are restricted to a critical period. This finding still needs further exploration with respect to language learning abilities (Werker & Hensch, 2015). Parallel to these approaches, there is increasing interest in cognitive-driven explanations. These accounts focus on differences in existing knowledge between children and adults (Arnon & Ramscar, 2012; Finn & Hudson Kam, 2008), and on differences in the maturation of other cognitive abilities such as cognitive control or working memory (Elman, 1993; Newport, 1990; Ramscar & Gitcho, 2007; Thompson-Schill et al., 2009). Maturational disadvantages for aspects of language learning are thus a reflection of the development of other (domain-general) cognitive control processes that rely on a late-maturing prefrontal cortex (PFC). These processes interfere with more basal, unconscious or implicit, learning patterns that are characteristic of children's language learning (Ramscar & Gitcho, 2007). This is referred to as the often-cited *less-is-more* hypothesis (Newport, 1990). The reasoning behind this hypothesis is

that more limited memory resources, such as reduced working memory capacity (Elman, 1993), make children attend to and select different components of a language structure, e.g., smaller structures. The simple components that children attend to are more amenable for recombination and memorization in the longer term (less is more). Although this intriguing idea has some experimental support in the language-learning literature (Cochran, McDonald, & Parault, 1999; Kareev, 2000; Kersten & Earles, 2001), and is recently getting some new attention again (e.g., Finn, Lee, Kraus, & Hudson Kam, 2014), the extent of the evidence remains up until now very limited. Recent work within this view has also proposed the idea that not having cognitive maturation, but rather a differential exposure to instructions in the environment, cause adults to rely more on attention and other cognitive abilities during language learning than do children (Lichtman, 2016). Accordingly, adults receive more explicit instructions than children in their direct environment, which cause them to use different strategies when learning language. These maturation and instruction accounts are important potential explanations that need further investigation.

In sum, in section 1, we explained that not all components of language appear to be equally restricted by age. Language acquisition is characterized by multiple sensitive periods. There are well-reported sensitive periods for some components such as the acquisition of phonology and syntax that open and close at different points in development. And there are other (less studied) components, such as vocabulary acquisition, that presumably remain open across the lifespan. Researchers particularly disagree on this latter point. We believe that this is in a great extent due to the complex nature of what it means to learn a novel word. Learning a novel word is a complex process that taps multiple cognitive processes, of which some are (perhaps) better developed in adults. We elaborate on the complexity of word learning below in section 2. We propose a novel theoretical memory framework on how to best approach the complex task of word learning when investigating child-adult differences.

2. What's in a word?

« When I'm dead, remember this contains all my juvenilia, the poems I wrote when I was sixteen, the sketches for sagas in six volumes made at eighteen, and so on … »

- From Umberto Eco, *Foucault's Pendulum*, translated by William Weaver, 1989.

If "*juvenilia"* was not yet part of your vocabulary, you have today, acquired a new word. You will probably need to hear the word a few more times before it is fully *integrated* in your mental lexicon. Nevertheless, you are able to learn new

words almost effortlessly. Word learning is identified as one of the most fundamental building blocks in the acquisition of language (Pinker, 1994). In this section, we will provide a more detailed view on what it means to learn a novel word.

2.1 Functional components

First, it is important to know that word learning entails several subcomponents. In spoken language, one must acquire a phonological representation of the word, or a *word-form*. In the present thesis, we define word-form *as a serially ordered pattern of phonemes (and/or allophones).* What is present as a stimulus during learning is a continuous stream of speech, and not a segmented entity on its own as one sees in written language (i.e., there are no spaces or breaks that indicate when a current word ends and when a new word begins). A useful starting point in thinking about spoken word learning is to accept that novel word-forms, on first exposure, are nothing more than a novel sequence of sounds that, based on prior experience with allowable sound combinations in one's native language, is segmented into shorter sequences. These new (isolated) lexical forms are subsequently consolidated or integrated in long-term memory, and *mapped to a meaning*. Hence, lexico-semantic development is the cumulative outcome of learning a word-form, a semantic representation and the link between the two (Swingley, 2010). This link goes in two directions, from form to meaning via a *receptive* link (i.e., when you hear the word you are able to retrieve what it means), and from meaning to form via an *expressive* link (being able to select the correct word form). The different components are explained in Figure 1.1, and these two types of link have generated several lines of research, that each focus on one of these subcomponents (Gupta, 2005).

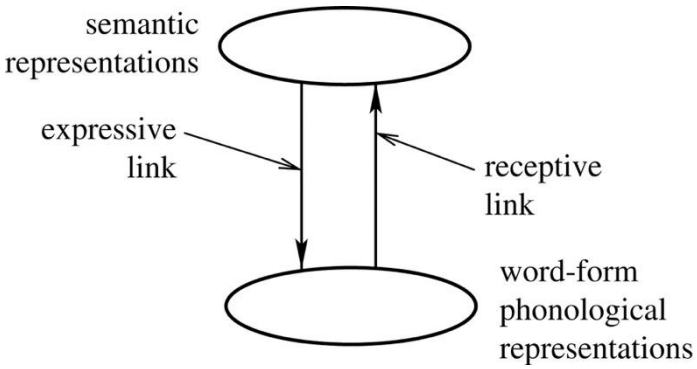

Figure 1.1. Functional components of word learning (From: Gupta & Tisdale, 2009b)

In the next paragraph(s) we elaborate on how several of these subcomponents of word-learning are processed in memory. We will particularly focus on the word-form component, as this will be the main focus of investigation in the present thesis.

2.2 Word-form learning

When acquiring a novel word-form, one first needs to acquire knowledge about its phonological structure. This means that you need to know about its phonetic elements and the constraints of their ordering. This is called *phonotactic constraint learning* which starts very early in life (Jusczyk, Friederici, Wessels, Svenkerud, & Jusczyk, 1993). For instance, in the example above (i.e., "juvenilia"), we know by experience that the phoneme /dʒ/ (or "j") is more likely to occur at the beginning of an English word (onset position) than at the end (coda position). This knowledge then helps to segment isolated word-units from an incoming stream of sounds (Mattys & Jusczyk, 2001; McQueen, 1998). Relevant work on the ability to *segment novel words* also comes from Saffran's statistical-learning studies (Saffran, Newport, Aslin, Tunick, & Barrueco, 1997). In her studies, eight-month-old infants were exposed to a continuous speech stream that consisted of three three-syllable novel word-forms repeated in a random order (e.g., pabiku, golatu, and daripo in pabikugolatudaropigolatupabikudaropi). Infants subsequently turned their head more often to the word-forms (e.g., golatu) compared with part-words (i.e., sequences spanning a word-boundary, e.g., bikugo). This research indicated that infants could segment new word-forms from a continuous stream of speech in a manner consistent with the probability of co-occurrence between the syllables (i.e., the transitional probabilities) that might be implicitly extracted from the input. Statistical learning has been widely investigated and offers a promising learning mechanism to investigate word-segmentation processes (Aslin & Newport, 2009).

Recently, Thiessen and Erickson (2013) investigated the word-segmentation mechanism slightly differently by assuming that word segmentation was not directly driven by the calculation of transitional probabilities, but rather by (natural) *chunking* mechanisms in memory. This is also the mechanism that we will propose in the current work. Within this view, adjacent speech sounds are spontaneously grouped into chunk representations that receive activation every time they are encountered. Representations of groupings across word-boundaries show less (re)activation because they are re-encountered less frequently during exposure; hence they suffer from competition with representations of groupings within word-boundaries (see also, Erickson & Thiessen, 2015; Perruchet & Vinter, 1998). This means that whereas learners may appear to be calculating transitional probabilities between syllables, they are actually storing chunks of the input stream, which—due to interference— are biased toward those chunks that happen to be statistically more coherent due to their frequent occurrence. Regular subsequences then gradually

consolidate in long-term memory due to repeated exposure of their serially-ordered constituents (syllables or phonemes) (Page & Norris, 2008, 2009).

2.2.1 A laboratory analogue to word-form learning

There has been abundant evidence showing a link between vocabulary knowledge, word-learning and performance on verbal immediate serial recall tasks and nonword repetition tasks (Baddeley, Gathercole, & Papagno, 1998; Gathercole, 2006; Gupta, 2003; Service, 1992). During immediate serial recall and nonword repetition, participants need to retain serially ordered items (such as phonemes, syllables or words) in a phonological short-term memory store for subsequent recall or repetition. Hence, the obtained association with measures of word-learning and vocabulary knowledge led several authors to assume that an (implicit) sequence-learning mechanism in short-term memory critically contributes to the integration of new word-forms in the long-term memory system (Gupta, 2009; McClelland, McNaughton, & O'Reilly, 1995; Page & Norris, 2008, 2009). Experimental evidence for this hypothesis comes from work with the Hebb learning paradigm (Hebb, 1961).

Back in the early sixties, Hebb demonstrated that participants who were asked to immediately recall a sequence of digits with one sequence repeated every third trial, performed significantly better in recalling the repeating sequence compared with nonrepeating sequences over the course of trials. This occurred even though participants were not made aware a priori of the repetition (see Figure 1.2). This advantage of the repeated over the nonrepeated sequences is known as the *Hebb repetition effect.* It is a reflection of how a sequence of information in short-term memory gradually develops into a stable, long-term memory trace though the principle of repeated exposure. First evidence for this hypothesis comes from correlational work by Mosse and Jarrold (2008). In their developmental study, five-to-six-year-old children were exposed to verbal and spatial immediate recall tasks. The extent of learning repeating sequences was correlated with several measures of word and nonword-paired associate learning. The children showed comparable learning of spatial and verbal Hebb learning. Interestingly, the magnitude of (verbal and spatial) Hebb learning was significantly correlated with the measure of novel word-learning. Novel word-learning was also significantly correlated with children's general ability to immediately recall the verbal sequences in short-term memory. This supports the hypothesis that lexical development depends on a domain-general long-term memory process of learning through repetition and a domain-specific short-term memory system.

IMMEDIATE RECALL

(1) 762935841
(2) 385271694
(3) 468291375
(4) 516982734
(5) 352748916
(6) 468291375
(7) 854329671
(8) 681437295
(9) 468291375
…

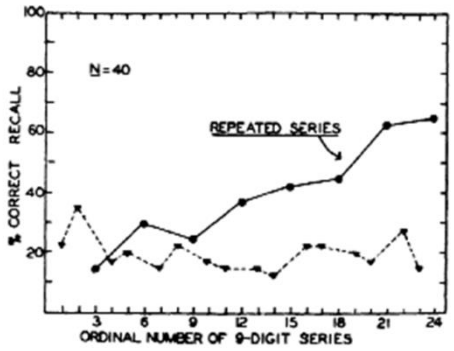

FIG. 7. Percentage frequency of completely correct recall of 9-digit numbers when tested immediately. The "repeated series" was a specific 9-digit sequence that occurred in the 3rd, 6th, 9th . . . 24th position in the series of tests. Other points represent nonrepeated 9-digit numbers (Hebb, 1961).

Figure 1.2. The Hebb repetition paradigm and results as originally designed and obtained by Hebb (1961).

Subsequent experimental work in the past decades has used the same Hebb learning paradigm to support the idea that novel words are integrated in the mental lexicon through the principle of long-term serial-order learning (Szmalec, Duyck, Vandierendonck, Mata, & Page, 2009; Szmalec, Page, & Duyck, 2012). In these studies, sequences of nine syllables, grouped into three subsets of syllables (e.g. so-wu-jo_le-ki-vi_lo-fo-du) were presented for immediate serial recall, and were repeated every third trial in a Hebb learning procedure (Szmalec et al., 2009). Only the order within the groupings was kept constant across repetition trials so that the sequences were segmented into three three-syllable groups. After learning was terminated, participants were tested on an auditory lexical decision task. Some of the nonwords in this lexical decision task were constructed from the syllables in the repeating Hebb sequence (i.e. sowujo, lekivi and lofodu). Participants were much slower in responding to these Hebb nonwords (i.e., recognizing them as "nonwords"), compared with control nonwords. This finding indicates that there was a tendency to identify the nonwords as (novel) words (Leach & Samuel, 2007). In a subsequent study, three three-syllable groupings that were, now close to existing (base) words that have no existing phonological neighbours (e.g., la-va-bu_no-ma-du_sa-fa-ro; which are close to the Dutch words "lavabo", "nomade", "safari") were presented in a Hebb learning procedure (Szmalec et al., 2012). Instead of a lexical decision task, a pause-detection task was presented after learning. In a pause-detection task, participants are asked to detect the presence of an artificially embedded pause in connected speech (inside the word-form). The speed at which such an artificial pause can be detected depends on the overall amount of lexical activity caused by the speech preceding this pause. For instance, upon hearing *blacb*… a person will activate a cohort candidates in the mental lexicon such as

blackboard, *blackberry or*, *blackbird*, that all compete for recognition. Therefore, the time needed to detect the pause is a function of the number of phonological neighbours of the target word, and therefore an indication of the lexical status of that word (Mattys & Clark, 2002). The participants in Szmalec et al. (2012) showed significantly slower pause-detection times on Dutch base words that overlapped with the Hebb sequence, compared with control base words (matched on neighbourhood size). This indicates that the Hebb sequences were integrated in the mental lexicon as novel lexical entries, acting as novel phonological neighbours to the existing base words, and therefore slowing down pause-detection.

Further work corroborated this hypothesis by showing that Hebb repetition learning is fast and long-lasting, just like natural word learning (Page, Cumming, Norris, McNeil, & Hitch, 2013), and that it is correlated with measures of word-learning abilities in adults (Majerus & Boukebza, 2013a; Majerus, Poncelet, Elsen, & Van der Linden, 2006) as well as in developmental samples (Mosse & Jarrold, 2008). Studies of Hebb repetition learning have also been extended to samples with specific language disorders (for which Hebb repetition learning is impaired; Archibald & Joanisse, 2013; Bogaerts, Szmalec, De Maeyer, Page, & Duyck, 2016; Bogaerts, Szmalec, Hachmann, Page, & Duyck, 2015; Hsu & Bishop, 2014; Szmalec, Loncke, Page, & Duyck, 2011). It is moreover important to know that learning in the Hebb repetition task does not critically depend on explicit awareness of the repetition (even though many participants become aware of the repetition when learning proceeds) (Couture & Tremblay, 2006; Gagnon, Bedard, & Turcotte, 2005; Gagnon, Foster, Turcotte, & Jongenelis, 2004; Guerard, Saint-Aubin, Boucher, & Tremblay, 2011). It also does not depend on explicit reproduction processes that occur during the recall phase (Kalm & Norris, 2016), and learning in the task is not affected in patient groups that suffer from focal hippocampal lesions. This is important evidence for the assumption that learning in the Hebb repetition task is driven by implicit (or unconscious) rather than by explicit learning mechanisms.

2.2.2 A computational analogue to word-form learning

Twenty years ago, Jordan (1986) already pointed out the importance of serially-ordered action in human behavior and the urge to develop a general theory of serial ordering (Gupta, 2012; Jordan, 1997). Some interesting computational models have been built in the context of immediate serial recall to account for word learning (e.g., Botvinick & Plaut, 2006; Burgess & Hitch, 1999; Gupta, 1996; Page & Norris, 2008, 2009). Although these accounts differ in numerous respects, they do all converge on the hypothesis that a serial-ordering mechanism in memory is needed to learn a novel word-form. We will elaborate on two existing connectionist models below.

Page and Norris (2008, 2009) explicitly related word-form learning to sequential learning mechanisms by use of a *localist* connectionist model. This model involves four layers of localist units representing phonemes (or possibly syllables) and other learned sequences constructed from them. The model is depicted Figure 1.3. Units in the occurrence layer get activated whenever their stimulus (e.g., the phoneme /k/, as in the sequence /kaet/ or "cat") is present in the environment. Initially, all units in this layer are not committed to representing a given phoneme, and they are described as "uncommitted" and potentially available to come to represent a new chunk (i.e., a short sequence of phonemes, made familiar by repetition). In the recognition layer above, there are units corresponding (one-to-one) with those in the occurrence layer, but these compete with each other for activation, as a means of determining the optimal description of a given phoneme sequence. For example, assuming that the word /kaet/ is familiar, occurrence units for the word itself, and for each of its three phonemes, will activate at the occurrence layer. At the recognition layer, we would expect the unit for the familiar word /kaet/ to outcompete units corresponding to the constituent phonemes. In this way, at least four units will activate fully at the occurrence layer (and maybe others, such as one corresponding to, for example, the word /aet/ or "at"). However, only one unit will enduringly activate at the recognition layer, acknowledging that this is the most efficient "parsing" of this input. Recognized items, and the order in which they occurred, will be subsequently stored in the top layer (the order layer), whose units are also in a one-to-one relationship with those in the lower layers. Exposure to a new word-form (e.g., the word /kaet/ before it has become familiar) will cause the units within the order layer, that correspond to the constituent phonemes, to respond with the highest activation for the first phoneme /K/, a little less activation for the second /AE/ and the lowest activation for the last /T/. This representation of the phoneme-order is referred to as a *primacy gradient* of activation (Page & Norris, 1998), which is subsequently copied (back) into the connection weights between the units in the occurrence layer representing the phonemes and a new unit that begins to learn the new word. This new unit is formed (or "committed") to represent the novel chunk equivalent to the entire subsequence (the serial-ordered items /kaet/). As learning proceeds (i.e., with every repeated presentation of the new stimulus), the primacy gradient at the response layer (that is a combination of the short-term activation gradient at the order layer, and a long-term gradient derived from learned weights) becomes stronger, leading to fewer immediate serial recall errors. Eventually, a long-term memory representation of the new word emerges that can represent the occurrence of that word by its activation alone, rather than by the activation of units representing its constituent phonemes. Hence, according to this model, two parameters are important for word-learning: A short-term sequential (or serial-order) representation of the word-form (the primacy gradient) and a long-term weight-change process through repeated exposure (learning rate).

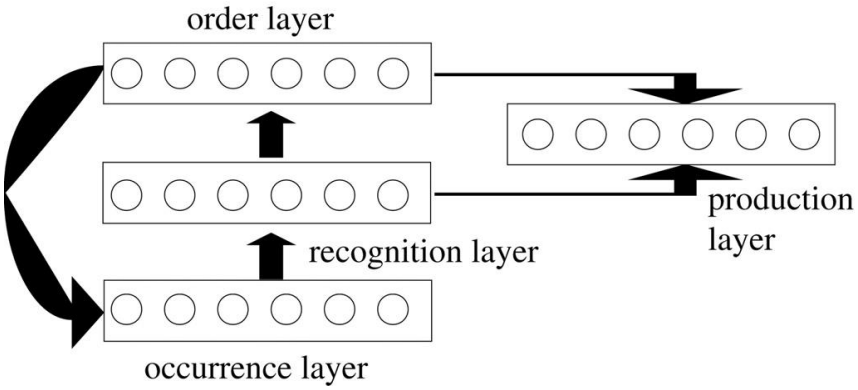

Figure 1.3. The structure of the connectionist localist model for word-form learning: by Page and Norris (2008, 2009).

Gupta and Tisdale (2009a) (see also, Gupta, 1996) similarly concretized the relationship between word-form learning and serial-order learning in the form of a computational model. The structure of their model is shown in Figure 1.4. The model has an input and output layer at which the representation of an entire syllable (e.g., CCVCC) is presented (and produced). This syllable is represented across a set of units that are divided into five slots. Activation of units in the first slot denotes the first phoneme (i.e., C) of the syllable, activation of units in the second slot denotes the second phoneme (i.e. C), and so on. Within each of these slots, the various phonemes that are legal for that slot (within the language) are represented as different patterns of activations across a set of units. In other words, the phonemes are represented in a distributed (instead of localist) fashion (i.e., different from the model of Page & Norris; 2008, 2009). The model also has a hidden layer that receives activation from the input layer and projects activation to the output layer. Every unit in the hidden layer additionally projects to its own and other units in the hidden layer by use of recurrent connections (the circular arrow). This way, the model is able to maintain previous state activation (the previous syllable) when the next syllable is presented. The task of the model is to receive a sequence of syllables as input, together with the activation of a recall unit, and to produce as output the same sequence of syllables. The activation of a stop unit in the output layer denotes the end of the word-form. At the end of presentation (and repetition) of the word form, the model's connection weights are adjusted using a backpropagation algorithm (i.e., by computing the errors between the actual output compared with the target output).

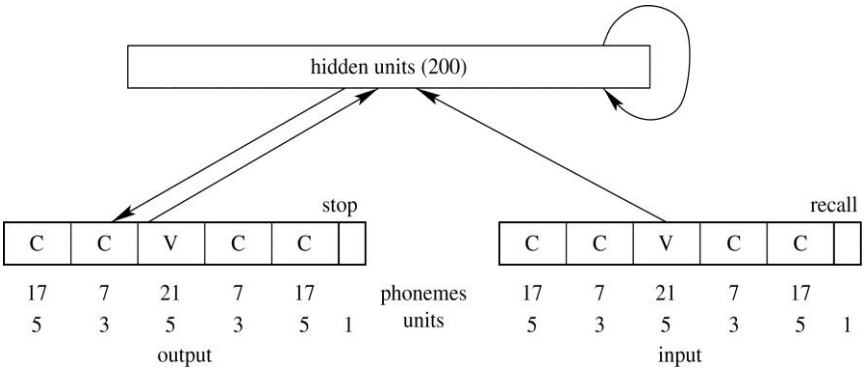

Figure 1.4. The structure of the connectionist distributed model for word-form learning: by Gupta and Tisdale (2009).

2.3 Semantic learning

« What's in a name? That which we call a rose by any other name would smell as sweet. »

- William Shakespeare

Another important aspect of word-learning considers the acquisition of semantics that represent the meaning of acquired word-forms. The mapping of phonological forms onto meaning does not follow identifiable patterns within a language. For example, nothing in the phonological form "hat" can give us the relevant information that it means "something to wear on the head". In other words, learning semantic associations is arbitrary or non-systematic. Most connectionist models for word-form learning (explained above) that incorporate incremental weight adjustments every time a correct response is given, are devices that instantiate systematic mapping. An arbitrary mapping can be described as a function in which pairs of input that are similar in the input space are mapped onto outputs that are not normally similar in the output space. A good example is the mapping between human proper names and personality characteristics (Gupta, 2012). My name is Eleonore and my twin sister's name is Laura, but the fact that these two names are phonologically dissimilar, tells us nothing about similarities and dissimilarities between our respective personalities. Likewise for the phonological overlap between the names Laura and Isaura (our family's dog). Learning semantic associations can occur quite swiftly in humans, often within a single encounter and apparently without catastrophic interference (Gupta, 2012). Catastrophic interference is the name given to a tendency to forget previously learned information because it gets overwritten by newly acquired information. It is a problem that is frequently described in relation to fully distributed connectionist models and is caused by the fact that gradual weight change can overwrite the memory of any

pattern that is not retained in the current training set (McCloskey & Cohen, 1989). The ability to rapidly learn semantic associations (often after a single exposure), is described, in the literature, as *fast mapping* (Carey & Bartlett, 1978).

2.4 An integrative memory approach

McClelland and colleagues proposed that the two functional aspects of word-learning (i.e., learning a phonological form and a semantic association), are possible in the human brain in the forms of procedural and declarative memory systems (McClelland et al., 1995). This view is illustrated in Figure 1.5. Within this view, the process of word-form learning depends on an implicit (procedural) learning mechanism that is rooted in non-hippocampal structures such as the neocortex and basal ganglia (Gupta & Dell, 1999; Gupta & Tisdale, 2009b; McClelland et al., 1995). Their formulation is explained by assuming distributed connectionist models (Gupta & Tisdale, 2009a). However, equivalent results can be obtained by a variety of localist connectionist models (see also, Page, 2000, 2016). The declarative memory system is rooted within the hippocampus and related medial-temporal lobe structures. It is assumed that this memory system is particularly important for semantic learning, even if it is not the ultimate locus of learned semantic memories. Evidence for this comes from studies with patients with hippocampal lesions. These patients are unable to learn word-meanings (e.g. Gabrieli, Cohen, & Corkin, 1988), which suggests that hippocampal-dependent memory mechanisms are needed for learning semantic representations.

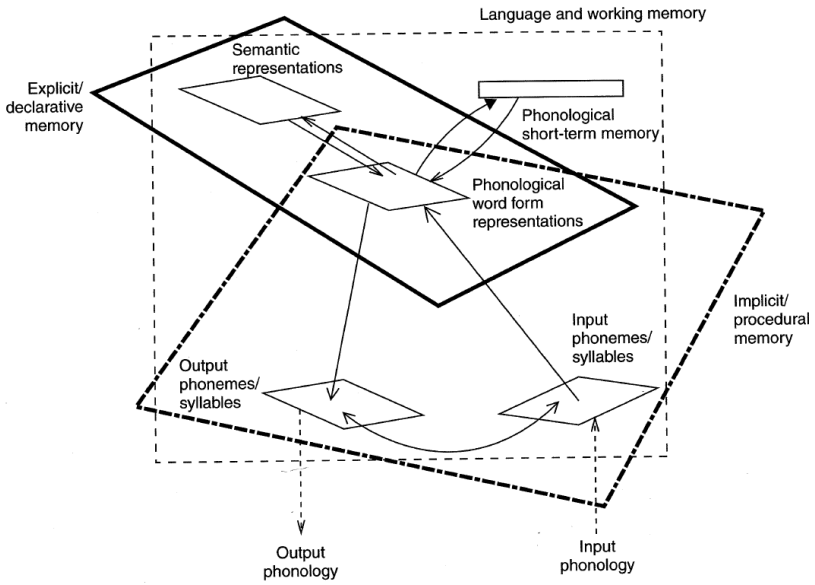

Figure 1.5. Word learning as a confluence of memory systems (from: Gupta, 2012)

McClelland and colleagues argued that the two memory systems interact during the first step of word-form learning. This is described as the complementary-learning hypothesis: novel word-forms first go through a process of (fast) hippocampal learning immediately after initial exposure. It is only after an offline consolidation period involving sleep that a stable procedural memory representation is formed (see also, Davis & Gaskell, 2009). The authors argue that this first step is needed to overcome catastrophic interference. Recent work has however shown that word-form learning can also take place immediately after initial exposure, without the need for sleep, or an offline consolidation period (Kapnoula & McMurray, 2016; Kapnoula, Packard, Gupta, & McMurray, 2015; see also, Szmalec et al., 2009; Szmalec et al., 2012, for evidence with the Hebb paradigm). These considerations indicate the complexity of word-learning.

This perspective on the role of two long-term memory systems in word-learning is very similar to the Declarative/Procedural model that was proposed by Ullman (Ullman, 2001, 2004, 2015). In this model, the procedural and declarative types of memory system were argued to play specific roles in different aspects of language learning, namely syntax development that is rooted within the procedural memory system and lexico-semantic development that is implemented by the declarative memory system. Nonetheless, as we noted above, even in lexico-semantic development alone, it is proposed that procedural and declarative memory play distinct roles. For example, it has been suggested that phonological forms are more effectively acquired by a procedural memory system, while other aspects, such as the mapping from word-forms to meaning, are better suited to the declarative memory system (Gupta & Cohen, 2002; Gupta & Dell, 1999).

Now that we have clarified the cognitive basis of word-learning, we come back to our main goal. In the present thesis, we test the hypothesis that children are better word learners than adults, at least for some components such as word-form learning. The reason for considering this hypothesis is that, as we argued before, word-form learning relies largely on implicit serial-order learning mechanisms. Interestingly, it has been shown in other cognitive domains outside language, such as motor learning, that children have a developmental advantage in implicit serial-order learning. Therefore, if word-form learning relies on a common, core cognitive process of serial-order learning, just like motor skill learning, the earlier insights about age-sensitivities in motor-sequence learning may turn out to be very helpful in addressing the issue of age-sensitivities in some aspects of language learning. Before we make this link more explicit, we first turn to what has been found about age-related differences in sequential or serial-order learning in the motor domain.

3. Serial-order learning in the motor domain

Some years ago, Janacsek and colleagues compared nine different age cohorts (from 4 to 85 years old) in a serial reaction time (SRT) paradigm (Janacsek, Fiser, & Nemeth, 2012). The SRT task consisted of a visual-motor sequence-learning procedure in which participants were asked to press a button that corresponded to a particular location on a screen. Unknown to the participant, a hidden structure was repeated throughout the task, and results showed better accuracy and faster reaction times for responses to stimuli consistent with the repeated structure than to inconsistent structures. This difference in performance between repeated and random sequences reflected the implicit learning of a novel (in this case, perceptual-motor) skill. Interestingly, the authors observed a peak in SRT performance before the age of twelve, after which performance dropped significantly. In another version of the task, participants were explicitly made aware of the repetition, and this time, they found no age-dependent shifts in learning performance (Nemeth, Janacsek, & Fiser, 2013). Additional measures of explicit knowledge about the repeating sequence (using verbal reports) revealed a different age-effect with significantly better scores on explicit knowledge after the age of twelve. The authors argued that cognitively controlled processes such as explicit attention, coming into play around the age of twelve, appeared useful for targeted explicit learning, but at the cost of a decreased ability to develop and stabilize new basic competences implicitly. The authors attributed this to neurological changes at the level of procedural (or implicit) and declarative (or explicit) memory systems. As explained earlier, the procedural memory system depends on non-hippocampal structures such as the basal-ganglia and the neocortex. These structures mature very early in life (Reber, 1993). The declarative memory system critically depends on frontal and medial-temporal circuits, which are known to develop throughout childhood (Ramscar & Gitcho, 2007). Within this view, children would rely on procedural memory mechanisms during skill learning. When children become older, they develop other cognitive functions within the declarative memory system (e.g., attentional control) that interacts with the procedural memory system (Albouy, King, Maquet, & Doyon, 2013; Brown & Robertson, 2007; Perez, Peynircioglu, & Blaxton, 1998; Poldrack et al., 2001; Robertson, 2012; Squire, 1992). This interaction might limit the amount of neuronal resources in the procedural memory system that can be allocated to the learning task. This view is illustrated in Figure 1.6.

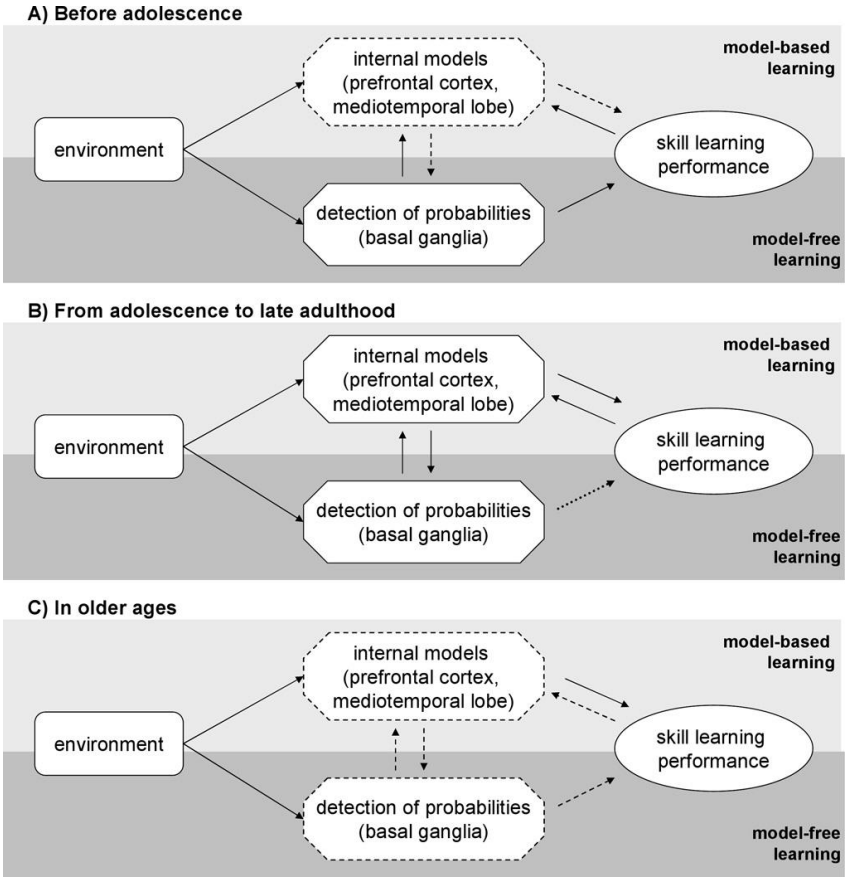

Figure 1.6. Interacting memory systems during skill learning across the life span (the present thesis is only interested in the two upper panels) (*From*: Janacsek et al., 2012).

3.1 Evidence for interacting memory systems in the adult brain

Virtually every textbook on human memory points out that memory is organized into distinct systems: a declarative memory system that is used for learning facts, and a procedural memory system that is used for learning skills (Cohen and Squire, 1980). Evidence however shows that this concept of independent memory systems is oversimplified. In 2007, Brown and Robertson provided initial evidence for the assumption that, instead of strictly dissociated structures, a rather dynamic relationship exists between the two memory systems. In a first experiment, participants were asked to perform a procedural learning task (the SRT) after which they immediately performed a declarative learning task (learning

word lists) or a control task (vowel counting). In a second experiment, the inverse was true: participants were introduced to the declarative learning task before they performed the motor learning task or the control task. Crucially, after an interval of being awake or a night of sleep, the participants in both experiments were retested on the primary task (so the motor task in Experiment 1 or the declarative task in Experiment 2). The authors found that, over the wake period, participants showed significantly decreased performance on the primary declarative or procedural task if this was followed by one of the contrasting memory tasks (compared with a vowel-counting control task). This decrease was also correlated with participant performance on the contrasting task. These findings clearly challenge the hypothesis that memories are supported by completely independent systems, and rather demonstrate that declarative and procedural memory have the capacity to interact during consolidation. This interaction was shown to be dynamic as it was modulated when consolidation took place. The memory systems interacted during waking hours, but operated independently over a night of sleep. The authors argued that interference occurred because the two memory systems probably share common neuronal resources. This was explained by assuming that the two systems have indirect connections that arise from brain areas such as the prefrontal cortex (Poldrack et al., 2001). Or, declarative memory processes may directly compete for the same neural resources in other brain areas related to procedural memory (Schendan, Searl, Melrose, & Stern, 2003). Hence, when one network is engaged (e.g. the secondary task), fewer resources become available for the other network, and therefore learning is disrupted. During sleep however, neurophysiological changes cause a decrease in functional connectivity between brain areas, and therefore functionally disconnect declarative and procedural memory systems. Their biological model is depicted in Figure 1.7 and shares important characteristics with the model that was proposed by Janacsek and colleagues.

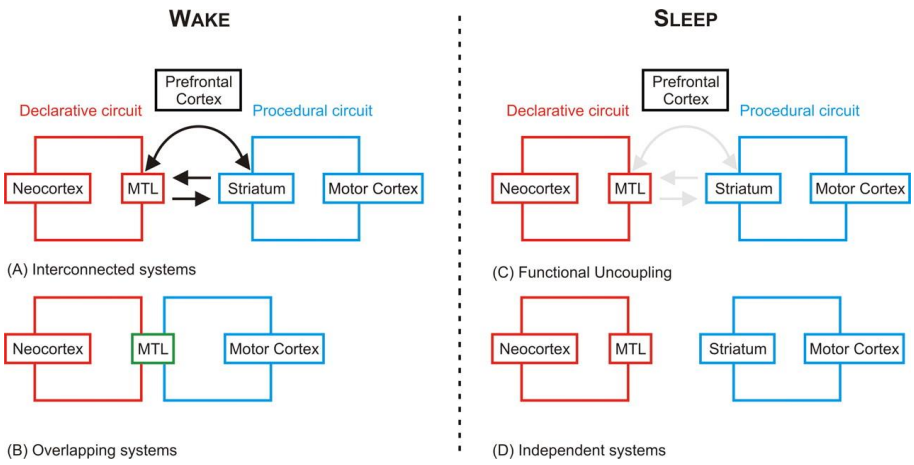

Figure 1.7. Interacting memory systems in the adult brain and how this is modulated by direct or indirect prefrontal networks in wake versus sleep (From: Brown and Robertson, 2007).

More recently, Galea and colleagues (2010) provided evidence for the notion of competing procedural and declarative memory systems. They showed that Transcranial Magnetic Stimulation (TMS) disruption of the Dorsolateral Prefrontal Cortex (DPFC) that supports declarative memory formation, immediately after performance on a motor-sequence learning task, resulted in enhanced skill performance after a wakeful period (Galea, Albert, Ditye, & Miall, 2010). TMS is a noninvasive method in which electrical currents are passed through a metal coil. This generates a rapidly changing magnetic field which, when held close to the scalp, induces a weak current in the adjacent brain tissue. This subsequently induces a temporarily disruptive lesion in the targeted area (Möttönen & Watkins, 2012). The findings of Galea et al. provided clear evidence for the idea that interacting memory systems can harm skill learning.

A series of other experiments, most of them using (variants of) the SRT task, similarly found evidence for the hypothesis that disrupting frontal-lobe and/or medial-temporal lobe related functions can lead to enhanced implicit learning or procedural memory in the adult brain (e.g. Fletcher et al., 2005; Foerde, Knowlton, & Poldrack, 2006; Nemeth, Janacsek, Polner, & Kovacs, 2013; Virag et al., 2015, to name just a few). This was demonstrated by a wide range of different tools used to weaken the declarative memory network, such as hypnosis (Nemeth, Janacsek, Polner, et al., 2013), alcohol consumption (Virag et al., 2015), benzodiazepines (Frank, O'Reilly, & Curran, 2006) and secondary tasks (Foerde et al., 2006). Some studies additionally demonstrated that the effect is modulated by individual differences in working memory performance, and in particular executive-function

abilities (Brown & Robertson, 2007; Nemeth, Janacsek, Polner, et al., 2013; Virag et al., 2015).

3.2 Controversial findings

The findings by Janacsek and colleagues lead to the assumption that maturational differences in motor skill learning have their roots in procedural memory. This hypothesis has however not gone unchallenged. For instance, some studies, in contrast to what was observed by Janacsek et al. (2012), showed no age-dependent change in implicit sequence learning (e.g., Meulemans & Van der Linden, 1998), or even an increase across age (e.g., Thomas et al., 2004). Also, the presumed disrupting role of the prefrontal/medial-temporal network and related cognitive functions (such as working memory or executive functioning) on sequence learning in the adult brain has not always been found. For instance, one (somewhat older) study found that disrupting the (dorsolateral) prefrontal cortex resulted in *weaker* instead of stronger skill performance (Pascual-Leone, Wassermann, Grafman, & Hallett, 1996). Several factors have the potential to explain these inconsistencies (see, Janacsek & Nemeth, 2013; Martini, Sachse, Furtner, & Gaschler, 2015, for an overview of the literature). First of all, the *explicitness* of what is learned seems to play an important role. Studies are more likely to find a positive effect of higher cognitive abilities such as working memory (WM) if learning is intentional. Secondly, WM is a complex construct and composed of several subcomponents (i.e., a phonological store and an executive control system) that are operationalized by different tasks (e.g., span tasks vs. change detection tasks) (Baddeley, Sala, Robbins, & Baddeley, 1996). This might have different effects on skill learning. For instance, studies using a span task have tended to observe a positive effect on skill learning (which is not surprising as more capacity opens a larger window for the length of the sequence to be processed). Third, the stage at which sequence learning is measured is also important. It is more likely to find an effect immediately after learning when no consolidation has taken place. When consolidation takes place, studies are more likely to find an effect after a period of wake than after a period nocturnal sleep. This was clearly demonstrated by the findings of Brown and Robertson (2007) explained above. Finally, sequence learning is sometimes confounded with general practice effects during the task. It is therefore important to control for these practice effects when investigating the impact of (disrupted) prefrontal/medial-temporal related cognitive functions. This can be done, for instance, by looking at the change in performance across repeated sequences *compared to* random sequences, assuming that the latter also improves through practice. These are all important factors that need to be considered when designing further experiments (Janacsek & Nemeth, 2013).

3.3 What does this tell us about language learning?

Overall, the hypothesis of competing memory systems suggests that optimal skill learning depends upon the disengagement of two potentially interacting memory systems (i.e., the declarative and procedural memory system), defined by different (but potentially overlapping) neural networks that rely on different functional demands and follow different developmental trajectories. This offers a promising framework for the study of developmental differences that are related to language learning. Recall that an important challenge within the sensitive-period debate is to investigate *what* adults experience as particularly difficult in language learning, and *why*. Some aspects of language rely primarily on procedural memory (e.g., phonology and grammar), while other aspects are mainly driven by declarative memory processes (e.g., semantics). The role of both memory processes is especially complex within the study of lexico-semantic development. Learning a novel word involves multiple cognitive processes, including the retention of the serial order of constituent phonemes or syllables, relying on procedural memory and the creation of long-term connections between phonology and semantics in declarative memory (Gaskell & Ellis, 2009; Gupta & Tisdale, 2009b). In the sensitive-period debate, word-learning, or lexico-semantic learning, are aspects of language that are argued to be least sensitive to age (Newport et al., 2001). As was outlined with more detail above however, the seemingly unitary process of learning a new word actually involves a rich (and complex) confluence of short-term, procedural and declarative learning mechanisms, that all follow different developmental trajectories. This is often neglected in theories about sensitive periods. Acknowledging all these factors opens a door (long shut) for investigating what adults find particularly hard in language, and why.

4. The present thesis

The overarching aim of this doctoral project is to explore whether child-adult differences exist for certain aspects of word-(form) learning; and whether this can be explained within a model of interacting memory systems. This research goal is achieved in four empirical studies, presented in four chapters.

In **Chapter 2** we were interested in comparing children and adults on word-form learning by use of the Hebb repetition paradigm (the procedural laboratory analogue to word learning). A sample of eight-year old children and adults were presented with auditory sequences of three three-syllable chunks and were asked to immediately recall these sequences after presentation. Exactly the same sequences were presented to both groups and were re-presented across multiple sessions that contained delays up to one year. The participants were made aware of the repeating

occurrence of one syllable-sequence while the other remained unannounced (or implicit) throughout the experiment. We predicted that children would outperform adults in learning the implicit sequence, but that this age-effect would disappear when attention was expressly allocated to the learning material (i.e., in the explicitly instructed sequence). This would provide evidence for the hypothesis that children are better word-form learners than adults, but that this depends on the implicit nature of the learning task. Within the same study, we were additionally interested in exploring at what time point across training, the learning differences between children and adults would appear. When children and adults are tested under the same learning conditions (i.e., they learn the same material), adults often have a benefit over children because they have higher memory capacities. This is not always taken into account when comparing children and adults in a laboratory setting and therefore sometimes leads to the possibly false belief that no age-effects exist. In this multiple-session experiment, we expected that child superiority would emerge only in the longer term. In particular, we predicted that children would show better offline retention abilities than adults. We additionally explored the role of individual differences across several cognitive abilities in relation to the Hebb learning ability, such as post-learning awareness, working memory and vocabulary knowledge.

In **Chapter 3,** we further explored the circumstances in which child benefits are revealed for Hebb repetition learning. Some studies that use the Hebb repetition paradigm in developmental samples observe weak learning in children. These studies typically presented sequences of existing lexical items instead of novel sequences of sublexical items. Within our working hypothesis, the latter sequences more resemble the natural conditions of word-learning. Moreover, Hebb and filler sequences are often anagrams of the same items because they are extracted from a limited pool of syllables (e.g., "lofodu" vs. "folodu"). We call this item-overlap. This causes proactive interference during serial-order learning, and therefore undermines (procedural-based) segmentation processes that are needed for word-learning. The role of these two factors was explored among a group of eleven-year-old children and adults in two Hebb experiments. We also elaborated on a chunking account, investigating the hypothesis that children's smaller working memory capacity forces them to segment syllable sequences in smaller chunks than adults, and that this might lead to superior performance for Hebb repetition learning. This idea was subsequently tested experimentally in a group of adults.

In Chapter 4, we went one step further to the study of Chapter 3, by directly testing the idea that adult's superior working memory abilities interfere with Hebb repetition learning by using Transcranial Magnetic Stimulation (TMS). In this study, a sample of adults was presented with overlapping and non-overlapping Hebb sequences immediately after a temporal disruption of activity within the dorsolateral prefrontal cortex (DLPFC) or a control region. DLPFC is a region that is related to

declarative memory and is known to mature rather late in development. We predicted enhanced Hebb learning for non-overlapping sequences as a function of the disruption. We additionally explored how individual differences in executive functions, and other working memory functions mediate the effect of TMS. Enhanced Hebb repetition learning as a function of a disruption to the DLPFC would provide direct evidence for the hypothesis that different memory systems compete during word-form learning in the adult brain, and that this interactive process undermines word-learning abilities.

In the final empirical **Chapter 5**, we again investigated child-adult differences for implicit word-learning abilities. However, in this chapter, we used a different learning paradigm than the Hebb repetition paradigm. We were particularly interested in the ability of children and adults to rapidly acquire novel phonotactic constraints that characterize word-forms in the native language (e.g., /ng/ can never be an onset in English). In the novel paradigm, speech errors were analyzed as a measure of implicit knowledge. Previous studies with adults on this novel paradigm showed that adults were able to learn novel rules such as */t/ is an onset and /k/ is a coda if the medial vowel is /i/ while the reverse is true if the medial vowel is /eu/* but only after an extensive training period. No work has yet been done using this approach with children. In the present study, nine-year-old children and adults were asked to produce sequences of non-words containing novel phonotactic constraints across a training of four days. We expected that adults' speech errors would reveal learning rather late during the experiment, from the second day onwards (in line with previous studies), while children would be able to pick up the novel constraints (as revealed by their speech errors) much earlier during the course of the experiment.

Finally, in **Chapter 6**, we conclude this thesis by summarizing our main findings together with some methodological caveats and potential avenues for future research. We also discuss whether children are really better language-learners than adults, and why. Within this discussion, we summarize our main theoretical position regarding the central hypothesis of this thesis, which proposes that child superiority in acquiring different skills, such as language, occurs at the level of procedural or serial-order memory. We further argue how our memory approach can be useful for understanding other related phenomena in the field of language such as adult's abilities to learn a second language, and learning strategies in young populations with a developmental language disorder. We end the discussion by framing our theoretical views in an evolutionary perspective.

CHAPTER 2

CHILDREN RETAIN IMPLICITLY LEARNED PHONOLOGICAL SEQUENCES BETTER THAN ADULTS

Whereas adults often rely on declarative memory, children appear to excel in procedural learning, which plays an important role in the acquisition of various skills such as certain aspects of language learning. However, experimental evidence for this dissociation, particularly collected under identical learning conditions for both children and adults, is not always conclusive. The current study aimed to test this assertion within a theoretical framework that explains the link between serial-order memory and word-form acquisition using the Hebb repetition paradigm. We conducted a one-year multiple-session longitudinal study in which we presented auditory sequences of syllables, co-presented with pictures of aliens, for immediate recall to a group of children (8-9 years) and adults. The repetition of one Hebb sequence was explicitly announced while the repetition of another Hebb sequence was unannounced and therefore implicit. Despite their overall inferior recall performance, the children showed a Hebb learning improvement similar to that of the adults. After four hours, the children showed offline learning gains for the implicit Hebb sequence while the adults showed decrements. There was no age-difference for the explicit Hebb sequence, with both groups showing no significant offline changes. One week and, again, one year later, the children showed better long-term consolidation of the implicit Hebb sequence than adults. Performance by adults was also positively correlated with measures of post-learning awareness and verbal short-term memory capacity, while performance by children was positively correlated with vocabulary knowledge. The findings are discussed in light of maturational sensitivities for language learning.

Reference

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Introduction

It is widely accepted that children should be introduced to sport, music and language early in life if they aim to develop a high proficiency in these skills. This is a little counterintuitive as children are poor on most tests of other cognitive abilities, especially those that rely on memory and attention-driven strategies that develop with age (Craik & Bialystok, 2006; Murphy, McKone, & Slee, 2003; Squire, 1992). The question of why children outperform adults on some, but not all measures of learning and cognitive ability is especially relevant within the domain of language learning. Children are generally accepted to be more sensitive to language input than adults (Johnson & Newport, 1989; Lenneberg, 1967), although this is not always true. For instance, children are especially strong in learning the phonological and grammatical patterns of language, whereas vocabulary acquisition and semantic processing abilities persist well into adulthood (Newport et al., 2001). The phenomenon of child-adult learning differences remains poorly understood (Kennedy & Norman, 2005), although various accounts have been put forward as an attempt to explain it. This ranges from pure biological/neural accounts (Werker & Hensch, 2015) to accounts that focus on differences in existing knowledge (Arnon & Ramscar, 2012; Finn & Hudson Kam, 2008) and cognitive abilities such as working memory that mature later in life (Elman, 1993; Newport, 1990; Ramscar & Gitcho, 2007). The challenge of current and future work is to investigate learning mechanisms that have the potential to explain why children outperform adults on some but not all aspects of language (and other skill) learning.

1. Implicit versus explicit learning

Some years ago, Janacsek and colleagues compared nine different age cohorts (from 4 to 85 years old) on an implicit and explicit version of the serial reaction time (SRT) task (Janacsek et al., 2012). The SRT task is a visual-motor sequence-learning task in which participants are asked to press a button that corresponds to a particular location on the screen. Unknown by the participant, a hidden structure is repeated throughout the task, and results show better accuracy and faster times for responses to stimuli consistent with the hidden structure than to inconsistent structures, indicating implicit learning. Interestingly, the authors observed a peak in task performance before the age of twelve, after which performance dropped significantly. In another version of the task where participants were explicitly made aware of the repetition, they found no age-dependent change in learning (Nemeth, Janacsek, & Fiser, 2013). Additional measures of explicit knowledge concerning the repeating sequence (using verbal reports) revealed a different age-effect with significantly better scores on explicit knowledge after the age of twelve. The authors

concluded that cognitively controlled processes such as explicit attention, coming into play around the age of twelve, are useful for targeted explicit learning at the cost of a decreased ability to develop and stabilize new basic competences implicitly. This suggests that children's superiority in various skills has its basis in underlying implicit-learning abilities, a hypothesis that is also gaining attention within the language domain (e.g. Finn et al., 2014; Morgan-Short, Steinhauer, Sanz, & Ullman, 2012). This is presumably attributed to a neurological change at the level of two separate long-term memory systems, namely an early developed basal-ganglia system (the procedural memory system), that is involved in implicit sequence learning, and the late maturing frontal/medial-temporal circuits (the declarative memory system), that is assumed to rely on explicit attention processes (Perez et al., 1998; Robertson, 2012; Squire, 1992). The hypothesis that children are superior in the acquisition of implicit procedural knowledge has, however, not gone unchallenged. For instance, Amso and Davidow (2012), Meulemans and Van der Linden (1998), and Reber (1993) all showed age-invariance for implicit-skill acquisition, whereas Huyck and Wright (2011), Vasudevan, Torres-Oviedo, Morton, Yang and Bastian (2011), Thomas et al. (2004) all showed adult superiority. This illustrates that experimental evidence is not always conclusive and that further work is needed.

2. Superior delayed memory in children

An important challenge for research related to the sensitive-period debate is to show evidence for superior performance in children even when they are exposed to the same learning materials as adults. Hudson Kam and Newport (2005, 2009) demonstrated that children are more likely than adults to regularize grammatical patterns despite inconsistent examples in the input. This is an important and valid indication of superior language-learning capacities in the immature brain. Other work demonstrated that children outperform adults in the subsequent formation of long-term memory representations (i.e., the consolidation phase) and not for the acquisition of material per se (the initial learning phase) (Adi-Japha, Badir, Dorfberger, & Karni, 2014). Ferman and Karni (2010) for example, compared eight- and twelve years old children and adults when learning the same implicit artificial-grammar rule. Although they found overall better within-session gains in adults than in children, their reaction time data revealed greater *between-session gains* in children, up to a delay of two months. This is compatible with a recent observation by Bishop, Barry and Hardiman (2012). Their study investigated whether children with specific language impairment (SLI) and their first-degree relatives (parents and older siblings) were generally impaired at learning novel word-forms compared with typical children and adults, both within and between learning sessions. This was investigated using a non-word repetition task in which unfamiliar sequences of phonemes were retained and repeated (session A), and re-presented after a delay of

one hour (session B). Surprisingly, they found that age, not SLI, had a significant effect on performance changes between sessions. In fact, the scores of the children tended to improve over the delay, while those of the adults declined significantly, independently of their SLI status. Interestingly, no age differences were observed for learning within sessions despite the observation that children initially started at a lower baseline owing to the fact that they were exposed to the same learning material as adults. Importantly, the authors also addressed the question of whether the decline between sessions observed in adults might be due to a ceiling effect at the end of the first session, allowing more room for them to decline across sessions compared with children. To answer this question, they compared typically developing children and adults with SLI who showed comparable scores on the last trial of session A. They found that typically developing children still retained better across the one-hour delay than adults with SLI. This provides promising evidence for superior delayed memory in children and suggests that maturational differences in language learning, in this particular case word-form learning, are to be found in long-term consolidation processes, even when no sleep is provided during this delay (e.g. Ashtamker & Karni, 2013), rather than in acquisition or learning per se (see also, Wilhelm, Prehn-Kristensen, & Born, 2012, for a review on superior consolidation processes in children).

3. The current study

We have summarized above, interesting lines of research that raise the important question of whether child-adult differences in implicit versus explicit learning, and in subsequent consolidation, may advance our understanding of child benefits in specific domains of language learning. Some aspects of language learning and processing are procedural in nature (Arciuli & Torkildsen, 2012; Christiansen, Conway, & Onnis, 2011; Saffran, 2001; Saffran, Aslin, & Newport, 1996). For example, sequences of phonemes that exhibit certain regularities form words, and words in turn are sequentially arranged to form legal grammatical phrases (Pinker, 1994). The aim of the current study was to investigate: 1) child-adult differences in sequential mechanisms that play a role in word-learning under implicit versus explicit encoding instructions; and 2) the possibility that child superiorities are revealed during long-term consolidation processes rather than during acquisition per se. We aimed to investigate these questions using a well-established implicit sequence-learning paradigm, namely the Hebb repetition paradigm (Hebb, 1961). In this task, sequences of items (e.g. phonemes/syllables) have to be retained in short-term memory for immediate serial recall. Unannounced to participants, there is one sequence (often called the Hebb sequence) that is repeated in exactly the same order every 3rd trial. Recall performance for the Hebb sequence usually improves relative to the non-repeating (filler) sequences. This finding is also known as the Hebb Repetition Effect (HRE), and reflects a gradual

transfer of serial-order information held in short-term memory to a longer-lasting representation in long-term memory.

It has been hypothesized that the HRE provides a source of evidence for the role of serial-order mechanisms in language learning, particularly with respect to the long-term acquisition of novel word-*forms* (Page & Norris, 2008, 2009). The acquisition of word-forms is regarded as one central aspect of word-learning, beside the acquisition of meaning (Gaskell & Ellis, 2009; Graf Estes, Evans, Alibali, & Saffran, 2007; Gupta & Tisdale, 2009b; Swingley, 2010), which follows an asymptotic developmental trajectory (see, Gupta & Tisdale, 2009b, p. 3764). The separate (and probably subsequent) process of associating a word-form with meaning is argued to rely on declarative (explicit associative) learning mechanisms that are assumed to develop with age (Gupta & Tisdale, 2009b; Ullman, 2004). During novel word-form acquisition, learners need to segment word units from phonological speech input by tracking transitional probabilities among sounds in the incoming stream (Saffran, 2001; Saffran et al., 1996), or (alternatively) by chunking mechanisms in memory (Thiessen & Erickson, 2013). Regularly occurring sub-sequences gradually consolidate into long-term memory due to repeated exposure of their serially-ordered constituents (i.e., syllables/phonemes) (Page & Norris, 2008, 2009). Hebb repetition learning of, for instance, a sequence of consonant-vowel syllables (e.g., lo-fo-du) is therefore, by hypothesis, functionally equivalent to the long-term memorization (hence, lexicalization) of a corresponding novel word-form (e.g., *lofodu*). In Page and Norris' model, this learning is explained within a connectionist model that involves several layers of localist units representing phonemes or syllables, together with a learning mechanism that progressively consolidates a short and repeatedly presented sequence into one (localist) chunk representation in long-term memory. Experimental work has supported this idea by showing that sub-sequences acquired through HRL are represented in the mental lexicon just like novel words, by showing competition effects with existing words (which is an important indication of lexicalization, see Leach & Samuel, 2007; Szmalec et al., 2009; Szmalec et al., 2012). An increasing amount of experimental work is consistent with the hypothesis that the mechanisms underlying HRL are related to word-learning. For instance, HRL is fast and long-lasting (Page et al., 2013), and is correlated with measures of word-learning and vocabulary knowledge (Majerus & Boukebza, 2013a; Majerus et al., 2006). Studies of HRL have also been extended to developmental participant samples (Mosse & Jarrold, 2008; Smalle et al., 2015), and participant samples with specific language disorders (for which HRL is impaired; Archibald & Joanisse, 2013; Bogaerts et al., 2016; Bogaerts et al., 2015; Hsu & Bishop, 2014; Szmalec et al., 2011). Learning in the Hebb repetition task is furthermore considered to depend on implicit learning mechanisms as it (a) occurs without explicit awareness of the repetition (Couture & Tremblay, 2006; Gagnon et al., 2005; Gagnon et al., 2004; Guerard et al., 2011), (b) is not affected by focal

hippocampal lesions (Gagnon et al., 2004), and (c) does not require explicit reproduction processes such as overt recall (Kalm & Norris, 2016).

Using the Hebb paradigm, we aim to show evidence for superior acquisition of novel phonological sequences, resembling novel word-forms, in children compared with adults. A valid test of child-adult differences requires that both adults and children should be exposed to the same input. Therefore, we conducted a one-year, four-session Hebb learning study in which we presented two nine-item auditory Hebb sequences and one set of filler sequences for immediate serial recall to a group of children (8-9 years old) and a group of adults. Participants were made explicitly aware of one of the two Hebb sequences by use of intentional encoding instructions (Gagnon et al., 2005), while the second Hebb sequence was repeated unannounced. On the first day, two learning sessions were carried out, separated by a four-hour delay. One week and, then again, one year after learning, the sequences were re-presented to measure their long-term consolidation. Initially, we expected to see a smaller HRE in children than in adults due to the fact that the length of the sequences was nine syllables long. This exceeds the verbal short-term memory capacity of children more than that of the adults (Dempster, 1981). Four hours later, however, we expected to see the first signs of child advantages in learning, with better delayed retention scores for the child group than for the adult group. This expectation was based on the previous observation of better delayed memory for nonwords in children than in adults (Bishop et al., 2012). One week and, then again, one year after learning, we expected to see superior retention of the Hebb sequences in children compared with adults. Additionally, in line with previous findings that showed a decline in implicit learning but not in explicit learning after age twelve (Janacsek et al., 2012; Nemeth, Janacsek, & Fiser, 2013), we expected to see child advantages particularly for the implicit (unannounced) Hebb sequence but not, or less so, for the explicit (instructed) Hebb sequence. Correlations with post-learning awareness of the implicit Hebb sequence, vocabulary knowledge and short-term memory capacity were also investigated to explore the potential role of explicit attention processes, lexical knowledge and short-term memory capacity in Hebb repetition learning (HRL) in both age groups.

Methods

1. Participants

Fifty-five participants took part in our longitudinal study, 29 children and 26 adults (Table 1). Children were recruited from two different schools in and around Ghent (Belgium). Adults were recruited by means of online advertising. All participants were Dutch speaking and had no reported history of speech, language, learning or hearing difficulties. All participants gave informed consent and received a financial compensation (€20) for their participation. Parental consent was obtained for the children's participation. The study was approved by the Psychology Ethics Commission at the Université catholique de Louvain.

Table 1. Gender, laterality, age, cognitive test scores and session intervals divided by age group.

	Children (n = 15F/14M)	Adults (n = 17F/9M)	Group difference
Age (yr)	8.7 (.47)	35.5 (11.09)	*p < .001*
Digit Forward Span (max = 9)	5.8 (1.5)	7.3 (1.7)	*p < .001*
Peabody Vocabulary Test – 3rd ed. (PPVT-III), max = 204, *rs*	111[(a)] (12)	185[(b)] (7)	*p < .001*
Session Interval			
A – B (in hours)	4:47 (.03)	4:34 (.03)	*ns*
B – C (in days)	7 (1.1)	7 (1.0)	*ns*
C – D (in months)	11.9 (.30)	12.0 (.47)	*ns*

F = female; M = male; rs = raw score; (a) one missing value replaced by the mean; (b) four missing values replaced by the mean.

2. Materials

Sequences of 9 syllables were presented to the participants for immediate serial recall. All syllables had a consonant-vowel structure (CV). The length of the sequences was matched to an average adult digit-span level, plus two more items to avoid ceiling effects. The same length was used for both the child and adult groups so that potential differences between the groups could not be attributed to differential input. To create the stimulus-sequences, four different sets (A to D), each set consisting of three CV-pools (1, 2, 3) with nine different CVs in each CV-

pool (see Table 2), were generated using WordGen (Duyck, Desmet, & Verbeke, 2004). We confirmed that the summed bigram frequencies (as measured within the speaker's native language; Duyck et al., 2004) for the entire sequences were comparable within and across sets (i.e., all *p*s > .05*).* Each CV-pool within a set could be used either to generate filler sequences, or, directly, as one of the two Hebb sequences. This was counterbalanced across participants in a Latin square order (i.e., sequences 123, 231, 312 were used for Fillers, Hebb 1 and Hebb 2 respectively for participants 1, 2 and 3), so that Hebb learning could not be confounded by unknown particularities in the sequences themselves. Every three subsequent participants were allocated to one of the four sets (A-D) in turn. The allocation of participants to sets was matched across child and adult groups.

Table 2. Stimulus materials for the Hebb learning task

SET	CV-pool	CV1	CV2	CV3	CV4	CV5	CV6	CV7	CV8	CV9
A	**1**	fu	ra	wo	mu	zu	vo	za	ku	wu
	2	wi	zi	vi	bo	ro	gi	ji	pe	hi
	3	su	ke	fo	wa	mo	ru	gu	ki	ga
B	**1**	fo	ro	zu	wi	gu	di	zi	fi	fu
	2	ru	ga	hi	ku	wu	ke	vi	fe	mo
	3	gi	wo	pe	za	da	wa	ra	vo	bo
C	**1**	wo	da	vo	fu	gi	su	hi	ga	bo
	2	fo	ra	pe	ku	wa	ki	wu	za	gu
	3	ru	wi	mo	zu	di	vi	ji	ke	mu
D	**1**	mu	da	vo	di	wu	vi	fu	ve	wa
	2	fo	su	gi	ke	ra	fe	ru	ji	wo
	3	ga	ro	zu	hi	wi	gu	fi	mo	za

To facilitate word-segmentation processes in the HRL task[1], and simultaneously make the task more attractive to children, the sequences were presented together with drawings of aliens derived from the TOTimals stimulus set (Gupta, 2003;

[1]In previous Hebb learning studies, chunking processes were facilitated by using pauses between every three syllables (see, Szmalec et al., 2009).

Schwartz & Smith, 1997). For each sequence of nine syllables, a given drawing was presented alongside each subgroup of three successive syllables within that sequence (Figure 2.1), so that each three-syllable subsequence might, potentially, become associated with the simultaneously presented drawing. From a total of 36 different drawings, nine drawings were associated with each set of three CV-pools. Of these nine drawings: three drawings were associated with the pool used to generate the filler sequences; another three drawings were associated with Hebb 1; and the remaining three drawings were associated with Hebb 2. In each case, the three drawings associated with a given type of sequence (Filler, Hebb 1, Hebb 2) were clearly distinguishable from each other and were always presented alongside the CV-sequence in the same order. The order of the CV-syllables within the Hebb sequences remained fixed throughout learning, so that, for the Hebb sequences, the mapping was constant between a given drawing and a given subsequence of three successive syllables. The order of the syllables within the filler sequences was determined randomly. For this reason, there was no systematic mapping, for the filler sequences, between CV-syllables and drawings.

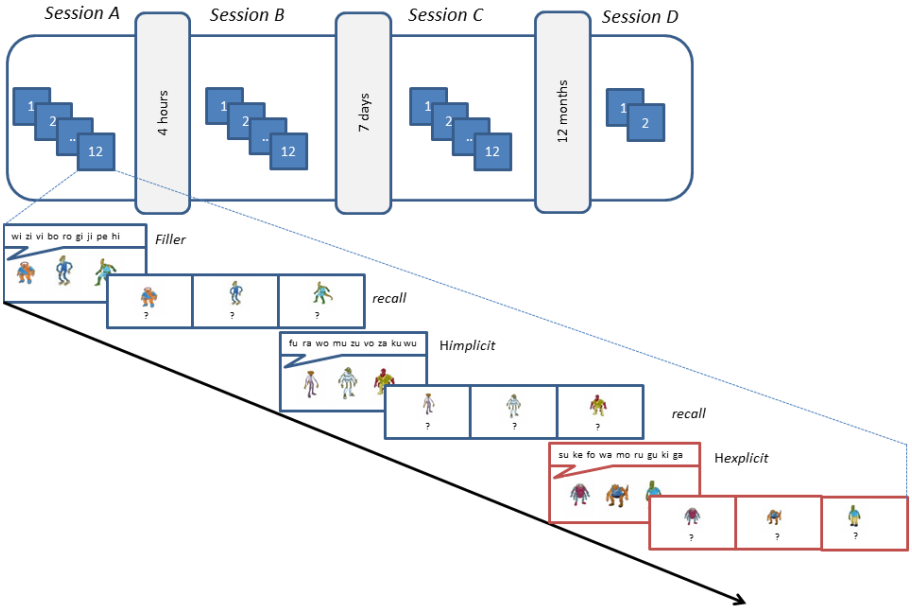

Figure 2.1. Design of the experiment. The Hebb Repetition Learning Task (HRL). For session A, B and C, 36 trials were presented for immediate serial recall (12 filler sequences and two Hebb sequences that were each repeated 12 times). In session D, six trials were presented (two filler sequences and two Hebb repetitions).

3. Procedure

The experiment started with a familiarization phase where participants were exposed to the syllable materials. Each participant listened carefully to the CVs that were also presented visually on the screen. Participants were instructed to repeat the CVs out loud, and they were corrected by the experimenter if the CV was not pronounced well. This familiarization phase was repeated three times to ensure that participants clearly distinguished the different syllables. All CVs were recorded by a female professional diction/pronunciation teacher and presented auditory at 60 dB using Bose QC 15 headphones.

On the first day of testing, two sessions of 36 sequence trials were presented for immediate serial recall: these were sessions A and B. The two sessions were separated by a four-hour break in which participants continued their regular daily activities. The two types of Hebb sequence were mixed within the same session and each was repeated on every third trial, making twelve repetitions for each of the two Hebb sequences. These were interspersed with a total of twelve filler sequences, resulting in 36 sequence trials per session. The syllables within a sequence trial were presented auditorily, one at a time, each having duration of 500ms and a silent inter-stimulus interval of 500ms. The Hebb learning procedure was similar to that in previous studies (e.g., Szmalec et al., 2009; Smalle et al., 2015). Different from previous studies, we accompanied each subsequence of three successive syllables within a given sequence with the visual presentation of an alien. The participants were told that they would see "aliens from the fictional planet *Erinominus*" and simultaneously would hear speech sounds. Each drawing appeared on the screen for 3s, and thus matched the time during which the three corresponding syllables were heard by the participant. The task was simply to repeat the speech sounds in the same order as presented after all nine syllables had been heard.

Before learning started, the participants were also explicitly told that one sequence of nine speech sounds was always repeated in the same order during the task. This is referred to as the explicit Hebb sequence or H*explicit* in the remainder of the paper. Every time H*explicit* was repeated, it was cued with a beeping tone and a red border around the screen. Participants were not made aware of the occurrence of the second repeating sequence, from now on referred to as the implicit Hebb sequence or H*implicit*. Two filler sequences were presented to familiarize participants with the Hebb recall procedure. Learning started with presentation of a filler sequence followed by one of the two types of Hebb sequences (implicit or explicit), the other type of Hebb sequence (explicit or implicit), again a filler sequence, etc. In total, 12 filler sequences and 12 repetitions of the two types of Hebb sequences (i.e., 36 trials in total) were presented. The order of the two types of Hebb sequence was counterbalanced across participants. Immediately after presentation of each sequence, a recall screen was presented with the first alien and

a question mark signaling that the participant had to repeat the first three syllables of the sequence. Subsequently (induced by a manual press on the space bar), the next alien appeared with a question mark signaling the requirement to recall the next three syllables of the sequence, and so on, until all nine CVs of the sequence were recalled. Participants were allowed to say "blank" when they had forgotten a syllable at a particular serial position. The uttered syllables were audiotape recorded and simultaneously written down by the experimenter. For a syllable to be judged correct, the consonant and vowel in the heard syllable had to be present in the response, in the correct order, and without the insertion of additional phonemes. Consonants and vowels that were pronounced ambiguously (e.g. /p/ for /b/, or /e:/ for /i:/) were always scored in favor of the presented phoneme with the condition that the ambiguous sound (i.e., /p/ or /e:/) did not occur elsewhere in the sequence.

One week and, then again, one year after learning (see also Table 1), participants returned to the lab for re-testing in sessions C and D on the HRL task. Participants were told that we were interested in how well they remembered the speech sounds presented one week/year before. The same Hebb procedure was used as above, but without a practice session. Participants were presented with 12 repetitions (for Hebb sequences) or presentations (for fillers) of each sequence type in session C (i.e., 36 trials in total), and 2 more sequence repetitions in session D (i.e. 6 trials in total). Over all four sessions, 114 trials including 38 fillers, 38 explicit and 38 implicit Hebb repetitions were presented.

At the end of each of the first three sessions (i.e., A, B and C), a verbal awareness report concerning explicit knowledge of the repeating sequences was administered. This questionnaire included three increasingly specific questions (based on Gagnon et al., 2005; Janacsek et al., 2012; Turcotte, Gagnon, & Poirier, 2005). In a first question, the experimenter asked whether participants were aware of the repeating Hebb sequence that followed the beep sound, presented within a red border. This was asked to ensure that the participant had understood the explicit instructions (this was the case for all participants). In a second question, the experimenter asked whether they *noticed something else special in the task.* Participants were free to respond. If the participant answered (or gave the impression) that there was another repetition, the experimenter acknowledged the participant as being aware. After this, two sub-questions were presented to all participants (also the unaware participants) **1.** To rate confidence (about what they had noticed) on a scale from 1 *'Not certain at all'* to 10 *'100% certain'* and **2.** To determine when in the task they started noticing something (i.e., *at the beginning, middle or at the end of the task*). Confidence ratings after each session were used as measure of post-learning awareness throughout the remainder of the paper. Participants who did not notice anything special or noticed something irrelevant (question two of the report) were allocated the number zero on the confidence scale (and their answers on the sub-questions were ignored for further analysis) so that no

exclusion was needed. The use of verbal reports after learning, in particular confidence ratings, is a common procedure and a relatively sensitive measure for demarcating explicit memory in humans (Cleeremans, Destrebecqz, & Boyer, 1998; Sandberg, Timmermans, Overgaard, & Cleeremans, 2010).

Finally, we measured verbal short-term memory capacity using the forward digit-span subscale of the Wechsler Intelligence Scales for Children-Revised (WISC-R) (Wechsler, 1974) following session B, and vocabulary knowledge using the Peabody Picture Vocabulary Test (3rd Edition, PPVT-III) (Dunn & Dunn, 1981), which was administered at the end of the experiment. Missing values were replaced by group means (Table 1). Additionally, immediately at the end of learning in session C, all twelve alien pictures that were presented during the Hebb task were randomly presented on the screen. Participants were asked to recall the names of the aliens they had seen during the experiment. The results of this task were of only secondary interest to us here and independent from the central research hypotheses. We briefly elaborate on what was observed during this additional task in the general discussion.

4. Statistical analyses

We scored trial performance using McKelvie's scoring method (McKelvie, 1987). In a first step, the number of items that were in the correct position from left to right, up to the first error was counted. Secondly, the same step was repeated from right to left, up to the first error. After this, the number of items in any correct sequence of two or more items between the first error from the left and the first error from the right was counted. Finally, any other items that occurred in the correct position from left to right were counted. The maximum possible score using this method was nine. All trial scores were transformed into percentage scores. The trial scores at each session are plotted in Figure 2.2 (upper panel). Initial learning gains were determined by comparing the average scores over the first four trials with the average scores over the last four trials of session A (Turcotte et al., 2005)[2]. This comparison is plotted in Figure 2.2 (lower panel). Offline consolidation was determined by fitting within-session data with a power-law function model for both groups (Pan & Rickard, 2015; Rickard, 2007). Delayed retention was then tested by comparing trial performance in the subsequent session (i.e., session B, or C, or D) with the performance level predicted by an extrapolation of the performance in the previous session (i.e., session A, or B, or C, respectively) (see also Adi-Japha et al.,

[2]Averaging across trials has been used for analyzing Hebb learning data in developmental samples (Mosse & Jarrold, 2008; Archibald & Joanisse, 2013; Smalle et al., 2016). It is likewise a procedure used in motor sequence learning (e.g. Adi-Japha et al., 2014; Csabi, Varszegi-Schulz, Janacsek, Malecek, & Nemeth, 2014).

2014 who used a similar approach). Extrapolation using power-law fitting is argued to be a more reliable measure for offline consolidation effects compared with measures solely based on pre-post difference scores (Pan and Rickard, 2015). All significant results are reported together with the η^2_p effect size and Greenhouse Geisser (GG) correction factors where applicable. Planned comparisons were conducted by Fisher's LSD comparisons.

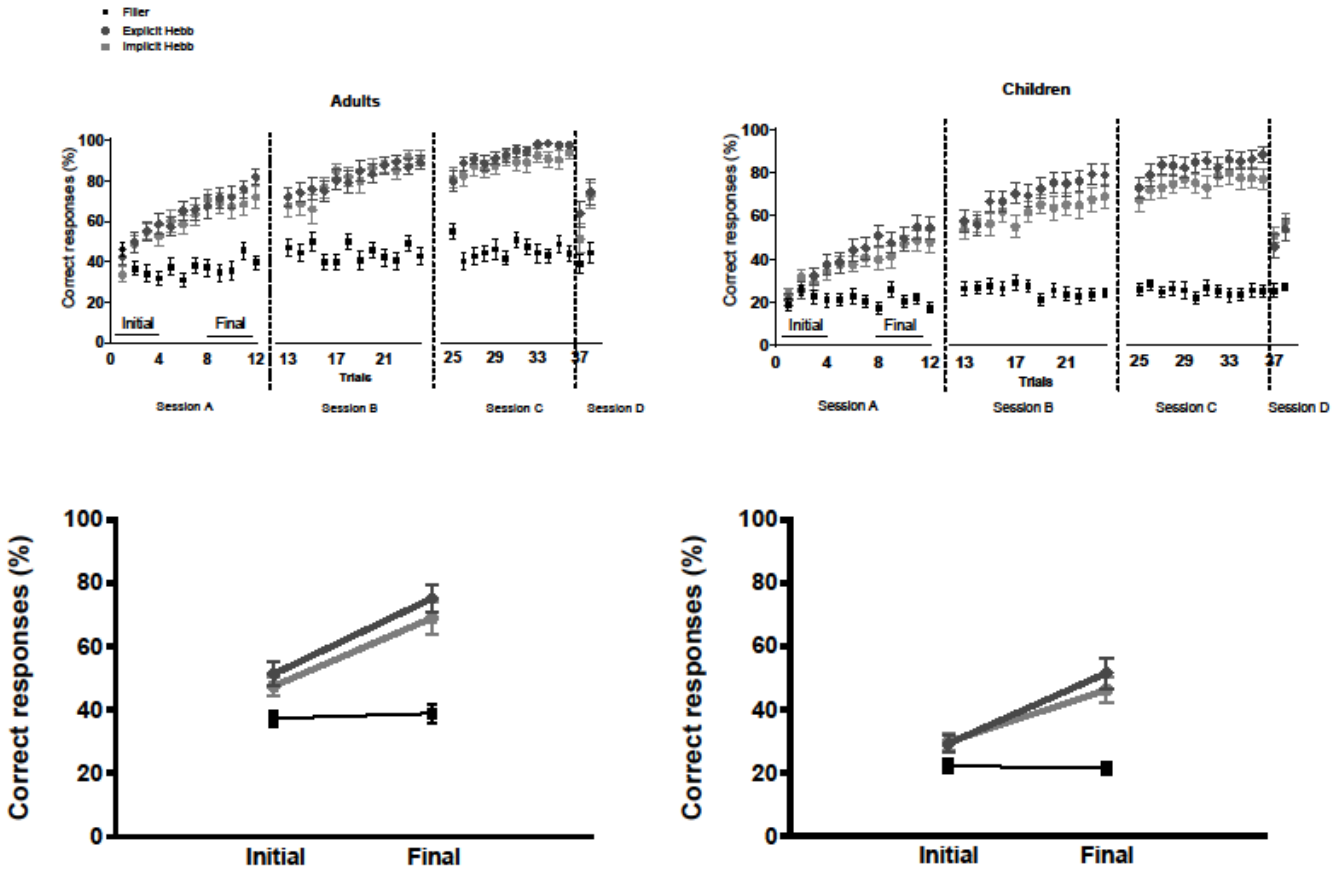

Figure 2.2. Performance (percentage of correct scores) as a function of Sequence Type (Filler, Explicit Hebb, Implicit Hebb) and Age group (Children and Adults). 1. **Upper panel**: performance across all sessions (i.e. repetition 1-12 for session A, repetition 13-24 for session B, repetition 25-36 for session C and repetition 1-2 for session D). 2. **Lower panel**: Performance across two time points (initial vs. final) in session A. Error bars denote SEM.

Results

1. Initial Hebb learning

The average performance levels for the initial and for the final four trials of session A were entered into a mixed-measures analysis of variance with Age group (child vs. adult) as between-subjects factor, and Time point (initial vs. final) and Sequence type (Filler vs. H*implicit* vs. H*explicit*) as repeated measures. While a main effect of Sequence type in favor of the Hebb sequence might provide some evidence of learning that sequence, only the demonstration of improvements in performance for repeated Hebb sequences relative to improvements in the baseline filler sequences may be considered a pure indication of learning. Thus, an interaction between Sequence type and Time point, due to higher scores on the Hebb sequences for the final time point, would provide evidence for Hebb-learning (Smalle et al., 2015). Overall, adults showed higher recall scores than children (main effect of Age group, $F(1,53) = 32.1$, $p < .001$, $\eta^2_p = .38$). There was also a significant main effect of Time point, $F(1,53) = 95.4$, $p < .001$, $\eta^2_p = .64$, such that recall scores for the final time point were higher than recall scores for the initial time point, and a significant main effect of Sequence type, $F(2,106) = 51.5$, $p < .001$, $\eta^2_p = .49$. Comparisons revealed higher recall scores for both types of Hebb sequence compared with the filler sequence (H*explicit*, $F(1,53) = 103.4$, $p < .001$, $\eta^2_p = .66$, and H*implicit*, $F(1,53) = 73.3$, $p < .001$, $\eta^2_p = .58$). There were no significant differences between the two types of Hebb sequence, $F(1,53) = 2.04$, $p > .15$, $\eta^2_p = .037$. Furthermore, there was a significant interaction between Time point and Sequence Type, $F(2,106) = 41.3$, $p < .001$, $\eta^2_p = .44$. Planned comparisons of the two-way interaction revealed a significant improvement across time points for H*explicit*, $F(1,53) = 90.83$, $p < .001$, $\eta^2_p = .63$, and H*implicit*, $F(1,53) = 73.5$, $p < .001$, $\eta^2_p = .58$, but not for the filler sequence, $F < 1$. There were no interactions with Age group, $F < 1$. Overall, these results show that Hebb *learning* within session A was not different for children and adults.

2. Offline consolidation

Based on previous observations in language and skill learning studies (Ashtamker & Karni, 2013; Bishop et al., 2012), we had anticipated that children would retain the sequences better between sessions. To estimate delayed retention differences, a power-law function was fitted to the data of the initially trained Hebb sequences, and we tested for the possibility of additional improvements or decrements beyond what could have been expected from an extrapolation.

2.1 Across four hours

A power law function, $f(r)=ar^b$ where r is the repetition number of the Hebb sequence and a and b are parameters estimated from the data, was fitted to the average recall data of session A for both the implicit and explicit Hebb sequence. This yielded a significant fit for the two age groups for both H*explicit* ($R^2 > .96$; $p < .001$) and H*implicit* ($R^2 > .93$; $p < .001$). The exponential coefficients (*b*s) were significantly different from zero (*t*s > 14.69, $p < .001$ for H*explicit*; and *t*s > 10.19, $p < .001$ for H*implicit*), indicating significant learning on session A for both sequences in both groups. The power-law models for the group-averaged data for the two types of Hebb sequence were extrapolated to 4 additional trial points and the differences between this extrapolation and each individual's performance at the four-hour post learning session (i.e., session B) were assessed (trial by trial) (Figure 2.3). Difference scores were averaged across the four trials and compared between groups. For H*implicit*, this revealed a main effect of Age group, $F(1,53) = 5.7$, $p < .05$, $\eta^2_p = .10$ with children showing overall larger gains across the delay (*M* difference score = 8.7%, SE = 4.1, $t(28) = 2.1$, $p < .05$) compared with adults who showed numerical but non-significant decrements across the delay (*M* difference score = -6.5%, SE = 4.9, $t(25) = -1.3$, $p = .196$). In a post-hoc analysis, to control for otherwise differing levels of recall across groups, we compared children and adults who showed similar recall scores on the last trial of session A. The 75% of children that showed the highest recall scores on trial 12 of session A (n = 21; *M* trial score = 60.3%, SD = 21.3) were compared with the 75% of the adults that showed the lowest recall scores on this trial (n = 19; *M* trial score = 61.4%, SD = 25.5). In terms of the difference scores, the age groups still diverged, with the child group having a mean difference score of 13.7% (SD = 20.5), $t(20) = 3.06$, $p = .006$, and the adult group having a mean difference score of -14.5% (SD = 21.9), $t(18) = -2.36$, $p = .030$. Thus, although both these subgroups were at an equivalent end performance in session A, the child group still increased their performance, while performance of the adult group dropped during the delay. Overall, there was no clear age-effect for H*explicit*, $F(1,53) = 2.5$, $p = .12$, with both groups showing retention although adults showed numerical but non-significant decrements (*M* difference score for

children = 2.1%, SE = 4.5, $t(28) = .472$, $p = .640$; *M* difference score for adults = -8.1%, SE =4.7, t(25) = -1.7, $p = .097$).

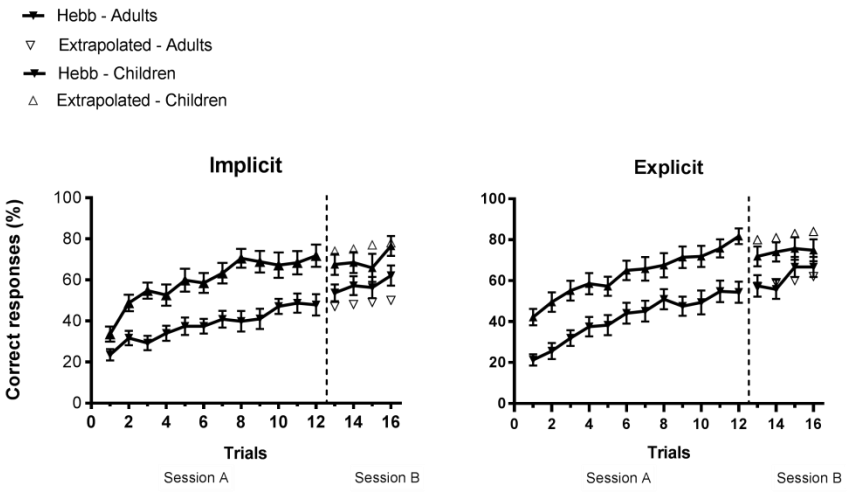

Figure 2.3. Offline consolidation performance after four hours as a function of Sequence Type (Explicit Hebb, Implicit Hebb) and Age group (Children and Adults). Hebb learning during session A is shown together with an extrapolation to four additional data points in session B. 1. **Left panel**: performance for the implicit Hebb sequence. 2. **Right panel**: performance for the explicit type of Hebb sequence. Error bars denote SEM.

2.2 Across one week

A similar power law function was fitted to the averaged recall data of session B for the two types of Hebb sequence. This yielded significant fits for the two age groups for both H*explicit* ($R^2 > .88$, $p < .001$) and H*implicit* ($R^2 > .79$, $p < .001$). The exponential coefficients (*b*s) were significantly different from zero (*t*s > 8.18, $p < .001$, for H*explicit*, and *t*s > 5.91, $p < .001$ for H*implicit*), indicating significant learning on session B for both sequences for both groups. Again, the power-law models for the group-averaged data for the two types of Hebb sequence were extrapolated to four additional trials and the differences between this extrapolation and each individual's performance at the one-week post learning session (i.e., Session C) was assessed trial-by-trial and averaged (Figure 2.4). For H*implicit*, there was a main effect of Age group, $F(1,53) = 4.8$, $p = .033$, $\eta^2_p = .08$, with children showing retention (*M* difference score = 3.9%, SE = 4.3, $t(28) = .89$, $p = .38$) compared with adults who showed a significant decrement across the delay (*M* difference score = -9.9%, SE = 4.5, $t(25) = -2.21$, $p = .037$). Again, when 75% of the

children that showed the highest score on trial 24 of session B (n = 21, M trial score = 83.1%, SD = 17.4) were compared with 75% of the adults that showed the lowest score on the end trial of session B (n = 19, M trial score = 87.7%, SD = 20.3), children retained, and even significantly increased performance across the delay (M difference score = 12.0 %, SD =4.2, $t(20) = 2.85$, $p = .010$) while adult performance decreased (M difference score = -11.01 %, SD =5.3, $t(18) = -2.077$, $p = .052$). There was no age-effect for H*explicit*, $F < 1$, with both groups showing numerical but non-significant decrements across the delay (child group, M difference score = -2.4%, SE = 4.3, $t(28) = -.55$, $p = .59$; adult group, mean = -3.4%, SE = 3.3, $t(25) = -1.01$, $p = .32$).

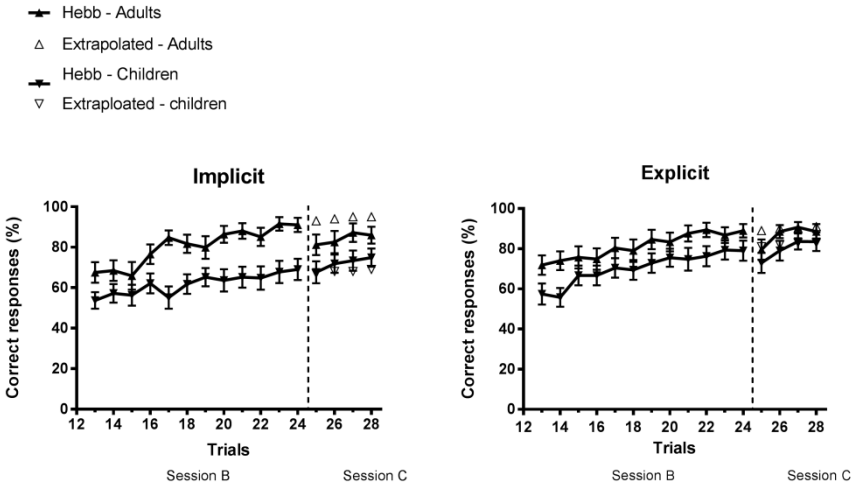

Figure 2.4 **.**Offline consolidation performance across one week as a function of Sequence Type (Explicit Hebb, Implicit Hebb) and Age group (Children and Adults). Hebb learning during session B is shown together with an extrapolation to four additional data points in session C. 1. **Left panel**: performance for the implicit Hebb sequence. 2. **Right panel**: performance for the explicit Hebb sequence. Error bars denote SEM.

2.3 Across one year

After one year, 28 children and 22 adults, i.e., 91% of the original sample, returned to the lab. Only these participants were included for extrapolation. A power law function, $f(r) = ar^b$, was fitted to the average trial scores of session C for the two types of Hebb sequences. This yielded significant fits for the two age groups for both H*explicit* ($R^2 > .84$, $p < .001$) and H*implicit* ($R^2 > .66$, $p < .01$). The exponential

coefficients (*b*s) were significantly different from zero (*t*s > 7.07, p < .001, for H*explicit*, and *t*s > 4.37, p < .001 for H*implicit*), indicating significant learning on session C for both sequences for both groups. The power-law models for the group-averaged data for the two types of Hebb sequences were extrapolated to 2 additional trial points and the differences between this extrapolation and each individual's performance at the one year post learning session (i.e. session D) was assessed (trial by trial) and averaged (Figure 2.5). For H*implicit*, both groups decreased across the delay (children, *M* difference score = -24.4%, SE = 3.6, $t(27) = -6.82$, $p = .001$; adults, *M* difference score = -35.7% , SE = 5.9, $t(21) = -5.97$, $p = .001$), with adults decreasing numerically, but not significantly more than children (main effect of Age group, $F(1,47) = 3.4$, $p = .07$, $\eta^2_p = .067$). When the 75% of the children that showed the highest score on trial 36 of session C ($n = 21$, *M* trial score = 90.0%, SD = 14.4) were compared with the 75% of the adults that showed the lowest score on the end trial of session C ($n = 16$, *M* trial score = 90.3% , SD = 16.6), adult performance dropped more than that of children (Adults, *M* difference score = -46.6 %, SD = 21.3; Children, *M* difference score = -20.0 %, SD = 18.5, $t(34) = 3.91$, $p < .001$). There was no age-effect, $F < 1$, for H*explicit* with both groups decreasing across the delay (children, *M* difference score = -38.7%, SE = 5.1, $t(27) = -7.63$, $p < .001$; adults, *M* difference score = -32.4%, SE = 5.9, $t(21) = -5.4$, $p < .001$). Moreover, there was a significant interaction between type of Hebb sequence and Age group ($F(1,47) = 4.5$, $p < .05$, $\eta^2_p = .088$) with children decreasing less for H*implicit* than for H*explicit*, $F(1,27) = 5.2$, $p < .05$, $\eta^2_p = .16$, compared with adults.

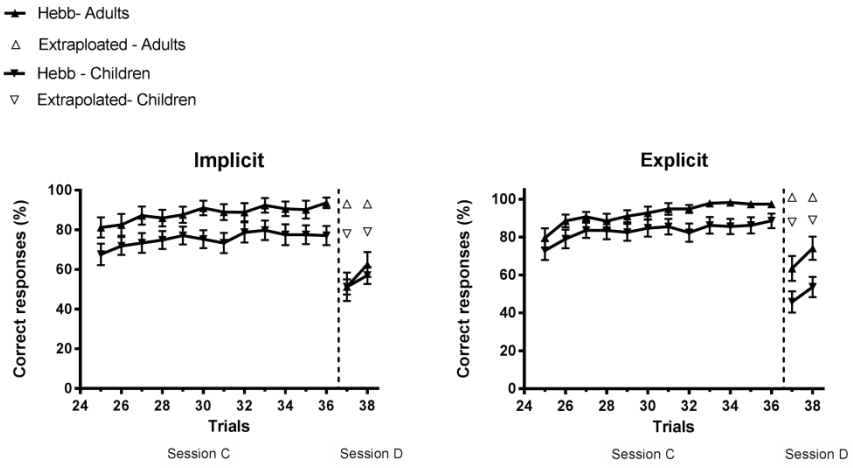

Figure 2.5. Offline consolidation performance across one week as a function of Sequence Type (Explicit Hebb, Implicit Hebb) and Age group (Children and Adults). Hebb learning during session C is shown together with an extrapolation to two additional data points in session D. 1. **Left panel**: performance for the implicit

Hebb sequence. 2. **Right panel**: performance for the explicit Hebb sequence. Error bars denote SEM.

3. Explicit knowledge of the sequences

After session A, only 41.4% of the participants in the child group had noticed that there was another repetition in addition to the explicit sequence, while 73.1% of adults were aware of this. The $\chi 2$-test revealed a significant difference across age groups ($\chi 2_{(1)} = 5.6$, $p < .029$). By the end of session B, only 48.3% of the children had noticed the unannounced repetition while 84.6% of the adults were aware of it ($\chi 2_{(1)} = 8.01$, $p < .005$). Finally, by the end of session C, almost all participants had noticed the unannounced repetition (i.e., 79.3% in the child group and 92.3% in the adult group), and the groups did not longer differ significantly ($\chi 2_{(1)} = 1.86$, $p > .259$). To further characterize age differences in explicit knowledge of the sequence repetition for these aware participants, we compared the time point at which the aware participants reported that they noticed the repetition and how certain they were about the repetition (on a rating scale of 1 to 10). Overall, by the end of session C, all aware children had noticed the repetition later (i.e., middle of the second session) in the task than aware adults (i.e., end of the first session), $t(45) = 2.58$, $p < .013$), and they were also less confident about their report ($M = 8.3$, $SD = 1.8$) than adults ($M = 9.8$, $SD = .53$), $t(45) = - 3.6$, $p < .001$. So, overall adults had gained more explicit knowledge of the sequence and at a faster rate than children.

4. Effect of explicit knowledge

It is possible that the child-adult differences obtained for offline consolidation of the implicit Hebb sequences (see main results) were driven by the fact that adults had gained more explicit knowledge of the repetitive occurrence of the hidden sequence. To further assess the nature of delayed memory among the age groups, a multiple linear regression was calculated to predict offline retention performance of the implicit Hebb sequence based on Age group and Awareness (i.e., level of confidence rating at the end of each session with inclusion of all participants). This allowed us to disentangle a number of relevant factors, such as explicit knowledge of the sequence that might have influenced retention performance differently in children versus adults. A summary of the results is provided in Table 3. Overall, the results indicate superior delayed memory for children across all offline periods, irrespective of the level of explicit awareness. Across one year however, post-learning awareness affected adults' retention scores more than children's: The more explicit awareness gained for the sequence, the better the retention performance across one year.

Table 3. Results of the Multiple regression analysis.

	Across four hours			*Across one week*			*Across one year*		
Variable	*B*	*SE*	*β*	*B*	*SE*	*β*	*B*	*SE*	*β*
(Constant)	.033	.051	--	-.015	.054	--	-.256	.082	--
Age group (child = 0)	-.287	.093	-.591**	-.373	.116	-.781**	-2.24	.855	-4.78**
Awareness	.018	.011	.306	.014	.009	.253	.002	.011	.026
Age group*Awareness	.013	.015	.226	.023	.015	.448	.218	.088	4.54*
Adjusted R^2		.219			.212			.119	

R^2 determination coefficient, *b* regression coefficient, □ standardized regression coefficient, *SE* standard error; *$p < .05$, *$p < .01$.

5. Correlation with cognitive measures

We further aimed to find out whether or not explicit knowledge of the sequences (i.e. confidence rating at the end of each session with inclusion of all participants), vocabulary knowledge and verbal short-term memory capacity are related to HRL in both groups. Therefore, a Pearson correlation analysis was conducted on the magnitude of learning at the end of session A (Table 4). Magnitude of learning was defined as immediate recall on the final time point of the Hebb sequence, whilst controlling for the performance at the final time point for the filler sequence. In addition, we performed correlational analyses between our cognitive measures and the extrapolated difference scores across each delay (see Table 6-8). All correlations show that HRL and subsequent offline retention was correlated positively with post-learning awareness and digit span in adults, and with vocabulary scores in children.

Table 4. Partial correlations between the magnitude of HRL (whilst controlling for filler performance) and post-learning awareness (collected after session A), Peabody vocabulary score, and digit span. *Df* equals 26 for children and 23 for adults.

Implicit type of Hebb sequence				
	Children		***Adults***	
	r	***Sig.***	***r***	***Sig.***
Post-learning awareness	.244	.211	.525	.007**
Peabody vocabulary score	.438	.020*	.056	.729
Digit Span	.089	.651	.294	.154
Explicit type of Hebb sequence				
	Children		***Adults***	
	r	***Sig.***	***r***	***Sig.***
Post-learning awareness	.342	.074	.431	.031*
Peabody vocabulary score	.343	.072	-.085	.687
Digit Span	.126	.524	-.261	.208

Table 5. Pearson correlations between average difference scores across four hours and post-learning awareness (collected after session A), Peabody vocabulary score, and digit span. *Df* equals 29 for children and 26 for adults.

Implicit type of Hebb sequence				
	Children		***Adults***	
	r	***Sig.***	***r***	***Sig.***
Post-learning awareness	.312	.105	.507	.008**
Peabody vocabulary score	.434	.019*	.145	.480
Digit Span	.208	.279	.373	.067°
Explicit type of Hebb sequence				
	Children		***Adults***	
	r	***Sig.***	***r***	***Sig.***
Post-learning awareness	.376	.045*	.421	.031*
Peabody vocabulary score	.267	.161	.203	.320
Digit Span	-085	.661	.390	.054°

Table 6. Pearson correlations between averaged difference scores across one week and post-learning awareness (collected after session B), Peabody vocabulary score, and digit span. *Df* equals 29 for children and 26 for adults.

Implicit type of Hebb sequence				
	Children		***Adults***	
	r	***Sig.***	***r***	***Sig.***
Post-learning awareness	.255	.181	.581	.002**
Peabody vocabulary score	.402	.032*	.028	.891
Digit Span	.092	.634	.266	.277
Explicit type of Hebb sequence				
	Children		***Adults***	
	r	***Sig.***	***r***	***Sig.***
Post-learning awareness	.396	.033*	.357	.073
Peabody vocabulary score	.260	.174	.178	.383
Digit Span	-.014	.944	.443	.027*

Table 7. Pearson correlations between averaged difference scores across one year and post-learning awareness (collected after session C), Peabody vocabulary score, and digit span. *Df* equals 28 for children and 21 for adults.

Implicit type of Hebb sequence				
	Children		***Adults***	
	r	***Sig.***	***r***	***Sig.***
Post-learning awareness	.065	.741	.597	.004**
Peabody vocabulary score	.368	.054°	.102	.659
Digit Span	.332	.084	.442	.051°
Explicit type of Hebb sequence				
	Children		***Adults***	
	r	***Sig.***	***r***	***Sig.***
Post-learning awareness	.159	.420	.414	.06°
Peabody vocabulary score	.341	.076	.231	.314
Digit Span	-.196	.319	.545	.01**

Discussion

Child-adult differences in implicit (vs. explicit) skill learning have been a topic of debate in cognitive science for decades. In this article, we investigated child-adult differences for some aspects of language learning in which sequence learning is hypothesized to play a role (e.g., phonology and grammar acquisition). Starting from the observation of a developmental trajectory for implicit sequence learning using SRT tasks and the observation of superior delayed memory for novel word-forms in children, we conducted a four-session, one-year longitudinal study in which we compared a group of children and adults on Hebb repetition learning, a sequential analogue to word-form learning. The same sequences of nine syllables were presented for immediate recall to a mixed group of 8 to 9 year-old children and adults. There were two (Hebb) sequences that were repeated on every third trial, with one of which participants were made explicitly aware. Long-term retention of the two Hebb sequences was tested over offline periods of 4 hours, one week and one year. Three important findings were obtained: (1) Despite overall lower performance in immediate serial recall for children, the increase in performance for the repeated sequences relative to the filler sequences (i.e., the Hebb effect) was equivalent for both groups; (2) Children showed better delayed retention of the

implicit Hebb sequence across all offline periods; (3) Adults gained more explicit awareness of the repeating sequence.

First of all, we found that, despite their lower memory capacity (number of items reproduced correctly in order), children were not disadvantaged in learning, but improved their performance as much across repetitions as did adults. The finding that children learn the Hebb sequences at the same rate despite their lower performance on filler sequences is an important finding. It shows that children compensate lower memory storage capacity by other, probably more implicit -or serial-order driven mechanisms, which become evident in the Hebb learning task. This is reconcilable with the less-is-more hypothesis that offers an explanation for the sensitive-period effects in language learning (Newport, 1990). The hypothesis postulates that children's language acquisition may be aided rather than hindered by their limited memory capacities. The reasoning behind this hypothesis is that more limited memory resources, such as reduced working memory capacity (Elman, 1993; Thompson-Schill et al., 2009), or less prior experience/knowledge (Arnon & Ramscar, 2012; Finn & Hudson Kam, 2008; Siegelman & Arnon, 2015) make children attend to different components of a language structure from those attended by adults, that are more amenable for recombination and memorization. For instance, when learning novel grammatical genders, children are found to attend more to sequential patterns in the input (e.g. 'article+noun' as a whole) than adults because, as argued, they have less prior experience with the individual components (i.e., article vs. noun) (Arnon & Ramscar, 2012). Similarly, in Hebb learning, children are found to chunk Hebb sequences into smaller subsequences than adults, which is argued to be a side-effect of smaller working memory capacities (Smalle et al., 2015). In both studies, implicit learning increased when adults were encouraged to attend to the same components of the sequence as children.

Second, and in line with the less-is-more hypothesis, we found evidence for better retention by children in the subsequent consolidation phase across a delay of up to 12 months. This was shown by a method of power-fitting and extrapolation similar to developmental work by Adi-Japha et al. (2014). Even when, on an exploratory basis, we extrapolate to more than 4 trial scores (Figure 2.6), our data show a fairly consistent pattern with children showing a gradual and non-intermittent evolution in performance while adults show a pattern of forgetting and slow recovery after some delay. The pattern of superior delayed memory in children emerged more strongly for the implicit Hebb sequence. Interestingly, this pattern was not diluted, and even got stronger, when we compared better performing children with worse performing adults by matching groups on end trial scores, thus comparing across participants with more similar memory capacities. This supports our hypothesis that an underlying maturational difference in implicit learning is likely explaining the observed child superiority for delayed memory of phonological sequences in the current study.

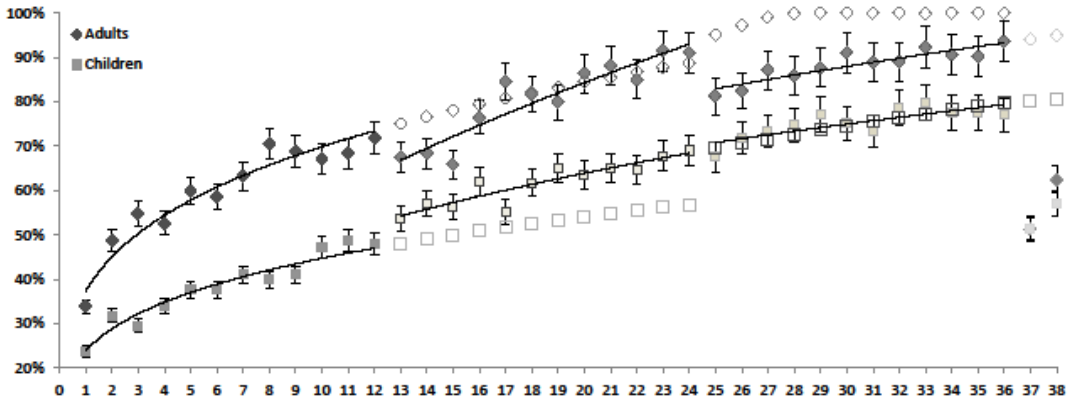

Figure 2.6. A visual depiction of learning performance for the implicit Hebb sequence in both children and adults, at each session, together with its power fit function and an exploratory extrapolation to its subsequent session. Error bars denote SEM.

Third, we found that awareness (and digit span) was positively correlated with performance in adults but not in children. The correlation with both post-learning awareness and digit span might suggest that adults use cognitive resources such as attention and working memory when learning novel information, while such mechanisms are less readily available for children. This then raises the question: On which mechanisms do children rely? Hebb-learning performance in children showed a consistently significant correlation with vocabulary scores. This observation is not new and has also been reported in statistical-learning literature (see for instance, Evans, Saffran, & Robe-Torres, 2009), consistent with the claim that a common implicit-learning mechanism is used for word-acquisition in everyday life. In previous memory-related work, correlations have been found between non-word repetition, immediate serial recall, and vocabulary knowledge (Gathercole, 2006; Gupta & Tisdale, 2009b; Majerus et al., 2006). In these studies, it was argued that a serial-order mechanism in short-term memory supported vocabulary development by facilitating learning of the phonological forms of new words during the initial learning stage (Majerus & Boukebza, 2013b). Additionally, a learner with a high vocabulary size (as measured with the Peabody test) was proposed to be expected to have greater phonological knowledge than a learner with a small vocabulary; this, in turn, was thought to facilitate novel word-form learning. Evidence for positive feedback loops comes from computational work (Gupta & Tisdale, 2009a). Hence, we argue that the correlation between HRL and vocabulary knowledge indicates that children's implicit serial-order learning abilities support the acquisition of novel word-forms that characterizes a fundamental aspect of their general vocabulary development. Adults' word-learning skills presumably rely on other explicit learning mechanisms.

Consistent with this, adults had overall gained more explicit knowledge of the sequences than children. This was revealed from the post-learning awareness questionnaire for which adults gained awareness at a faster rate and with more confidence than children. In the supporting information, we provide some post-hoc analyses demonstrating that explicit knowledge of the sequence cannot explain why adults forget more across the delay. Children improved their performance for the implicit sequence, and adults dropped in performance, after controlling for differences in awareness. This corroborates our hypothesis that a maturational difference for implicit memory underlies the child advantage that we observed in the current study. This is in contrast to the instructional hypothesis that has been put forward as an alternative explanation for maturational differences in language learning (Lichtman, 2016). According to this hypothesis, children are superior implicit learners of language structures than adults, not because of cognitive maturation, but rather because adults receive more explicit instruction than children in the natural environment. For that reason, it is supposed that adults would be more likely to gather explicit knowledge of input that has been trained implicitly, and this may influence their learning strategies. The present findings suggest that there is a

maturational benefit in delayed procedural memory performance that cannot be entirely explained by differences in explicit knowledge in both groups. Note that for learning, explicit instruction had no significant effect on performance across age. This indicates that instruction has no effect at an early stage of learning, but only at a later stage, namely during offline consolidation. The small effect size indicates that the effect is absent and not due to a lack of power, but the null finding nevertheless needs to be taken with caution.

Finn and colleagues demonstrated that adult's superior cognitive abilities may also facilitate some aspects of language learning (Finn et al., 2014). In their study, cognitive effort or attention interfered with learning phonological categories of novel word-forms whereas segmentation of the word-forms (by statistical cues) benefitted from attention. This is in line with the positive correlation between post-learning awareness and HRL that was found for the adult group (previous paragraph). Adults presumably rely on other more mature declarative memory mechanisms (like attentional control or working memory) that might help other properties inherent to word-learning such as segmentation processes. We are aware that the sequence-picture (aliens) pairings during HRL might have induced explicit associative processes (also inherent to word-learning) that likewise benefit from attention and other related declarative abilities in adults (Graf Estes et al., 2007; Gupta & Tisdale, 2009b). An additional recall task for the aliens at the end of learning in session C showed no reliable child-adult differences in retrieving the correct form that was associated with the alien, once differences in recall accuracy at the last Hebb learning trial had been controlled. However, we remain careful in drawing strong conclusions from this. Future studies will further delineate the likely differential age-sensitivity for different components of language learning.

Conclusion

We have provided empirical evidence, collected within a controlled setting, for the hypothesis that children have the potential to outperform adults in the long-term memory consolidation of implicit phonological sequences. Our findings highlight a complex interaction between phonological sequence learning and other cognitive abilities such as attention, working memory and vocabulary knowledge, offering some new perspectives on why children may be better at certain aspects of language learning than adults. Our tentative hypothesis is that a (perhaps) domain-general procedural learning mechanism, namely, implicit serial-order learning, may account for the observed child superiorities in the learning of various skills in everyday life (e.g., music, sport, and formal aspects of language). Finally, and perhaps most importantly, this study proposes a theoretical (Hebb-learning)

framework that can be further developed to improve our understanding of word-learning abilities, and perhaps other language abilities across life.

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Supporting information

1. Post-hoc analyses for offline consolidation.

It is possible that the child-adult differences obtained for offline consolidation of the implicit Hebb sequence (see main results) were driven by the fact that adults had gained more explicit knowledge of the repetitive occurrence of the hidden sequence. To investigate this, post-hoc analyses were conducted in which we compared difference scores between children and adults that showed an equivalent level of explicit knowledge of the hidden sequence (measured by their rate of confidence at the end of learning on the previous session). A detailed description of the analyses/results can be found in the supporting information. Overall, this showed child-adult differences for offline retention performance that may not solely explained by differences in awareness of the implicit sequence (perhaps making it explicit).

1.1 Across four hours

75% of the children that reported the highest awareness (collected after session A, n = 21, *M* confidence rating = 4.2, SD = 4.0) were compared with 75% of the adults that reported the lowest awareness (n = 21, *M* confidence rating = 4.6, SD = 3.9). In terms of difference scores, the two groups still diverged, $t(38) = -2.48$, $p = .018$, with children showing a significant gain of 10.3% (SD = 22.5), $t(20) = 2.1$, $p = .05$, and adults showing a non-significant decrement of -8.8% (SD = 26.1), $t(18) = -1.47$, $p = .16$.

1.2 Across one week

The 75% most aware children (collected after session B, n = 21, *M* certainty = 5.5, SD = 4.3) and the 75% least aware adults (n = 19, *M* certainty = 7.1, SD = 4.0, $t(38) = -1.21$, $p = .24$), again differed on the difference scores, $t(38) = 2.91$, $p = .006$, with children showing retention of performance (M = 6.3%, SD = 21.4, $t(20) = 2.1$, $p = .19$) and adults showing a significant decrement of -14.7% (SD = 24.8), $t(18) = -2.6$, $p = .02$.

1.3 Across one year

When the sixteen[3] most aware children (reported after session C, *M* certainty = 9.4, SD = .72) were compared with the sixteen least aware adults ($n = 16$, *M* certainty = 9.7, SD = .60, $t(30) = -1.33$, $p = .19$), adults still decreased more than children (Adults, *M* difference score = -46.6 %, SD = 21.4; Children, *M* difference score = -24.3 %, SD = 19.5, $t(30) = 3.08$, $p = .004$).

[3] If we selected the 75% most aware children (*M* certainty = 8.7, SD = 1.6), we were not able to match awareness reports of the children with those of the adults. Therefore we selected the 16 participants who were at the extreme in both groups.

CHAPTER 3

CAN CHUNK SIZE DIFFERENCES EXPLAIN DEVELOPMENTAL CHANGES IN LEXICAL LEARNING?

In three experiments, we investigated Hebb repetition learning (HRL) differences between children and adults, as a function of the type of item (lexical vs. sub-lexical) and the level of item-overlap between sequences. In a first experiment, it was shown that when non-repeating and repeating (Hebb) sequences of words were all permutations of the same words, HRL was slower than when sequences shared no words. This item-overlap effect was observed in both children and adults. In a second experiment, we used syllable sequences and we observed reduced HRL due to item-overlap only in children. The findings are explained within a chunking account of the HRL effect on the basis of which we hypothesize that children compared with adults, chunk syllable sequences in smaller units. By hypothesis, small chunks are more prone to interference from anagram representations included in the filler sequences, potentially explaining the item-overlap effect in children. This hypothesis was tested in a third experiment with adults where we experimentally manipulated the chunk size by embedding pauses in the syllable sequences. Interestingly, we showed that imposing a small chunk size causes adults to show the same behavioral effects as those observed in children. Departing from the analogy between verbal HRL and lexical development, the results are discussed in light of the less-is-more hypothesis of age-related differences in language acquisition.

Reference

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Introduction

In this paper, we will investigate whether the Hebb learning effect in immediate serial recall (Hebb, 1961) can shed light on whether children learn verbal sequences differently from adults. It is assumed that children learn complex structures by chunking them into small units, and that this could provide them with a cognitive advantage when learning novel word-forms (c.f., the less-is-more hypothesis; Elman, 1993; Newport, 1990). Hebb repetition learning is a well-known sequential-learning paradigm that is assumed to rely on the same cognitive resources as word-form learning (Page & Norris, 2008, 2009). In line with the less-is-more hypothesis, therefore, we hypothesize that children chunk Hebb sequences in smaller units than do adults, resulting in stronger Hebb-learning effects. Previous Hebb learning studies found weak Hebb effects in children (Archibald & Joanisse, 2013; Bogaerts, Szmalec, De Maeyer, Page, & Duyck, under review; Hsu & Bishop, 2014; Mosse & Jarrold, 2008). It should be noted, however, that previous studies (a) employed exclusively sequences of lexical items (i.e., word or digit sequences) and (b) tested Hebb repetition learning under circumstances in which all sequences, whether repeated or not, were permutations of the same small set of items (i.e., conditions of "item-overlap"). This does not resemble naturalistic word-form learning. In two experiments, we will address both of these issues by directly comparing children and adults on a Hebb-learning task with overlapping and non-overlapping sequences, first using lexical items (i.e., sequences of words, Experiment 1) and then using sub-lexical items (i.e., sequences of syllables, Experiment 2). In a third experiment, we will investigate whether we can induce "child-like" behavior in adults by encouraging them to chunk syllable sequences in small units. Before describing these experiments, we will sketch out the theoretical background in more detail.

1. Starting small in language development

It is widely accepted that sensitivity to language input varies as a function of age, including the consensus that language acquisition should preferably take place before adolescence to achieve native-like performance (Birdsong, 2006; Johnson & Newport, 1989; Lenneberg, 1967; Penfield & Roberts, 1959; Pinker, 1994; Singleton, 2007). However, the exact nature, cause and magnitude of this *sensitive period* phenomenon in language learning remains an issue of wide controversy (Birdsong, 2006; DeKeyser, 2013; Hyltenstam & Abrahamsson, 2003), to the extent that the journal *Science*, in its 125th anniversary edition, labeled the sensitive-period hypothesis as one of the most fundamental yet unresolved questions in human science (Kennedy & Norman, 2005). According to one language acquisition theory, maturational constraints on language learning are explained by constraints on cognitive resources in childhood. Newport's (1990) *less-is-more* theory of language

development posits that children are more successful at language acquisition than adults because their limited working memory capacity forces them to process a truncated portion of the input, allowing them better to analyze their language into its smallest component structures rather than memorizing larger, misleading chunks of input (Elman, 1993; Erickson & Thiessen, 2015; Newport, 1990). Elman (1993) tested this idea by training a simple recurrent network (SRN) to learn complex language structures. Under normal conditions, the network was unable to learn the sequential regularities of an artificial language. But when Elman simulated children's working memory limitations and the network was exposed to a staged input (item-by-item) instead of the entire structure at once, the neural network's performance improved. The empirical evidence gathered from human participants is, however, still far from conclusive (Conway, Ellefson, & Christiansen, 2003; Lai & Poletiek, 2011).

2. Sequential learning in novel-word acquisition

Sequential learning, defined as the ability to encode and represent the order of discrete elements occurring in a sequence, is an important aspect of human cognition and skill learning (Conway & Christiansen, 2001). Sequential inputs are typically *chunked* into units or subsequences of items (Lashley, 1951), recombined and, hence, memorized to acquire a full representation of the sequential structure (Brooks & Vokey, 1991; Lafond, Tremblay, & Parmentier, 2010; Perruchet & Pacton, 2006; Saffran, 2001; Saffran et al., 1996). It is generally accepted that several aspects of language learning and processing are sequential in nature (Conway & Christiansen, 2001; Hsu & Bishop, 2014; Lafond et al., 2010; Saffran, 2001; Saffran et al., 1996). For example, sequences of phonemes form words and words in turn are sequentially aligned to form legal grammatical phrases (Pinker, 1994). An important source of evidence for sequential learning in language acquisition is Saffran's statistical learning approach in young infants (Saffran, 2001; Saffran et al., 1996). In her studies, infants were exposed to a continuous speech stream, which consisted of three three-syllable "pseudowords" that were repeated in random order (e.g., *pabiku*, *golatu* and *daripo* in *pabikugolatudaropigolatupabikudaropi)*. In a subsequent test, infants turned their heads more often and looked longer to the "pseudowords" (e.g., golatu) compared with part-words (i.e., sequences spanning a word-boundary, e.g., bikugo). This demonstrates that infants can segment a continuous speech input stream on the basis of the probability of co-occurrence between the syllables (i.e., the transitional probabilities). It has been argued that this sensitivity to transitional probabilities is a reflection of underlying chunking mechanisms according to which adjacent syllables are grouped into chunk representations that receive activation every time they are encountered. Within this view, representations of groupings across word boundaries will show less (re)activation because they are re-encountered less frequently during exposure; hence they will suffer in competition

with representations of groupings within word boundaries (see PARSER, Perruchet & Vinter, 1998; and, Extraction and Integration Framework, Erickson & Thiessen, 2015). This means that whereas learners may appear to be sensitive to transitional probabilities, they are actually storing chunks of the input stream, which – owing to interference in memory - are biased towards those statistically coherent chunks that are frequently encountered during exposure (Erickson & Thiessen, 2015). This chunking hypothesis offers a different perspective on the way we learn sequences, compared with an explanation based solely on transition probabilities (Jones, 2012).

Further experimental evidence for the role of sequential learning in language acquisition comes from research within the Hebb repetition-learning paradigm (Hebb, 1961; Lafond et al., 2010; Mosse & Jarrold, 2008). When, unannounced to participants, one particular sequence of items (i.e., letters, phonemes) is repeated in the same order during an immediate serial recall task, performance for the repeating sequence (often called a Hebb sequence) improves relative to non-repeating (filler) sequences (Hebb, 1961). This finding is known as the Hebb repetition effect (HRE), and reflects the gradual transfer of newly acquired serial-order information from short-term to long-term memory. Learning in the Hebb repetition task can be considered to be implicit, as it occurs even without explicit awareness of the repetition (Couture & Tremblay, 2006; Gagnon et al., 2005; Gagnon et al., 2004; Guerard et al., 2011). It has been hypothesized that the HRE relies on the same underlying mechanisms as word-form learning. In the model of Page and Norris (2008, 2009), a new word-form is conceived as a familiarized sequence of sub-lexical components (e.g., *lo-fo-du).* Repetitive learning of a syllable sequence in a Hebb repetition experiment is, according to this hypothesis, functionally equivalent to acquiring a corresponding novel word-form (e.g., "lofodu"). Previous work on the Hebb paradigm corroborated this hypothesis by the use of subsequent lexicalization tasks (Szmalec et al., 2009; Szmalec et al., 2012). Participants recalled sequences of nine CV syllables, grouped by pauses into three sets of three syllables, for immediate serial recall. One repeating (Hebb) sequence contained nonsense syllable groups that were neighbors of existing base-words (e.g., la-va-bu, sa-fa-ro, no-ma-du, that are close to the existing Dutch words lavabo, safari and nomade). After learning and following an offline consolidation period of several hours, lexical decision and pause detection tasks showed higher reaction times for existing words that, by hypothesis, had acquired new competitors in the lexicon as a result of Hebb learning, slowing down their lexical decision and pause detection. This indicates that novel entries corresponding to repeated syllable sequences are created in the mental lexicon through the process of repetitive serial-order (Hebb) learning. An increasing amount of experimental work is consistent with this hypothesis (Gaskell & Ellis, 2009; Hurlstone, Hitch, & Baddeley, 2014; Majerus & Boukebza, 2013a; Mosse & Jarrold, 2008; Page et al., 2013), and has extended these findings towards developmental samples (Mosse & Jarrold, 2008) and samples with developmental

language disorders (Archibald & Joanisse, 2013; Bogaerts et al., 2015; Hsu & Bishop, 2014; Szmalec et al., 2011).

3. Item-overlap effects in the Hebb repetition paradigm

As briefly mentioned above, Page and Norris (2008, 2009) described a unifying model that accounts for the Hebb repetition effect and the generic long-term learning of sequences, such as phonological word-forms. According to their model, the learning of a particular sequence (e.g. *lo-fo-du-be-ka-li-da-mu-vo*) comprises the allocation of one or more new chunk representations that are activated by subsequent presentations of the learned sequence, hence enhancing recall performance as Hebb learning proceeds. The occurrence of a Hebb effect is a result of two important assumptions. First, that any novel sequence that occurs during the Hebb task will activate a number of previously uncommitted chunk representations. One of these will become *engaged* in response to that sequence, and a *commitment* starts in learning that sequence. Second, as a result of this first-trial learning, the engaged chunk representation will be more strongly activated on several subsequent presentations (i.e., repetitions) of the same sequence. As learning proceeds, the chunk representation becomes more order-sensitive and a competitive process starts during which chunk representations start *competing* with each other to represent a given stimulus sequence.

The Page and Norris (2008, 2009) model offers an explanation for several findings with the Hebb repetition paradigm, and explicitly addresses the hypothesis that HRE is underpinned by the same mechanisms as word-form learning. For example, the model can explain (a) why Hebb repetition learning still occurs when repetitions are spaced further apart (e.g., every sixth trial, or even every twelfth trial, instead of every third trial), (b) why learning of multiple Hebb sequences is possible when they are presented in interleaved fashion (e.g. one Hebb sequence is presented on trials 2, 6, 10 etc. and another Hebb sequence is presented on trials 4, 8, 12 etc. with filler sequences as non-repeating, intervening trials), and (c) how sequences can still be represented in memory three to four months after initial learning. All this is encouraging evidence for the hypothesis that the Hebb effect is a laboratory analogue of the word-form learning process; given that novel word-form representations are unlikely to be closely spaced in daily life or to occur in the absence of other competing word-forms. Interestingly, Mosse and Jarrold (2008) further also found that the magnitude of Hebb learning using both verbal (i.e., sequences of digit words) and visuospatial stimuli, correlated significantly with non-word (sublexical) learning in a paired-associate learning task, when testing young children. This provides further evidence for the hypothesis that Hebb learning, and more precisely the core ability to represent and learn serial-order information across

modalities, taps into similar mechanisms as does word-form learning (Szmalec et al., 2009; Szmalec et al., 2012).

Page and colleagues (Page et al, 2013) further developed their model of the Hebb effect by manipulating the overlap between item-sets used in repeating and non-repeating sequences in the Hebb task. Overall, they observed reduced Hebb learning in adults when all sequences were permutations of the same items. Remember that, according to their model, Hebb learning requires that every distinct sequence in the task (including every filler sequence) engages a previously uncommitted chunk-node on its first presentation. In other words, every sequence will be partly learned on its first presentation – this is a logical requirement, given that it is not known in advance which sequences will subsequently repeat and which will not. When all sequences (repeating and fillers) are derived from the same item-set, therefore, by the time that the first repetition of a Hebb sequence occurs, there will be several engaged chunk representations, of which one is engaged to the Hebb sequence and all the others are engaged to perfect anagrams of this Hebb sequence (since the filler sequences are permutations of the same items – this explanation assumes, for simplicity, that each sequence is learned as a single chunk, an assumption that is relaxed below). As a result, early in learning, when representations are not yet very order-selective, the chunk representations of all filler sequences will substantially co-activate in response to presentation of the repeating (Hebb) sequence. This mass co-activation of chunk units representing filler sequences makes it harder to identify the chunk unit that is committed to the repeating Hebb sequence. As a result, by hypothesis, learning of that repeating sequence is slower.

4. Hebb learning in children

Although Hebb representations are learned relatively fast and in a manner that is stable across time, Hebb repetition effects observed in children appear to be relatively weak (Bogaerts et al., under review; Hsu & Bishop, 2014; Mosse & Jarrold, 2008). This is surprising because, when considering the ease with which children acquire novel word-forms from linguistic input in their environment, one might anticipate that children would be good or even better at Hebb learning than adults. However, the few studies that have investigated Hebb learning in children have used sequences of digits or words instead of sequences of the phonemes or syllables that constitute the true sublexical basis of novel word-forms. Furthermore, in previous Hebb learning studies, Hebb and filler sequences showed full item-overlap, which is not the case for real-world word-form acquisition (see also Page et al., 2013); this might have contributed to children's weak Hebb effects, consistent with the way in which it contributed to a weakening in adults' Hebb repetition learning (see Page et al., 2013).

5. The current study

Using the Hebb repetition paradigm, the present work aims to clarify the cognitive origins of novel word-form learning in adults and children, within a model that explicitly links word-form learning to the establishment of chunk representations in memory (Jones, 2012; Miller, 1956; Servan-Schreiber, 1990). In the first two experiments, we address the issues of (sub)lexical stimulus material and item-overlap, which may account for children's weak Hebb learning effects in previous studies. Experiment 1 was designed to estimate the effect of item-overlap between the filler and Hebb sequences in adults and children, using sequences of lexical stimuli. We expected to see an item-overlap effect in adults (similar to Page et al., 2013) and also in children. In Experiment 2, the same manipulations were adopted in a Hebb-learning experiment using sequences of sublexical materials (i.e., syllables). We assume that Hebb-sequence learning of sublexical items is more comparable to naturalistic word-form learning and therefore sublexical materials offer us a more valid means of comparing verbal sequence (or word-form) learning in adults and children. We anticipated that children would show stronger Hebb learning effects compared with adults, but only when there is no item-overlap. In order to estimate more directly whether the age-related differences in Hebb learning in Experiment 2 reflect chunking differences, we conducted Experiment 3. In this final experiment, we inserted pauses in the verbal sequences in order to investigate whether we can induce "child-like" behavior in adults by encouraging them to chunk the Hebb sequences into smaller units, as an approximate simulation of children's chunking preferences (Elman, 1993; Jones, 2012; Newport, 1990).

Experiment 1

In this experiment, we aimed to replicate Page et al.'s (2013) findings of reduced Hebb repetition learning in adults as a result of item-overlap between sequences, and to extend these findings to children. The same type of material was used as in Page et al., that is, sequences of one-syllable words. Unlike Page et al., and to make the Hebb task child-friendly, we presented word sequences auditorily and participants were required to recall the sequence orally. Moreover, overlap of items was manipulated within one Hebb learning block, instead of between separate blocks as in Page et al. To this end, two Hebb sequences were presented in an interleaved fashion, with one Hebb sequence being a permutation of the same items as the non-repeating filler sequences and the second Hebb sequence being constructed from different items. This within-block design is illustrated in Figure 3.1. Including both Hebb sequences in the same block allows a direct comparison

between overlapping and non-overlapping Hebb sequences, ensuring that the overlap effect is not confounded with baseline differences in filler performance (which in a mixed design is the same for both conditions of overlap). Children and adults were directly compared. Overall we predicted that learning (i.e., improvement in recall performance across trials) for the overlapping Hebb sequence would be weaker compared with learning for the non-overlapping Hebb sequence, independently of the age group.

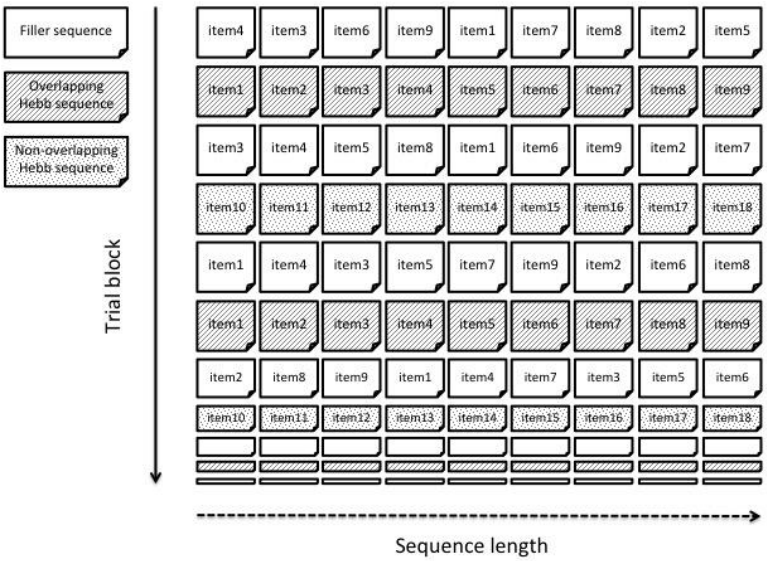

Figure 3.1. An example of a within-block overlap manipulation. Two different Hebb sequences are presented within one learning block. The overlapping Hebb sequence contains the same items as the intervening filler sequences. The non-overlapping Hebb sequence contains different items. Only the first 10 trials are shown.

1. Participants

In total, 40 twelve-year old children and 39 adults took part in the study. All children were recruited from four different schools in and around Brussels, the capital city of Belgium. Adults were recruited by means of advertising. We excluded participants who were diagnosed with dyslexia or dyscalculia (n = 4 in the children group) based on earlier evidence that Hebb repetition learning is impaired in dyslexia (Bogaerts et al., 2015; Szmalec et al., 2011). As a result, 36 children (mean age 11.7 ± .6 SD; 8F/28M) and 39 adults (mean age 31.4 years ± 12.4 SD;

21F/18M) were included for analysis. All participants were French-speaking[4]. None of them suffered from any developmental, psychiatric or neurological disorder. All participants gave informed consent (parental consent was obtained for children). Neither children nor adults received any financial compensation for their participation. The experimental procedure was approved by the Ethics Committee of the Université catholique de Louvain.

2. Materials

Sequences of single-syllable French nouns, all with an age of acquisition (AoA) lower than 6 years, were presented to the participants for immediate serial recall. The stimuli can be found in Table 1. We adjusted the length of the sequences to the mean span of the age group and increased this by two more items to avoid ceiling effects in Hebb repetition learning (resulting sequence-lengths were eight items for children and nine items for adults). A pilot study on two twelve-years-olds and two adults was performed to confirm that the two groups were tested at a comparable performance level (i.e., similar filler performance across trials). To create the sequences, two item sets (A and B) of nine words were generated by using Lexique 3.80 (New, Pallier, Brysbaert, & Ferrand, 2004), and matched for AoA ($F < 1$ for both groups) (see Table 1). For the twelve-years-olds, the word *doigt* from set A and *feu* from set B were excluded to obtain 8-item sequences that were matched on mean AoA to the adult's 9-item sequences. Ten different sequence orders were created from each item set and counterbalanced across our two Hebb conditions (i.e., overlapping Hebb condition (H*o*) vs. non-overlapping Hebb condition (H*n*)) to avoid stimulus-specific effects. The filler sequences contained the same sequence-items as the overlapping Hebb sequence, but in a different order. The order of words within the filler sequences was determined randomly by using the E-prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) algorithm (Schneider, Eschman, & Zuccolto, 2002). The Hebb learning block consisted of 32 sequences in total, which were all presented for immediate recall. Both the H*o* and H*n* sequences were mixed within the same block and were repeated on every fourth trial, that is, eight times in total, interspersed with a total of 16 filler sequences.

[4] Both native and non-native French speakers were included. All participants used French on a daily base (i.e., in school or at work).

Table 1. Stimuli material for experiment 1a. Eight and nine single-syllable words were used for twelve-years-olds and adults respectively. Age of Acquisition (years) for each word is reported.

Set A		***Set B***		
CV	*AoA*	*CV*	*AoA*	
CHAT	3.80	PIED	3.60	*Children + Adults*
OEIL	4.10	RUE	5.20	*Children + Adults*
OEUF	4.50	BOUE	5.80	*Children + Adults*
BEAU	4.50	PLUIE	4.40	*Children + Adults*
DOUX	5.10	OIE	5.60	*Children + Adults*
TRAIN	5.10	JOUR	4.70	*Children + Adults*
MAIN	3.60	NUIT	4.10	*Children + Adults*
BRAS	4.20	LOUP	4.70	*Children + Adults*
DOIGT	3.70	FEU	4.90	*Adults*

3. Procedure

The experiment started with a familiarization phase in which participants listened to each word that would be used in the task. They were instructed to repeat the words out loud and were corrected if necessary. We ensured that all words were known by the participants by asking them to define each word separately. All words were recorded by a female voice and presented auditory at 60 dB using Sennheizer HD265-1 headphones. The experiment was presented electronically using the E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA) running on a Windows PC. The words were presented one at a time for 750 msec with an inter-stimulus interval of 250 msec. The Hebb learning procedure was similar to that in previous studies (Page, Cumming, Norris, Hitch, & Norris, 2006; Page et al., 2013; Szmalec et al., 2009; Szmalec et al., 2012). The task always started with presentation of three filler sequences followed by one of the Hebb sequences, one filler sequence and the other Hebb sequence (i.e. f, f, f, H*n*, f, H*o*,f, H*n*, f, H*o*, ... or f, f, f, H*o*, f, H*n*,f, H*o*, f, H*n,...*), counterbalanced across participants. The two first filler sequences were introduced as a practice. Immediately after sequence presentation, a recall screen was presented with a question mark signaling that the participants had to recall the CVs in the same order as presented. They were allowed to say "blank" when they forgot a word at a particular serial position. The Hebb learning task lasted approximately 30 minutes.

4. Results

We scored Hebb recall performance using McKelvie's (1987) scoring method. This method takes into account both the position and the serial order of recalled items. In a first step, the number of items is counted that are in the correct position from left to right up to the first error. Secondly, the same step is repeated from right to left up to the first error. After this, the number of items in any correct sequence of two or more items between the first error from the left and the first error from the right is counted. Finally, any other items that occur in the correct position from left to right are counted[5]. The maximal possible recall score using this procedure was 8 for the children (i.e., for sequences of 8 items) and 9 for the adults (i.e., for sequences of 9 items). Recall performance for the filler sequences was averaged across two consecutive filler trials to obtain an equal number (i.e., eight) of filler and Hebb repetition scores. An arcsine square root transformation was completed on all percent scores in order to transform the fixed-limit distribution of percentages to a normal distribution appropriate for statistical analyses (Archibald & Joanisse, 2013). For clarity, all descriptive statistics presented in the tables and figures represent the untransformed percentage of correct scores. The data are plotted in Figure 3.2.

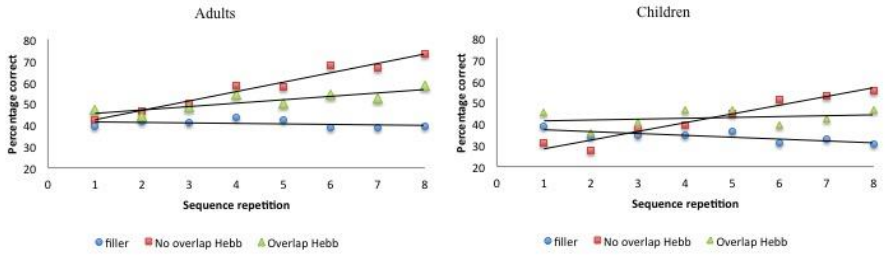

Figure 3.2. Performance (percentage of correct scores) as a function of Sequence type (filler vs. Hebb non-overlap vs. Hebb overlap) and Sequence repetition (1 to 8) in both children and adults, Experiment 1. **Left pane**l: performance for adults. **Right panel**: performance for children.

Recall accuracy was analyzed using a 2 (Group: children vs. adults) x 2 (Half: first vs. second) x 3 (Sequence type: filler vs. Hebb non-overlap vs. Hebb overlap) repeated measures ANOVA. In order to evaluate implicit learning in the Hebb task, we employed the procedure adopted by Mosse and Jarrold (2008) as well as

[5] For example, a sequence such as "bras pied rue boue oie pluie jour nuit" could be recalled as "bras pied rue oie pluie nuit". This response would be scored as follows: 3 correct in the first step (i.e., "bras pied rue" from left to right); 1 correct in the second step (i.e., "nuit" from right to left); 2 correct in the third step (i.e., "oie pluie" occur together); and 0 in the last step (i.e., no other items in the correct position), for a total score of 6 (3 + 1 + 2 + 0) out of 9.

Archibald and Joanisse (2013) that involves comparing performance on the first and second halves of each sequence type (for similar procedure, see also Turcotte et al., 2005)[6]. While a main effect of Sequence type in favor of the Hebb sequence might provide some evidence of learning that sequence, only the demonstration of improvements in performance for repeated Hebb sequences, relative to the baseline filler sequences, can be taken as an indication of implicit learning. Thus, an interaction between Sequence type and Half due to higher scores on the Hebb sequences for the second half of the trials would provide evidence of Hebb learning (Archibald & Joanisse, 2013). The ANOVA revealed a significant main effect of Group [$F(1,73) = 12.89$, $p < .001$, $n^2_p = .15$] with adults showing higher recall scores than children ($49.66 \pm 1.17_{SE}$ vs. $39.58 \pm 1.32_{SE}$). There was also a significant main effect of Half [$F(1,73) = 37.24$, $p < .001$, $n^2_p = .34$], such that recall scores for the second half of the repetitions were higher than recall scores for the first half of the repetitions ($47.75 \pm 1.40_{SE}$ vs. $41.88 \pm 1.13_{SE}$), and a significant main effect of Sequence type [$F(2,146) = 19.61$, $p < .001$, $n^2_p = .21$]. Comparisons revealed higher recall scores for the non- overlapping Hebb sequence ($50.42 \pm 1.93_{SE}$) compared with the overlapping Hebb sequence ($46.59 \pm 1.45_{SE}$) [$F(1,146) = 19.35$, $p < .00$, $n^2_p = .12$] and the filler sequence ($37.45 \pm 1.02_{SE}$) [$F(1,146) = 147.09$, $p < .001$, $n^2_p = .50$]. Recall scores for the overlapping sequence were also significantly higher than for the filler sequence [$F(1,146) = 59,75$, $p < .001$, $n^2_p = .29$]. Further, there was a significant interaction between Half and Sequence type [$F(2,146) = 47.74$, $p < .001$, $n^2_p = .40$]. This did not differ significantly between groups [$F < 1$]. The significant two-way interaction is illustrated in Figure 3.3. Planned comparisons of the significant interaction between Half and Sequence type revealed a significant increase across halves for the non-overlapping Hebb sequence [$F(1,146) = 141.28$, $p < .001$, $n^2_p = .49$]. Comparable contrasts for the other sequences were non-significant. During the first half of the task, recall was higher for both the overlapping and non-overlapping Hebb sequence compared with the filler sequences [$F(1,146) = 49.56$, $p < .001$, $n^2_p = .25$ and $F(1,146) = 3.86$, $p < .051$, $n^2_p = .03$ respectively]. There was no difference between the two Hebb sequences. During the second half of the task, as during the first half, recall was higher for both the overlapping and non-overlapping Hebb sequence compared with the filler sequences [$F(1,146) = 61.55$, $p < .001$, $n^2_p = .30$ and $F(1,146) = 230.65$, $p < .001$, $n^2_p = .61$ respectively]. However, the non-overlapping Hebb sequence scored significantly higher than the overlapping Hebb sequence [$F(1,146) = 66.38$, $p < .001$, $n^2_p = .31$].

[6] We present the first/second half analysis for matters of comparability with earlier studies on Hebb learning in developmental samples (e.g. Mosse and Jarrold, 2008; Joanisse and Archibald, 2013). The same analysis with regression slopes as a measure of Hebb repetition learning yielded qualitatively similar results. The entire dataset (i.e. with regression measures and with first/second half measures) can be downloaded at: Github.com/NOORES

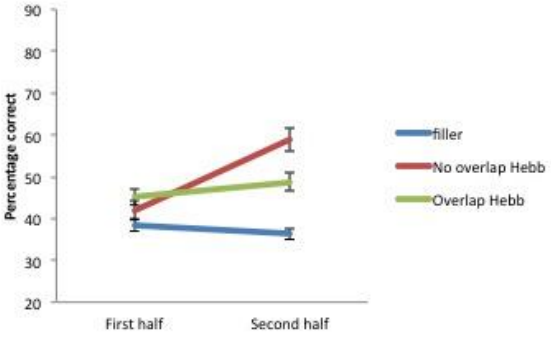

Figure 3.3. Mean percentage of items correctly recalled (with standard errors) for Hebb and filler sequences by sequence Halves, Experiment 1.

5. Discussion

In Experiment 1, we manipulated overlap between the lexical items of Hebb and filler sequences. The results showed that although recall was significantly better for both the non-overlapping and overlapping Hebb sequences compared with the filler sequences, the non-overlapping Hebb sequence showed the strongest learning pattern. This was indicated by the significant improvement across halves and the better recall during the second half of the task. These results are similar to what was found with adults in Page et al. (2013), and these observations can be extended, for the first time, to younger learners. Note that in the current study a different presentation modality (auditory) and recall modality (oral) were used, and that overlap was manipulated within the same Hebb learning block, compared with Page et al. This shows that the overlap effect is robust. Importantly for the current study, no interactions with group were found. This indicates that Hebb repetition learning and its sensitivity to overlap can be generalized across development. Note that recall during the first half of the task was higher for Hebb sequences compared with filler sequences. We argue that this can be explained by the rapid memorization of the Hebb sequence during the first four repetitions (see Figure 3.2).

In the next experiment, we aimed to test the effect of item-overlap in children and adults when using sublexical items (i.e., sequences of syllables). Because children are assumed to show very strong word-learning skills throughout childhood (e.g., Pinker & Jackendoff, 2005), we predicted that the children in the current experiment would acquire the sublexical sequences, which are functionally equivalent to novel words, more rapidly than the adults and that this would be reflected in a stronger Hebb-learning effect. In addition, in line with Page et al.'s theoretical framework, and in an attempt to offer an explanation for weak HRE with

children in previous studies, we predicted that children would, if anything, be more significantly affected by item-overlap during learning.

Experiment 2

1. Participants

The same participants took part as in Experiment 1.

2. Materials and Procedure

Exactly the same procedure was used as in Experiment 1, except for the items, which were nonsense syllables instead of words. All syllables had a consonant-vowel structure (CV). Again the length of the sequences was adjusted to the memory span of the age group, increased by two syllables and piloted in two children and adults. Two sets (A and B) of nine syllables were generated by the use of WordGen (Duyck, Desmet & Verbeeke, 2004) and matched for biphone frequency ($F < 1$ for both groups). Both item sets are presented in Table 2. For the twelve-year-old children, the CVs *xu* from set A and *wu* from set B were excluded to match sequences used in children with sequences used in adults (on mean biphone frequency). We ensured that consecutive phonemes could not sound like existing words in French (e.g., *cave* or *colis).* All CVs were recorded by the same female voice as in Experiment 1 and presented auditorily at 60dB using Sennheizer HD265-1 headphones. The CVs were presented for 500msec with an inter-stimulus interval of 500msec. The Hebb learning task lasted approximately 30 minutes.

Table 2. Stimuli material. Eight and nine syllables were used for twelve-years-olds and adults respectively. French biphone frequency for each syllable is reported.

Set A		***Set B***		
CV	*Biphone*	*CV*	*Biphone*	
TI [ti]	3440	LI [li]	2843	*Children + Adults*
RI [ri]	3880	NA [na]	1262	*Children + Adults*
JA [ʒa]	981	GU [gy]	173	*Children + Adults*
MU [my]	438	CO [ko]	1388	*Children + Adults*
SO [so]	155	FI [fi]	1142	*Children + Adults*
VE [vɔ]	765	PE [pɔ]	960	*Children + Adults*
BE [bɔ]	354	ZE [zɔ]	631	*Children + Adults*
KA [ka]	2251	DA [da]	497	*Children + Adults*
XU [ksy]	197	WU [wy]	3	*Adults*

3. Results

Again, McKelvie scoring was used to obtain immediate serial recall scores. The data are plotted in Figure 3.4.

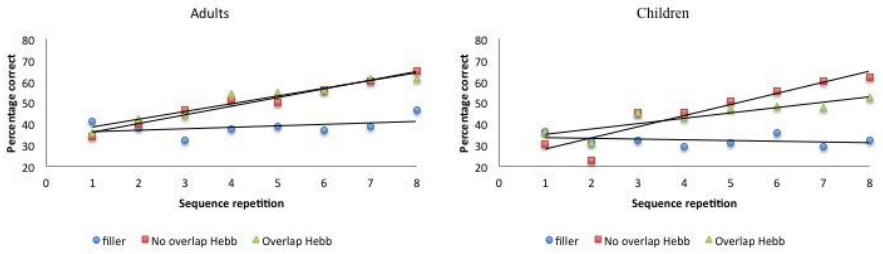

Figure 3.4. Performance (percentage of correct scores) as a function of Sequence type (filler vs. Hebb non-overlap vs. Hebb overlap) and Sequence repetition (1 to 8) in both children and adults, Experiment 2. **Left panel**: performance for adults. **Right panel**: performance for children.

For each participant, the percentage correct scores were averaged across the first four and last four sequence repetitions, to obtain two halve scores, and transformed using arcsin square root transformation. The transformed scores were entered into a 2 (Group: children vs. adults) x 2 (Half: first vs. second) x 3 (Sequence type: filler vs. Hebb non-overlap vs. Hebb overlap) repeated measures ANOVA, as before. This yielded no significant effect of Group [$F(1,73) = 2.32$, $p = .13$, $n^2_p = .03$]. There was a significant main effect of Half [$F(1,73) = 93.66$, $p < .001$, $n^2_p = .56$] such that recall scores for the second half of the repetitions was higher than recall scores for the first half of the repetitions ($48.22 \pm 1.39_{SE}$ vs. $38.15 \pm 1.05_{SE}$), and a significant main effect of Sequence type [$F(2,146) = 26.46$, $p < .001$, $n^2_p = .27$]. Comparisons revealed better recall for the non-overlapping Hebb sequence ($47.95 \pm 1.73_{SE}$) compared with the filler sequences ($34.80 \pm .99_{SE}$) [$F(1,146) = 122.74$, $p < .001$, $n^2_p = .46$], and better recall for the overlapping Hebb sequence ($46.80 \pm 1.64_{SE}$) compared with the filler sequences [$F(1,146) = 88.71$, $p < .001$, $n^2_p = .38$]. There were no differences between the two Hebb sequences. Crucially, there was a significant interaction between Half and Sequence type [$F(2,146) = 25.54$, $p < .001$, $n^2_p = .25$], that in turn interacted significantly with Group [$F(2,146) = 4.34$, $p < .01$, $n^2_p = .13$]. This three-way interaction is illustrated in Figure 3.5. Planned comparisons within both groups revealed a significant non-overlapping Hebb effect (i.e. the different improvement across halves between filler and non-overlapping sequences) for children [$F(1,146) = 41.31$, $p < .001$, $n^2_p = .22$], and adults [$F(1,146) = 10.83$, $p < .01$, $n^2_p = .07$]. This non-overlapping Hebb effect was significantly larger for children compared to adults [$F(1,146) = 5.55$, $p < .05$, $n^2_p = .04$]. Further comparisons revealed the presence of an overlapping Hebb effect in both children [$F(1,146) = 8.00$, $p < .01$, $n^2_p = .05$] and adults [$F(1,146) = 11.97$, $p < .001$, $n^2_p = .08$]. This did however not differ between groups, $F < 1$. Children showed a significantly lower improvement across halves for the overlapping Hebb sequence compared with the non-overlapping Hebb sequence [$F(1,146) = 12.95$, $p < .01$, $n^2_p = .08$]. There was no such difference for adults, $F < 1$. Children and adults did not differ on differences across halves for the filler sequences, $F < 1$.

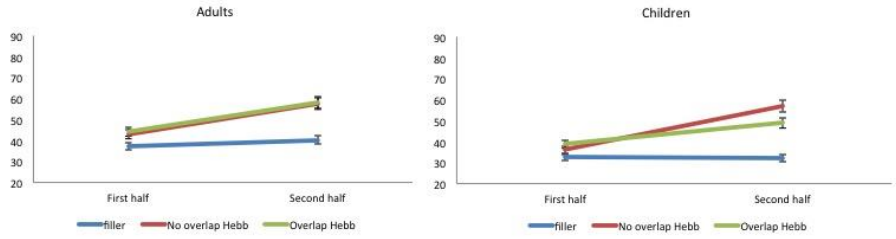

Figure 3.5. Mean percentage of items correctly recalled (with standard errors) for Hebb and filler sequences by sequence Halves, in both children and adults, Experiment 2. Left panel: performance for adults. Right panel: performance for children.

4. Discussion

In Experiment 2, Hebb sequences were made of nonsense CV syllables instead of existing words. While children showed reduced Hebb learning due to item-overlap with filler sequences, surprisingly no such overlap effect was observed in adults. Although children (and adults) were still able to learn the overlapping sequence, as reflected by the improvement across halves (in contrast to Experiment 1), children showed less improvement on the overlapping compared with the non-overlapping Hebb sequence. Finally and very importantly, we observed a larger Hebb repetition effect in children compared with adults for non-overlapping syllable sequences.

In an attempt to explain what is driving the different results for item-overlap obtained for children versus adults in the current experiment, we considered some recent simulation work on children's non-word (sublexical) repetition behavior using a computational instantiation of the chunking hypothesis, that is, the Elementary Perceiver and Memorizer (EPAM) (Feigenbaum & Simon, 1984; Jones, 2012). Overall, the chunking hypothesis suggests that repeated exposure to a stimulus set, for example, a sequence of phonemes or syllables, leads to the stimuli being represented in larger and larger chunks (Miller, 1956). Chunking may be very beneficial when one considers that short-term memory has a limited capacity. Only information that requires less than 2s to process can be reliably stored in working memory (see Jones, 2012, using an approximation from Baddeley, Thomson & Buchanan, 1975). Hence, take as an example a sequence of phonemes *l o f o d u*. According to the EPAM model of phoneme (chunk) learning, a time of 400 ms would be needed to encode each phoneme of that sequence (see Jones, 2012). This means that encoding the sequence *l o f o d u* would require a time of more than 2s (i.e. 6x400ms), and hence would not be reliably stored in working memory. If, however, the sequence *l o f o d u* is learned by chunking the sequence into adjacent phonemes, *lo fo du,* and if we assume that an additional 30ms is needed to process each phoneme within a chunk (excluding the first phoneme; see Jones, 2013*)* less than 2s (3x430ms) would be needed to process the sequence. Jones (2012) argues that chunking leads to the false perception that short-term memory capacity increases across development: instead, he asserts that it is not capacity that increases across development but the size of chunks (with the use of larger chunks leading towards apparently higher capacity). In an attempt to demonstrate this, Jones used the EPAM model to simulate earlier developmental work on non-word repetition learning. In his simulation, the model was trained on linguistic input (e.g. the non-word *hampent*) while holding capacity and processing speed constant. Over time, the model learned chunks of phoneme sequences. Early in training, many small chunks were extracted from the non-word (e.g. *ha, m, pe, nt*), matching repetition performance of the younger children. Late in training, however, the model extracted a few larger chunks (e.g. h, amp, ent), matching performance of the older children.

This illustrates that chunking may offer an important explanation for developmental changes in task performance that involves learning novel word-forms (even when controlling for developmental changes in capacity and processing speed).

According to our working hypothesis, learning within the Hebb repetition paradigm establishes new chunks that are enhanced in memory by subsequent repetitions (Page et al., 2013; Page & Norris, 2008, 2009). Jones' (2012) findings let us further hypothesize that encoding of chunks within the sublexical Hebb task takes place at different grain sizes in children compared with adults, with children using a larger number of *small chunks* and adults using a smaller number of *large chunks.* If a Hebb sequence, such as *ja ve ri ka be ti so mu,* is chunked in four two-item chunks as *jave rika beti* and *somu* (note that when chunking this way, the list can be more reliably encoded in working memory, i.e. 4x490 = 1960ms which is below Jones' presumed capacity of 2s), four chunks will engage for learning on the first presentation of that sequence. As long as the filler sequences are from a different syllable set, there should be nothing to interrupt that learning. If, however, the fillers are made up of the same set (i.e., in the overlap condition), it is likely that anagrams of these chunks, e.g., veja kari tibe muso, will turn up quite often in the non-repeating filler sequences[7], and hence slow down learning (i.e., an overlap effect as modeled by Page & Norris, 2009). If on the other hand the same Hebb sequence is chunked into a few larger units, let us say two chunks of four items, *javerika* and *betisomu,* the probability that a full anagram of that chunk (e.g., *vejakari)* turns up early in the filler trials is relatively low (see the same footnote). Hence, larger chunking of syllable sequences representing new word-forms, could explain why adults did not show an overlap effect in the current experiment.

The aim of the third experiment was, therefore, to investigate whether the absence of an overlap effect in adults in Experiment 2 was indeed due to the use of a different chunk size in adults. To test this hypothesis, we encouraged (through a manipulation of time parameters) a sample of adult participants to group Hebb sequences in small, two-item chunks (e.g., jave rika beti somu), just like we suppose children do. We predicted that an overlap effect would emerge when adults are encouraged to memorize small chunks, in contrast to a group of control adults who

[7] The probability that a syllable *ve* turns up in a random filler sequence at an odd position is 0.5, and in 1/7 of these occasions there will be a *ja* following this syllable, giving it a 1/14 chance that *veja* turns up as a learnable chunk in the filler sequence. The same applies for each of the other chunks, giving a probability of around 0.29 that a random filler sequence contains a chunk that is a perfect anagram of one of the chunks in the Hebb sequence. In contrast, when chunking Hebb sequences in larger, say two 4-item, chunks, the probability that any combination of *ja ve ri* and *ka* (other than *javerika* itself) occurs as a chunk in either half of a filler sequence would be only 0.027. So if you chunk the Hebb sequence in fours it is relatively unlikely that you will get perfect anagrams of those chunks in similarly chunked filler sequences, thus minimizing the extent to which learning is slowed by item overlap between Hebb sequences and fillers.

were not encouraged to chunk small. Furthermore, we predicted that adults who chunk small would show a larger non-overlapping Hebb learning effect compared with that of the control adults, in line with the larger non-overlapping Hebb-learning effect seen for children in Experiment 2. If the small-chunk group of adults indeed shows an item-overlap effect, and a superior non-overlapping Hebb effect, we will be more secure in concluding that chunking strategy (more particularly, preferred chunk size) drives developmental differences in sublexical verbal Hebb sequence learning.

Experiment 3

1. Participants

In total, 59 participants took part in the experiment. All participants were recruited by means of advertising and were randomly allocated to a Hebb-learning condition with chunking (n = 29, mean age 29.72 ± 11.33_{SD}, 20F/9M) or without chunking (n = 30, mean age 28.86 ± 12.13_{SD}, 21F/9M). All participants were living or working in the French part of Belgium. Two participants (one in each condition) were living and working in the Flemish part of Belgium but had a good understanding of the French language. None of them suffered from any developmental, psychiatric or neurological disorders. All participants gave informed consent, and the Ethics Committee of the Université catholique de Louvain approved the experimental procedure.

2. Materials and Procedure

The same materials and procedure were used as in Experiment 2. For the Hebb learning condition *with* chunking, however, no interstimulus interval was provided except after CV_2, CV_4, CV_6 and CV_8 for which the interval was 1000msec. These spacing parameters were designed to encourage the participant to chunk the sequence in four two-item chunks, and one one-item chunk (i.e., CV_1CV_2 CV_3CV_4 CV_5CV_6 CV_7CV_8 CV_9). After each sequence, explicit recall was required by use of a recall screen. On the recall screen, presented immediately after presentation of the last CV, the nine CVs were arranged randomly in a circle around a central question mark. Participants were required to recall the CVs in the same order as they were presented by clicking with the mouse device on the syllable. Participants received no cue for clicking, so that a given CV could be clicked more than once. In contrast to the response format used in Experiments 1 and 2 (in which participants had to respond out loud), the recall method did not allow intrusion of CVs that were

not presented. The participants were instructed to click the question mark in order to indicate that a CV was omitted in their response. They were told that it would take the position in the sequence where the CV occurred. After each trial, the spacebar was pressed to start the next trial. Note that the positioning of the CVs around the question mark was random on each trial, preventing Hebb learning from being confounded by the learning of a spatial-clicking pattern. All CVs were recorded by a new female voice and presented auditorily at 60 dB using Bose QC 15 headphones. The experiment was presented using a Dell PC running software written in E-prime 2.0.

3. Results

McKelvie scoring was used to obtain immediate serial recall scores. The data are plotted in Figure 3.6.

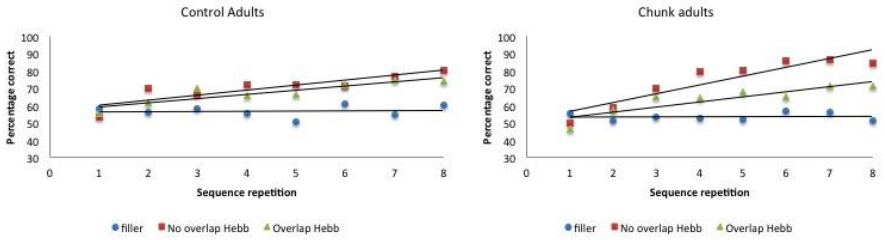

Figure 3.6. Performance (percentage of correct scores) as a function of Sequence type (filler vs. Hebb non-overlap vs. Hebb overlap) and Sequence repetition (1 to 8) in the group with chunking and the control group, Experiment 3. Left panel: performance for control adults. Right panel: performance for chunk-encouraged adults.

For each participant, the percentage correct scores were averaged across the first four and last four sequence repetitions, so as to obtain two scores, one for each half, and scores were transformed using arcsin square root transformation. The transformed scores were entered into a 2 (Group: chunk adults vs. control adults) x 2 (Half: first vs. second) x 3 (Sequence type: filler vs. Hebb non-overlap vs. Hebb overlap) repeated measures ANOVA. This yielded no significant effect of Group [$F < 1$]. There was a significant main effect of Half [$F(1,57) = 78.74$, $p < .001$, $n^2_p = .58$] such that recall scores for the second half of the repetitions was higher than recall scores for the first half of the repetitions ($68.39 \pm 1.39_{SE}$ vs. $60.22 \pm 1.07_{SE}$),

and a significant main effect of Sequence type [$F(2,114) = 52.16$, $p < .001$, $n^2_p = .48$]. Comparisons revealed better recall for the non-overlapping Hebb sequence ($72.29 \pm 1.67_{SE}$) compared with the filler sequences ($55.07 \pm 1.05_{SE}$) [$F(1,114) = 259.42$, $p < .001$, $n^2_p = .69$], and better recall for the overlapping Hebb sequence ($65.53 \pm 1.48_{SE}$) compared with the filler sequences [$F(1,114) = 90.43$, $p < .001$, $n^2_p = .44$]. There was also a significant difference between the two Hebb sequences [$F(1,114) = 43.52$, $p < .001$, $n^2_p = .28$]. Crucially, there was a significant interaction between Half and Sequence type [$F(2,114)= 29.18$, $p < .001$, $n^2_p = .45$], that in turn interacted significantly with Group [$F(2,114) = 4.09$, $p < .05$, $n^2_p = .16$]. This three-way interaction is illustrated in Figure 3.7. Planned comparisons within both groups revealed a significant non-overlapping Hebb effect (i.e., a different improvement across halves for filler and non-overlapping sequences) for chunk adults [$F(1,114)= 50.56$, $p < .001$, $n^2_p = .31$], and control adults [$F(1,114)= 12.92$, $p < .01$, $n^2_p = .10$]. This non-overlapping Hebb effect was significantly larger for chunk adults compared with control adults [$F(1,114)= 6.51$, $p < .05$, $n^2_p = .05$]. Further comparisons revealed the presence of an overlapping Hebb effect in both chunk adults [$F(1,114)= 10.86$, $p < .01$, $n^2_p = .09$] and control adults [$F(1,114)= 9.80$, $p < .01$, $n^2_p = .08$]. This did however not differ between groups, $F < 1$. Chunk adults showed a significant lower improvement across halves for the overlapping Hebb sequence compared with the non-overlapping Hebb sequence [$F(1,114)= 14.56$, $p < .001$, $n^2_p = .11$]. There was no such difference for control adults, $F < 1$. Chunk adults and control adults did not differ on differences across halves for the filler sequences, $F < 1$. During the first half of the task, both groups showed significantly better recall for the non-overlapping Hebb sequence compared with the filler sequence [control, $F(1,114)= 15.63$, $p < .001$, $n^2_p = .12$; chunk, $F(1,114)= 21.26$, $p < .001$, $n^2_p = .16$], and for the overlapping Hebb sequence compared with the filler sequence [control, $F(1,114)= 8.66$, $p < .01$, $n^2_p = .07$; chunk, $F(1,114)= 4.07$, $p < .05$, $n^2_p = .03$]. The chunk group also showed significantly better recall for the non-overlapping Hebb sequences compared with the overlapping Hebb sequence, $F(1,114)= 6.73$, $p < .05$, $n^2_p = .06$]. For all contrasts, there were however no differences between groups, $Fs < 1$. During the second Half of the task, only the chunk group showed better recall for the non-overlapping Hebb sequence compared with the filler sequence, $F(1,114)= 63.86$, $p < .001$, $n^2_p = .36$]. During the second half of the task, the non-overlapping Hebb effect (i.e. difference between Hebb and filler sequence) was significantly higher for the chunk group compared with the control group [$F(1,114)= 17.01$, $p < .001$, $n^2_p = .13$].

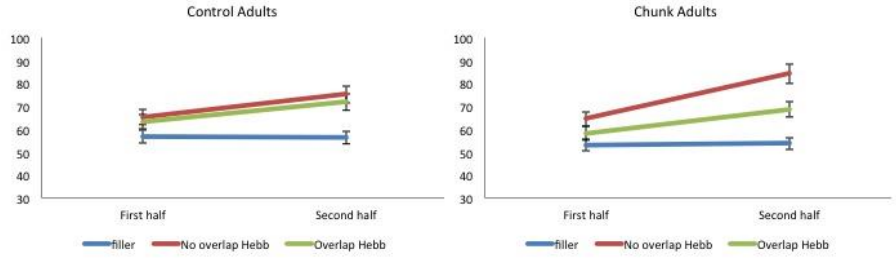

Figure 3.7. Mean percentage of items correctly recalled (with standard errors) for Hebb and filler sequences by sequence Halves, in both control and chunk adults, Experiment 3. Left panel: performance for control adults. Right panel: performance for chunk adults.

4. Discussion

In Experiment 3, the same sublexical material was used as in Experiment 2. One sample of adult participants (i.e. the chunk adults) was, however, encouraged to group Hebb and filler sequences in small, two-item chunks (e.g., *jave rika beti somu*). While the control adults again showed no effect of item-overlap, replicating the null effect for adults in Experiment 2, adults that were encouraged to chunk small did show a reliable item-overlap effect, similar to the children in Experiment 2. Indeed, small-chunk adults showed less improvement on the overlapping compared with the non-overlapping Hebb sequences. Moreover, we observed a larger (non-overlapping) Hebb repetition effect in adults that were encouraged to chunk small compared with the control adults that were not encouraged to do so. Note that recall during the first half of the task was higher for Hebb sequences compared with filler sequences. This again indicates a rapid memorization of the Hebb sequence during the first four repetitions (see Figure 3.6). Chunking in particular helped rapid learning of the non-overlapping Hebb sequence (as reflected by better recall for the non-overlapping Hebb sequence during the first half of the task, only in the chunk group).

General Discussion

Words are essentially sequences of smaller, sublexical constituents (i.e., phonetic features, phonemes, syllables) that combine to make larger lexical representations (Pinker, 1994). In order to learn such a (complex) combinatorial set, children must be able to isolate starting elements from the sequential input they are

exposed to and then gradually acquire the pattern of legal combinations (Newport, Hauser, Spaepen, & Aslin, 2004). Although children are commonly believed to be better language learners than adults, it remains to this day unclear whether or how children and adults differ in terms of the serial-order learning mechanisms that underlie novel word-form learning. In the present work, we investigated serial-order learning differences between children and adults, using a laboratory analogue of novel word-form acquisition, better known as the Hebb repetition learning effect. In a first experiment, sequences of existing words were presented for immediate serial recall. One of the repeating Hebb sequences contained the same words as the filler sequences (the overlap condition). We found comparable Hebb repetition effects in both children and adults. Moreover, we found reduced Hebb learning due to overlap in adults, replicating previous studies, and, for the first time, the same effect was also observed in children. One limitation regarding this experiment and previous studies, though, concerns the use of lexical items (words) in the sequential input. Sequences of lexical items are not equivalent to novel words, which are essentially sequences of sublexical items, and the word sequences might therefore have obscured potentially stronger learning effects in children. To address this question, a second experiment was designed to compare children and adults on a Hebb repetition-learning task using sublexical sequences mimicking novel words. Importantly, we found that children now showed a stronger Hebb repetition effect compared with adults. Surprisingly, however, only children showed reduced learning due to item-overlap between Hebb and filler sequences. This is a very interesting finding, particularly if we assume that children learn new word-forms by chunking them in smaller units than do adults (Jones, 2012). Small two-syllable chunks in Hebb sequences (e.g. AB CD EF GH) are more sensitive to item-overlap than larger, three or four-syllable chunks (e.g., ABCD EFGH). With reference to the chunk-learning account of Page and Norris (2009), it is more likely that a perfect anagram of a small chunk shows up in the filler sequences, slowing down Hebb repetition learning, compared to a perfect anagram of a larger chunk, which is assumed to have a less detrimental effect on Hebb learning. This was tested more directly in a third experiment in which we encouraged adults to chunk sublexical sequences smaller, i.e. into four two-syllable units. This resulted in the appearance of an item-overlap effect and most importantly, it improved Hebb repetition learning in a similar manner as we observed in children.

The notion of starting small has already been proposed within word-learning theories (Elman, 1991, 1993) and was also supported by subsequent empirical studies (Conway et al., 2003). This gave rise to the less-is-more hypothesis in language learning (Newport, 1990). Newport explained that children are better able to learn languages than adults *because* they have fewer cognitive resources available (smaller working memory capacities). Children will naturally proceed by beginning with small parts and will proceed to more complex constructions as they mature. More competent adults will begin by trying to acquire

larger structures from the start because their cognitive resources allow them to do so. Interestingly, Jones (2012) proposes an alternative view in which he argues that chunking (or starting small) should be considered as an explanation for developmental differences in cognitive behavior *without* the need for additional developmental changes in short-term memory capacity or processing speed (see 3.4). In his view, changes in short-term memory capacity can more likely be seen as the consequence, rather than the cause of changes in chunk behavior. According to Rhode and Plaut (2002), starting small is, by itself, not a critical condition to reach linguistic fluency and is only beneficial for children because their learning is characterized by a (connectionist) system that is still unorganized and inexperienced yet still highly flexible to future adaptation, in contrast to that of adults. This also accords with the granularity effect that has been described within the grammar-learning domain (Arnon & Ramscar, 2012). Arnon and Ramscar showed that, during grammatical gender learning (i.e., learning new article + noun combinations), adults benefited more from exposure to the full complex sentence before exposure to the single nouns. Similarly, in the current study, we found that small chunking was beneficial for Hebb repetition learning but only when there was no full item-overlap between sequences. Item-overlap causes strong competition from interfering structures in the filler sequences making Hebb learning difficult. This suggests that for complex linguistic input, other more adult-adapted learning strategies are necessary. We assume that chunking sequences in larger units is one of those strategies. It explains the lack of an overlap-effect in the nonword Hebb task because it is less likely that anagrams of a large chunk show up in the filler sequences.

What is still not clear from the current study is whether children and adults, if anything, use a different grain size for chunking the lexical Hebb sequences. In Experiment 1, when lexical sequences were presented for immediate recall, children and adults both showed a comparable item-overlap effect. There are two chunking sizes that could explain this item-overlap effect. Either, both children and adults chunk lexical Hebb sequences in small two-word units for which competing anagrams turn up quite often in the filler sequences, or, adults represent the entire lexical Hebb sequence as one large chunk that receives competition from its perfect anagram in every filler sequence (the same sequence but in a different order – this was the explanation originally offered by Page & Norris, 2009). According to Jones (2012) chunking depends on the amount of exposure to the stimuli in the environment (prior knowledge): more exposure leads to larger chunks. Recently, it has been found that prior learning of item-by-item transitions affects immediate recall of word sequences (e.g. *chou feu veau pain,* etc.) and non-word sequences (e.g. *chon zin bi leuh,* etc.) (Majerus, Martinez Perez, & Oberauer, 2012). In contrast, immediate recall of digit sequences is only affected by prior learning of the entire sequence. The authors argue that digits are linguistic chunks that we frequently experience in large arbitrary combinations (e.g., phone numbers) while this is not the case for sequences of random words or non-words. This results in the

false perception that short-term memory "capacity" for digits is superior to short-term memory for words. With this in mind, we might assume that children vs. adults use different chunking strategies for lexical vs. sublexical sequences, resulting in different competition effects in Experiments 1 and 2. This could be a reflection of underlying differences in experience with the sequential input, independently of potential differences in working memory capacity. Future research should shed more light on the dissociation between working memory capacity and prior knowledge as possible factors driving developmental sensitivities in Hebb learning.

Conclusion

Why are children better language learners than adults? This is an important question in the light of the sensitive-period theory of language acquisition. The current study approaches this question from a memory and learning perspective in which we assume that children are better language learners because they chunk linguistic structures in smaller subsequences compared with adults (a species of the *less-is-more* hypothesis). Previous studies showed that Hebb repetition learning, a sequential learning analogue of word-form learning, is rather weak in children. This is not in accordance with the sensitive-period hypothesis, according to which we would predict strong Hebb learning effects in children. The lack of strong Hebb learning effects in children in previous studies is likely to be explained by (a) the use of stimulus materials that do not resemble naturalistic word learning (i.e. sequences of words or digits instead of sequences of syllables or phonemes), and (b) the item-overlap between sequences that results in weaker Hebb learning, at least in adults. The current study was the first to test these hypotheses by directly comparing children and adults on a Hebb-learning task that contains either lexical or sub-lexical sequences, and with or without item-overlap. Furthermore, children and adults' Hebb-learning differences were directly assessed within the less-is-more hypothesis of language acquisition by encouraging adults to chunk Hebb sequences into small units. Overall, we found that children (Experiment 2) and small-chunking adults (Experiment 3) showed superior Hebb repetition learning performance. This suggests that children and adults differ in the way they chunk verbal sequential material, potentially offering insights into the sensitive-period hypothesis for language acquisition. Most importantly, the present study shows that human-memory theories have a significant potential to improve our understanding of the cognitive processes that lay the foundation of language acquisition across life.

Acknowledgement

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CHAPTER 4

LANGUAGE LEARNING IN THE ADULT BRAIN: DISRUPTING THE DORSOLATERAL PREFRONTAL CORTEX FACILITATES WORD-FORM LEARNING

Adults do not learn languages as easily as children do. It has been proposed that late-developing executive functions interfere with procedural mechanisms that support some aspects of language learning, such as learning novel phonological sequences, i.e., word-forms. We used transcranial magnetic stimulation (TMS) to investigate whether a disruption of the Dorsolateral Prefrontal Cortex (DLPFC) – a brain region that supports executive functions - can improve procedural learning of words in adults. Young adults were presented with repeating audio-visual sequences of syllables for immediate serial recall in a Hebb repetition learning task that simulates word-form learning. Inhibitory theta-burst TMS was applied to the left DLPFC or to the control site before the Hebb task. The DLPFC-disrupted group showed improved recall for the repeating Hebb sequence compared with the control group, indicating enhanced learning of the hidden syllable-sequence. Moreover, Hebb learning was negatively correlated with the executive functions in the control group. The results support the hypothesis that mature frontal lobe mechanisms, in particular executive functions, reduce the ability to learn word-forms. The findings provide new insight into competing cognitive and procedural mechanisms that contribute to language learning in the mature brain.

Reference

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Introduction

It is well known that children surpass adults in their language learning ability, in particular for certain aspects of language that involve grammar and phonology (Lenneberg, 1967; Newport, 1990), but it has remained unclear why this is the case (Kennedy & Norman, 2005; Newport et al., 2001). Adults outperform children in most measures of cognition, especially those that rely on the prefrontal cortex that maturates until adulthood, such as executive functions, attention and working memory (Craik & Bialystok, 2006). Yet, they fail learning languages with the ease that children do. It has been proposed that the mature cognitive systems interfere with implicit/procedural learning, which contributes to certain aspects of language learning such as word-forms or grammar (Cochran et al., 1999; Finn et al., 2014; Gupta, 2012; Ullman, 2015). However, there is little experimental evidence supporting this hypothesis.

Multiple cognitive systems support learning in cooperative and sometimes competitive ways (Poldrack et al., 2001; Poldrack & Packard, 2003). For example, procedural and declarative memory systems are known to interact during learning (Brown & Robertson, 2007). The declarative memory system is characterized by voluntary processes that rely on attentional resources mediated by prefrontal and medial-temporal lobe structures. Procedural memory on the other hand relies on automatic, implicit processes mediated by fronto-striatal structures. Procedural memory plays an important role in automatic skill learning such as motor learning (e.g., riding a bicycle) as well as certain aspects of language learning, in particular for grammar and phonology (Gupta, 2012; Ullman, 2004). Studies on motor learning suggest that suppression of prefrontal functions, due to hypnosis (Nemeth et al, 2013), repetitive Transcranial Magnetic Stimulation (TMS, Galea et al, 2010), use of secondary or distraction tasks (Brown & Robertson, 2007; Foerde et al., 2006), alcohol consumption (Virag et al., 2015), or intake of benzodiazepines (Frank et al., 2006), can enhance procedural learning. Moreover, motor learning studies have shown that enhancing cognitive effort during learning results in impaired procedural learning (D. V. Howard & Howard, 2001) with greater activity in the prefrontal cortex (Fletcher et al., 2005). These studies support the idea that the suppressed reliance on frontal lobe functions, and in particular conscious executive functions (EF) that support declarative memory, improves implicit/procedural learning in the motor domain.

A hypothesis of interacting cognitive and procedural mechanisms during learning is also gaining attention in the field of language (e.g., Finn et al., 2014; Krishnan, Watkins, & Bishop, 2016; Ullman, 2015). For instance, learning a novel word involves multiple cognitive processes, including segmentation abilities as well

as retention of sequences of constituent phonemes or syllables and creation of long-term phonology-to-semantic connections (Gaskell & Ellis, 2009; Gupta & Tisdale, 2009b). The long-term memorization of phonological sequences, or word-forms, is argued to rely on procedural memory mechanisms (Gupta, 2012). Experimental evidence for this comes from research with the *Hebb repetition paradigm* (Hebb, 1961; Page & Norris, 2008, 2009). In this task, sequences of items (e.g., phonemes/syllables) have to be retained in short-term memory for immediate serial recall. One sequence (often called the Hebb sequence) is repeated in exactly the same order every n^{th} trial but this is not told to the participants. Recall performance for the Hebb sequence usually improves across trials relative to the non-repeating (filler) sequences. An increasing amount of experimental work is consistent with the hypothesis that the mechanisms underlying the Hebb repetition effect (HRE) are related to word-form learning, in particular to the consolidation of novel word-forms in memory. Indeed, syllable sequences acquired through Hebb repetition learning compete with existing word-forms in the lexicon indicating that the learned sequences are integrated in long-term memory as novel lexical forms (Leach & Samuel, 2007; Szmalec et al., 2009; Szmalec et al., 2012). Learning in the task is also fast and long-lasting (Page et al., 2013), and is found to correlate with measures of vocabulary development in young children (Majerus & Boukebza, 2013b; Mosse & Jarrold, 2008). Similarly to novel word-form learning, the HRE does not rely on declarative memory but mostly on implicit learning mechanisms. For instance, prior awareness of the repeating sequence or explicit reproduction during the recall phase, and focal hippocampal lesions do not affect the HRE (Couture & Tremblay, 2006; Gagnon et al., 2005; Gagnon et al., 2004; Guerard et al., 2011; Kalm & Norris, 2016).

Recent developmental studies show that eight–year-old and eleven-year-old children outperform adults in implicit learning of novel phonotactic constraints in words (Smalle, Muylle, Szmalec, & Duyck, in press), and in the Hebb learning of novel word-forms (Smalle et al, 2015). Interestingly, in this latter, the age-effect depends on the overlap between Hebb and filler sequences. When the phonological Hebb sequences contain different syllables as used in the random filler sequences (so-called non-overlapping sequences), the HRE is greater in children than adults. This child advantage is absent and the HRE decreases in both adults and children, when the phonological Hebb sequences contain the same syllables as used in the random filler sequences (so-called overlapping sequences). It is likely that the item-overlap with the filler sequences interferes with the sequence or procedural learning processes that are necessary for the long-term memorization of the phonological forms in the Hebb task (Page et al., 2013; Smalle et al., 2015). When adults are forced to attend to smaller two-syllable-structures within the sequence (thereby simulating children's smaller working memory capacity), the HRE for non-overlapping, but not overlapping, sequences increases to the same level as children (Smalle et al., 2015). These findings suggest that children outperform adults in

procedural language learning tasks that benefit from limited capacity in working memory.

The aim of the present TMS study was to investigate whether inhibition of frontal-dependent functions, in particular executive functions (EF) that support declarative memory, facilitate learning of word-forms in the Hebb-learning paradigm in adults. Participants received disruptive repetitive TMS over the left dorsolateral prefrontal cortex (DLPFC) or a control site just before performing the Hebb repetition learning task. We hypothesized that TMS-induced disruption of DLPFC should increase the HRE for the non-overlapping Hebb sequences (but not for the overlapping Hebb sequences; Smalle et al., 2015) if EF interfere with implicit learning of novel phonological forms in adults. We also predicted that the individual differences in EF would correlate with individual differences in the HRE, so that participants with high performance in EF tasks would show a decreased HRE relative to participants with lower performance in EF tasks.

Methods

1. Participants

Thirty participants were recruited in the present study. One male participant was excluded from further analysis because he performed more than 2 standard deviations (SD) below mean on overall recall accuracy in the learning task. One female participant was excluded as she performed more than 2SD below mean for performance on the EF tasks. Hence we report the data of 28 participants, who were randomly assigned to the left DLPFC group (10 females; mean age: 23.9 SD: 2.8) and the control group (8 females; mean age: 22.8; SD: 2.4). All participants provided signed informed consent and were blind to the purpose of the study. Participants were right-handed, with no hearing or language impairment and no neurological conditions. They were all native English speakers except for two (one in each group) who were fluent English speakers (native German). Participants received financial compensation at the end of the experiment (£10/hour). The procedure was approved by the Central University Research Ethics Committee (CUREC) at the University of Oxford.

2. Experimental Design

Participants were familiarized with the Hebb learning task before receiving the continuous Theta Burst Stimulation (cTBS) to the left DLPFC or the control site. cTBS was immediately followed by the Hebb learning task, which lasted

approximately 30 min. During a follow-up session that took place five to six hours later, two EF tasks and one verbal short-term memory task were administered. The administration took place in a separate session in order to avoid possible confounding effects between the cognitive tasks and the stimulation. After the completion of the experiment, participants filled in a post-learning awareness questionnaire in which they were asked to report their knowledge about the unannounced sequence repetitions.

3. Continuous Theta-burst TMS (cTBS)

TMS was delivered using a 70-mm diameter figure-eight coil (Rapid^2 stimulator; Magstim, Whitland, UK). The control site was located 2 cm posterior to the vertex while the DLPFC was localized using the BeamF3 algorithm (Beam, Borckardt, Reeves, & George, 2009; Mir-Moghtadaei et al., 2015). For each participant, the left motor cortex was identified as the spot eliciting reliable twitches in the resting contralateral hand. The active motor threshold (aMT) was defined as the lowest intensity at which TMS elicited at least five out of ten visible muscle twitches, whilst the subject sustained a light contraction of their pinch (index finger and thumb). There were no significant differences in aMT between groups (i.e. DLPFC group, M = 57.5%, SD = 8.2; Control group, M = 57.0%, SD = 6.5; $F < 1$). The intensity of the stimulation was set at 80% of the aMT. The coil was placed tangentially to the scalp with the handle pointing posterior at a 45° angle with respect to the anterior-posterior axis for DLPFC and at 0° for the control site. A modified cTBS protocol was used in which 600 pulses were delivered in a continuous train of 200 bursts. Each burst consisted of 3 pulses at 30 Hz, repeated at 6Hz. This modified cTBS protocol has been shown to inhibit cortical excitability lasting at least 30 minutes after stimulation over the primary motor cortex (Goldsworthy et al, 2012).

4. Tasks

4.1 The Hebb repetition task

The Hebb repetition task was composed of 48 trials. During each trial, ten consonant-vowel (CV) syllables were presented to the participants for immediate serial recall. Participants were, in total, exposed to three different types of trials: the filler sequence (24 trials), the Hebb sequence with CV syllables overlapping with the filler sequence (12 trials) and the Hebb sequence with CV syllables non-overlapping with the filler sequence (12 trials). Two pools of 20 unique CV's were created (Table 1). Half of the participants in each group were exposed to the two first CV pool while the other half was exposed to the second CV pool. From each pool, two sequences of 10 serially ordered CV's were created to represent the two Hebb sequences (Table 1), and matched for summed bigram frequencies (as

measured within the speaker's native language; Duyck et al., 2004) (i.e., all *p*s > .05). The filler sequences were composed of the same CV's as one of the two sequences but in a random order. This order changed every trial.

Table 1. The sequences that were presented during the Hebb learning task

	CV1	CV2	CV3	CV4	CV5	CV6	CV7	CV8	CV9	CV10
Pool 1	SE	FU	BE	DI	ZA	RU	GU	MI	TU	VY
	MA	PO	FE	BY	HY	SA	FI	TA	RE	JI
Pool 2	HY	RU	FE	FU	ZA	SA	RE	MA	FI	MO
	TU	DI	ME	JI	VI	RI	SE	PO	GU	VY

A trial consisted of the successive presentation of the ten CV syllables both in their auditory and written forms for 500 ms each with an inter-stimulus interval of 388 ms. All syllables were recorded by a female native British-speaker. They were presented auditory at 60 dB using Sennheizer HD201 headphones and appeared visually using Courrier New letter type with point size 24. Immediately after presentation of the ten syllables, a recall screen was presented on the screen with all ten syllables randomly organized in a circle around a central question mark. The participants were asked to click the syllables using the mouse in the order the syllables were presented. To maximize free recall of the sequences, participants did not receive feedback about their performance. Prior to cTBS, participants were familiarized with the task by performing two filler sequences trials (that were derived from the other pool). After cTBS, the task continued with a filler sequence, one of the two Hebb sequences, another filler sequence and the other Hebb sequence. Hence, the two Hebb sequences, the one overlapping and the one not overlapping with the filler sequences, were mixed within the same task and were repeated every fourth trial. The order of the type of Hebb sequence (overlapping first or non-overlapping first) within the task was counterbalanced across participants. In total, the Hebb repetition learning task lasted for ~20 minutes. This kind of design, mixing overlapping and non-overlapping sequences, does not affect the occurrence of a HRE (De Visscher, Szmalec, Van Der Linden, & Noël, 2015; Smalle et al., 2015).

4.2 Digit span

The digit span task is a measure of phonological storage capacity in working memory (Isaacs & Vargha-Khadem, 1989). In this task, participants listen to an experimenter reading sequences of digits of increasing length and repeat them forward or backward. First the forward digit span was administered followed by the backward one. Starting with two-item sequences, a maximum of two trials was presented at each length. If one of the two trials at a particular sequence length was correctly repeated, the sequence length increased by one. The task stops when the participant fails to repeat two sequences of the same length. The digit span refers to the maximum length that the participant can repeat successfully. The forward and backward digit spans were summed to obtain one global score for the digit span task.

4.3 Winsconsin Card Sorting Task (WCST)

WCST is one of the most well-known measures of EF, assessing cognitive flexibility and inhibitory control in working memory (Berg, 1948; Grant & Berg, 1948). In this task, participants are required to derive a correct card-sorting rule (e.g., cards are sorted as a function of color similarity) based on a trial-by-trial feedback. As the rule changes without announcement (e.g. the cards are sorted as a function of shape similarity), the participant has to detect the novel rule and modify the previously learned response strategy based on the feedback he receives from the experimenter. The key measure is the number of perseveration errors that is counted when the participant persists in using the old rule despite negative feedback. The lower the number of perseveration counts, the better the EF performance. The test was run using the online software package PsyToolKit (G. Stoet, 2010; Gijsbert Stoet, 2017).

4.4 Semantic Fluency Task

The semantic fluency task is another widely used task to measure EF evaluating lexical-access ability from declarative memory (Shao, Janse, Visser, & Meyer, 2014). In this task, participants are instructed to produce as many words belonging to the same category (i.e. animals) as possible in 60sec, without repetitions, synonyms, or altered forms of the same word (Lezak, Howieson, Bigler, & Tranel, 2012). Higher scores (i.e. more words) reflect better EF.

4.5 Post-learning awareness

At the end of the experiment, a pencil-and-paper awareness report concerning explicit knowledge about the repeating contents of the Hebb task was administered. This questionnaire included two questions in the following order (based on Gagnon et al., 2005; Ramsøy & Overgaard, 2004): "*Did you notice that*

there were two sequences in which the same order was repeated every fourth trial?"; and "*Did you also notice that one of the two sequences that were repeated every fourth trial contained the same syllables as the other nonrepeating sequences?"* On each question, the participant rated his/her awareness with the following four-point scale: 1) No experience: I had no impression during the whole duration of the task; 2) Weak experience: I had a feeling that "something" was occurring, but I would not have been able to specify myself what is was.; 3) Almost clear experience: I sometimes had the impression but I was not always sure. Now- because you say so – I am sure there is.; 4) Clear experience: I already had this impression clearly during the course of the task, no doubt. The use of verbal reports after learning is a common procedure and a relatively sensitive measure for demarcating task awareness in humans (Cleeremans et al., 1998; Sandberg et al., 2010).

5. Statistical Analysis

The Hebb learning performance was scored using McKelvie's method (1987) implemented into a script running in Python (2.6+). This scoring method takes into account both the position and the serial order of correctly recalled items. In a first step, the number of syllables that are in the correct position from left to right is counted up to the first error. Secondly, the same step is repeated from right to left up to the first error. After this, the number of items in any correct sequence of two or more items between the first error from the left and the first error from the right is counted. Finally, any other items that occur in the correct absolute position from left to right are counted. The maximum possible score using this method is ten (the entire length of the sequence). Recall scores for the filler sequences were averaged across two consecutive filler trials to obtain an equal number of filler and Hebb scores. All correct trial scores were subsequently transformed into percentage scores (Figure 1 upper panel) and organized into three blocks of 4 trials for analysis (Figure 1 lower panel).

Statistical analyses were performed with the SPSS Statistics software package (IBM, Armonk NY, USA). An arcsine square root transformation was completed on the percent scores in order to reduce skew and make the distribution appropriate for statistical analyses (Archibald & Joanisse, 2013; Smalle et al., 2015). In order to test whether TMS-induced disruption affected Hebb learning, we analyzed the transformed trial scores using a mixed design ANOVA with Sequence Type (3: overlapping Hebb, non-overlapping Hebb vs. Filler) and Block (3) as within-subject factors and with TMS Group (2: DLPFC vs. Control) as between-subject factor. In order to interpret significant interactions, we run separate ANOVAs for each sequence type. Planned comparisons were conducted using Fisher's LSD tests.

In order to further investigate the relationship between EF and Hebb learning, we calculated a composite score for EF by transforming measures of fluency task and WCST into positive z-scores and summing them for each participant as in Nemeth et al (2013). We then tested whether these composite scores for EF correlated with Hebb learning scores (calculated as the difference between the Hebb and Filler scores in the last block of trials). Awareness scores from the post-awareness questionnaire were also compared between groups using non-parametric Wilcoxon tests. All significant results ($p<0.05$) are reported together with the η^2_p effect size and Greenhouse Geisser (GG) ε correction factors, where applicable.

Results

1. DLPFC disruption specifically enhances the learning of non-overlapping sequences

The immediate-recall performance for the non-overlapping and overlapping Hebb sequences and the filler sequences is presented in Figure 4.1. The accuracy of the recall increased across three blocks for non-overlapping (main effect of Block: $F_{2,52} > 41.2$, $P<0.001$, $n_p^2 > 0.77$) and overlapping (main effect of Block: $F_{2,52} > 20.9$, $P<0.001$, $n_p^2 > 0.63$) Hebb sequences but not for the Filler sequences (no significant effect of Block, Sequence Type × Block interaction: $F_{4,104} > 19.8$, $P<0.001$, $n_p^2 > 0.43$). These improvements in performance show that participants were able to learn both overlapping and non-overlapping Hebb sequences. However, the improvement in performance was greater for non-overlapping sequences than for overlapping sequences ($F_{1,26} > 14.41$, $P<0.001$, $n_p^2 > 0.36$). TMS-induced disruption of DLPFC modulated learning (significant Sequence Type x Block x TMS Group interaction: $F_{4,104} > 2.88$, $P < 0.05$, $n_p^2 > 0.10$). More specifically, performance for the non-overlapping sequence was enhanced in the DLPFC group compared with the control group at the last block of trials (main effect of TMS Group for the non-overlapping Hebb sequence, $F_{1,26} > 6.5$, $P<0.05$, $n_p^2 > 0.20$; Block x TMS interaction: $F_{2,52} > 4.7$, $P<0.05$, $n_p^2 > 0.15$). No differences between groups were found for the overlapping Hebb sequence or for the filler sequence. These findings support our hypothesis that the DLPFC interferes with Hebb learning.

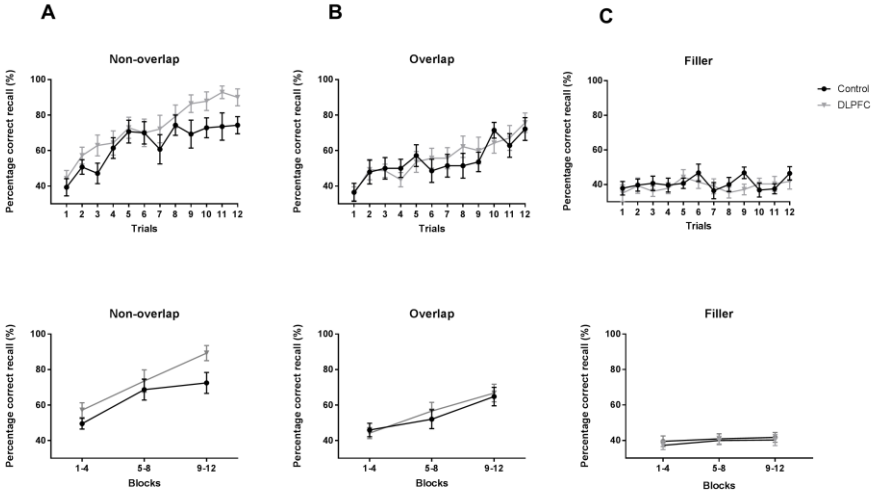

Figure 4.1. The effect of TMS-induced disruption of DLPFC on Hebb learning. Sequence learning across trials (upper panel) or block of trials (lower panel) is plotted for (A) the non-overlapping Hebb trials, (B) the overlapping Hebb trials, and (C) the filler trials, after repetitive TMS over the left DLPFC and control site. Percentage correct recall of the non-overlapping Hebb sequence was higher in the DLPFC-disrupted group than in the control group during the last block of trials. Error bars represent the standard error of the mean.

2. Correlations between Hebb learning EF

To further explore the relationship between Hebb learning and EF, we ran correlational analyses for the control and DLPFC-disrupted group separately. There were no significant differences between these groups in EF that were measured in a separate follow-up session (DLPFC group, M_{EF}= -.001, SD = 1.5; Control group, M_{EF} = .002, SD = 1.2; $F < 1$).

The Hebb learning score for the non-overlapping sequences showed a significant negative correlation with EF in the control group ($r_{(14)}$ = -.601, P = .023, Figure 4.2A), but no significant correlation in the DLPFC-disrupted group ($r_{(14)}$ = -.149, P = .612, Figure 4.2A). In addition, we ran further correlation analyses controlling for phonological working memory (measured by the digit span task; similar to Virag et al., 2015) and found a negative correlation between Hebb learning and EF in the control group ($r_{(11)}$ = -.613, P = .026), but not in the DLPFC-disrupted group ($r_{(11)}$ = -.174, P = .570). Moreover, the correlation was significantly stronger in the control group than in the DLPFC group (Z = 1.68, P = .05, one-tailed). These results give further support for our hypothesis that EF interfere with Hebb-learning.

The correlations between Hebb learning scores for overlapping sequences and EF were non-significant in both groups (DLPFC: $r_{(11)}$ = .088, *P* = .776; Control: $r_{(11)}$ = -.513, *P* = .073; controlled for phonological working memory, Figure 4.2B). The close to significant trend in the control group was caused by one participant, who had a large HRE for overlapping sequences (correlation without this outlier: $r_{(10)}$ = -.151, *P* = .640).

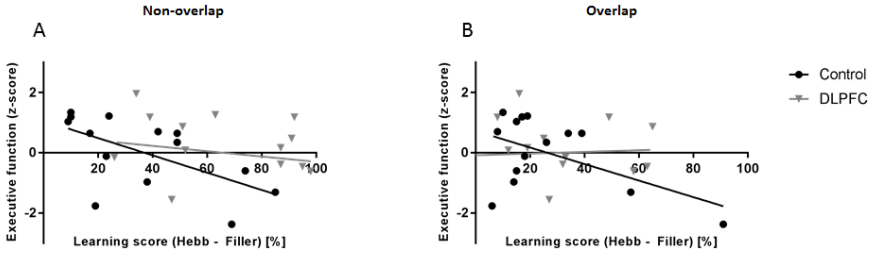

Figure 4.2. Relationship between Hebb learning and EF. HRE for non-overlapping sequences (A) and overlapping sequences (B), and an index of EF is plotted for each participant. **A.** HRE for non-overlapping sequences correlated significantly with EFs in the control group (black circles), but not in the DLPFC-disrupted group (grey triangles). **B.** HRE for overlapping sequences did not correlate with EF in either group.

3. Post-learning awareness

Participants gained a moderate awareness for the repetitive occurrence of the two Hebb sequences (question 1, DLPFC, *M*rating = 3.2, SD = .80; control, *M*rating = 3.4, SD = .74) and a weak awareness for the overlapping nature between one of the Hebb sequences and the filler sequences (question 2: DLPFC, *M*rating = 2.2, SD = .89; control, *M*rating = 2.2, SD = .70). There was no difference in awareness between the two groups (question 1, *Z* = -.481, *P* = .630; question 2, *Z* = -.099, *P* = .921) suggesting that the increased learning performance for the non-overlapping Hebb sequence of the DLPFC group is not due to a difference in awareness of the sequence repetition.

Discussion

We addressed the hypothesis that in the adult brain the EF compete with procedural learning mechanisms that are important for language learning, explaining the inferior language learning skills relative to children. We used TMS to examine whether inhibition of the left DLPFC – the brain area that supports EF - would improve the implicit sequence learning that underlies word-form learning in adults. We found that the group with disrupted DLPFC showed improved Hebb repetition learning compared to the control group, but only for sequences that did not overlap with the filler sequences. This supports our hypothesis that in the adult brain frontal-lobe dependent processes compete with procedural learning processes that are important for word learning. Moreover, we found a negative relationship between Hebb learning and EF in control participants – such that participants with higher EF scores showed reduced Hebb repetition learning for the non-overlapping Hebb sequences compared to participants with lower EF scores.

Overall, our findings are in line with previous motor learning studies demonstrating that reducing the reliance on EF that support declarative memory improves procedural learning (Galea et al., 2010; Nemeth, Janacsek, Polner, et al., 2013; Virag et al., 2015). For example, Galea and colleagues found that disrupting the DLPFC using TMS enhanced performance in the serial reaction times task, which is a well-known motor sequence learning task (Galea et al., 2010). The current study tested, for the first time, interactions between EF and procedural memory, using the Hebb repetition paradigm that links procedural sequence learning to word learning. Procedural memory is thought to be important for certain aspects of language learning, such as grammar and word-forms, while other more idiosyncratic aspects, such as associating semantics with phonology, rely more on an explicit declarative memory system. In a recent study, Finn and colleagues demonstrated that adults' cognitive functions that involve attention and effort interact with specific language-learning processes (Finn et al., 2014). For instance, directing effort or attentional control toward the phonological input benefits word-segmentation but disrupts learning phonological categories of a novel word-form structure. The authors argued that competition from cognitive EF abilities, such as effort or the allocation of attention that support a late-developing declarative memory system, can explain why adults have difficulties in some but not all aspects of language learning compared to children, especially in the aspects that are related to procedural memory. In a previous Hebb learning study, we showed that children outperform adults in learning phonological sequences that resemble novel word-forms (Smalle et al., 2015). Moreover, when adults were forced to attend to the small parts of the sequence instead of the entire sequence as a whole, thereby simulating children's limited working memory capacity, Hebb learning performance

for the non-overlapping sequences increased to the same level as in children. The findings of the current TMS study extend these behavioral findings by providing direct evidence for the disruptive role of the DLPFC, the brain region related to the conscious executive processes in working memory and assumed to develop late across childhood, during Hebb learning in adults. Together with earlier studies on motor learning, the current results support the idea that different memory systems compete during automatic skill learning (Brown & Robertson, 2007; Janacsek & Nemeth, 2015; Robertson, 2012).

The HRE was smaller for the overlapping sequences than for the non-overlapping sequences, and TMS-induced disruption of the DLPFC modulated Hebb learning performance for the non-overlapping sequences, but not for the overlapping sequences. The overlap with the filler sequences therefore seems to counteract the sequential learning processes that underlie Hebb repetition learning. In an fMRI study, Kalm and colleagues showed that activity in the medial-temporal lobe is correlated with learning overlapping sequences in a Hebb repetition paradigm (Kalm, Davis, & Norris, 2013). Although no comparison was done with non-overlapping sequences, this may suggest that item-overlap potentially recruits different, declarative-based memory resources, or more attentional control, to deal with the proactive interference between sequences. It could explain why lesioning the DLPFC did not yield the same beneficial effect on overlapping sequences as it did on non-overlapping sequences. Further research is needed to explore what role memory and other cognitive processes play in word-form learning, and how this is modulated by item-overlap or interference between sequences.

Correlation analyses showed that performance in the EF tasks, i.e. the Winsconsin Card Sorting Task and the Semantic Fluency Task, was negatively correlated with learning the non-overlapping Hebb sequences in the control group only. This supports our hypothesis that EF interfere with sequential processes related to word-form learning. The lack of a significant correlation in the DLPFC-disrupted group may have been caused by a ceiling effect due to Hebb learning scores that are close to 100% in the final block of trials in this group. Although the negative correlation between EF and sequence learning in the control participants is in line with a number of previous studies (e.g., Virag et al., 2015), it is not a consistent finding (Janacsek & Nemeth, 2013; Martini et al., 2015). Some studies found no relationship between executive functions (or related working memory processes) and sequence learning (e.g., Fletcher et al., 2005) and others even found a positive (supporting) relationship (Pascual-Leone et al., 1996). Working memory is a complex construct that is composed of several components (i.e., domain-specific stores and an executive control system) that are operationalized by different tasks (e.g., span tasks vs. change detection tasks) (Baddeley et al., 1996). The use of different tasks could have lead towards inconsistent outcomes in previous studies (Martini et al., 2015). In a Hebb-learning task, participants must retain a sequence of

syllables in short-term memory for immediate serial recall, suggesting a supportive role of working memory processes in sequence learning. This does not suggest, however, that all working memory processes, such as EF, support implicit learning. More research is needed to understand the complex relationship between working memory and implicit sequence learning across development (Janacsek & Nemeth, 2013).

Conclusion

In summary, the present study demonstrated that TMS-induced disruption of the left DLPFC improves phonological sequence learning in young adults. This is in line with earlier studies, which found a similar beneficial effect of suppressed frontal lobe functions, in particular executive control resources, on motor sequence learning (Galea et al., 2010; Nemeth, Janacsek, Polner, et al., 2013; Virag et al., 2015). The current findings build on developmental studies with the Hebb paradigm, showing that adults do not learn Hebb sequences as easily as children do (Smalle et al., 2015). Procedural memory maturates early in development and is an important system for skill acquisition and language learning (Krishnan et al., 2016). In contrast, EF that rely on frontal lobes, and are related to declarative memory, mature late in development (Craik & Bialystok, 2006). Our findings support the hypothesis that a mature DLPFC interferes with procedural memory, and that this could potentially explain differences between adults and children in learning some aspects of language. The findings suggest that competing cognitive (e.g., EF) and procedural memory systems offer a domain-general mechanism for understanding maturational sensitivities in various skills (including language) that we acquire across life.

Acknowledgment

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Appendix

The post-awareness questionnaire included two questions in the following order (based on Gagnon et al., 2005; Ramsøy & Overgaard, 2004):

1. *Did you notice that there were two sequences in which the same order was repeated every fourth trial*?
2. *Did you also notice that one of the two sequences that were repeated every fourth trial contained the same syllables as the other nonrepeating sequences?*

The participant rated his awareness on both questions with the following four-point scale:

1. ***No experience****: I had no impression during the whole duration of the task;*
2. ***Weak experience****: I had a feeling that "something" was occurring, but I would not have been able to specify myself what is was."*;
3. ***Almost clear experience****: I sometimes had the impression but I was not always sure. Now- because you say so – I am sure there is.*
4. ***A clear experience****: I already had this impression clearly during the course of the task. No doubt.*

CHAPTER 5

THE DIFFERENT TIME COURSE OF PHONOTACTIC CONSTRAINT LEARNING IN CHILDREN AND ADULTS

EVIDENCE FROM SPEECH ERRORS

Speech errors typically respect the speaker's implicit knowledge of language-wide phonotactics (e.g., /ŋ/ cannot be a syllable onset in the English language). Previous work demonstrated that adults can learn novel experimentally-induced phonotactic constraints by producing syllable strings in which the allowable position of a phoneme depends on another phoneme within the sequence (e.g., /t/ can only be an onset if the medial vowel is /i/), but not earlier than the second day of training. Thus far, no work has been done with children. In the current 4-day experiment, a group of Dutch-speaking adults and nine-year-old children were asked to rapidly recite sequences of novel word-forms (e.g., kieng nief siet hiem) that were consistent with phonotactics of the spoken Dutch language. Within the procedure of the experiment, some consonants (i.e., /t/ and /k/) were restricted to onset or coda position depending on the medial vowel (i.e., /i/ or "ie" versus /ø:/ or "eu"). Speech errors in adults revealed a learning effect for the novel constraints on the second day of learning, consistent with earlier findings. A post-hoc analysis at trial-level showed that learning was statistically reliable after an exposure of 120 sequence-trials (including a consolidation period). Children, however, started learning the constraints already on the first day. More precisely, the effect appeared significantly after an exposure of 24 sequences. These findings indicate that children are rapid implicit learners of novel phonotactics, which bears important implications for theorizing about developmental sensitivities in language learning.

Reference

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Introduction

Phonotactics refer to the constraints for allowed sound sequences in a language. For example, an English speaker easily accepts that "ming" is a possible English word, but that "ngim" is not. This is because the sound /ŋ/ always occurs at a coda position (e.g., as in "king" or "sing") and never at onset in English words, although other languages may allow this (e.g., as in the word "nghiệp", which is Vietnamese for "industry"). Sensitivity to phonotactic constraints in one's native language starts very early in life (Jusczyk et al., 1993). Evidence for this also comes from the statistical-learning literature in which infants not older than 8 months are already able to track the distributional probabilities of syllables within and across word boundaries (Saffran et al., 1996). The ability to acquire phonotactic patterns in a language, as is demonstrated in artificial language paradigms, continues in adulthood (e.g., Onishi, Chambers, & Fisher, 2002). This is an important skill for learning second languages that sometimes contain phonotactics that deviate from the native language system.

A series of experiments provided evidence for adults' ability to pick up novel phonotactics by looking at their speech errors (Dell, Reed, Adams, & Meyer, 2000; Warker, 2013; Warker & Dell, 2006, 2015; Warker, Dell, Whalen, & Gereg, 2008). Speech conforms to the phonotactic constraints of a language and therefore these constraints are rarely violated when speech errors are made (Fromkin, 1971). For example, it is extremely unlikely that a native English speaker will spontaneously slip the phoneme combination /ŋ/ to an onset position as in "ngik" when intending to say "king" because an initial /ŋ/ violates English phonotactics (Dell et al., 2000). The sensitivity of slips to the sound distributions in one's language changes with experience. In 2000, Dell and colleagues introduced the novel phonotactic constraint paradigm as an experimental analogue of this phenomenon. They argued that speech errors can be used as a promising tool to implicitly measure the acquisition of new arbitrary phonotactic constraints after limited exposure. In this paradigm, English native participants are exposed to written sequences of consonant-vowel-consonant (CVC) syllables that form novel word-forms (e.g., *hes meg fen keng*), which they are asked to recite. Some consonants are restricted in the native language and are therefore *language-wide* restrictions (e.g., /h/ can only be onset and /ŋ/ can only be coda) while other consonants are *unrestricted* according to the English language (e.g., /k/, /m/, /n/ and /g/ can appear both as onset and as coda). Crucially, there are also two consonants that, although they are unrestricted in English, appear restricted within the setting of the experiment. For example, for some participants, the consonant /f/ always appears

as onset in the experiment and the consonant /s/ always appears as a coda, while the inverse is true for other participants. These are called the *experiment-wide* constraints. Across four days, participants are asked to repeat each sequence of four CVC word-forms three times at a fast tempo applied to elicit speech errors. Consonants that erroneously move to another syllable position (i.e., from onset to coda or from coda to onset) are counted and labeled as "other-position" errors. Consonants that erroneously move but thereby do not change syllable position (i.e., from onset to another onset or from coda to another coda) are also counted and labeled as "same-position" (or legal) errors. The erroneous consonant movements are coded according to the constraint type, i.e., language-wide, experiment-wide or unrestricted. Errors involving the language-wide consonants should be 100% legal, which means that the consonants will never slip to the opposite syllable position. This is also better known as the phonotactic regularity effect (Fromkin, 1971).

The key aspect of the paradigm concerns the contrast between errors involving the experiment-wide constraints and those involving the unrestricted consonants (see, for instance, Dell et al., 2000). For the unrestricted consonants, the percentage of errors that are "same-position" provides a baseline measure of the extent to which a participant's speech errors preserve their syllable position within a trial. This is also called the syllable-position effect (Dell et al., 2000; Fromkin, 1971; Warker et al., 2008). For experiment-wide consonants, the key question is whether the percentage of errors that is legal (i.e., same-position movements) *rises significantly above* this unrestricted baseline rate. This would be evidence that new phonotactic constraints have been acquired and significantly influence production (errors) in the longer term. In other words, the difference between experiment-wide and unrestricted same-position percentages is described as the phonotactic learnings score (with positive values suggesting that phonotactic learning has taken place). It thus reflects implicit learning of the novel experiment-induced constraint that cannot solely be explained by correctly labeling the syllable positions within the recited sequence (i.e., the syllable-position effect).

Using this paradigm, Dell and colleagues (2000) observed that adult speech errors for the experiment-wide (restricted) consonants obeyed their position almost 100% of the time, close to what one observes for errors involving language-wide constraints (that never violate their constrained positions), while only between 65 to 80% of the errors involving unrestricted consonants were of same-position. When the position of the consonants did not depend on other phonemes within the syllable sequence (i.e., the constraints were simple or of first-order; e.g., */s/ occurs as onset or /s/ occurs as coda*), learning occurred already from the first day, suggesting that adults learned these simple constraints very quickly (see also, Goldrick, 2004; Taylor & Houghton, 2005). However, when the novel constraints were more complex by making the consonant's position dependent on the type of other phonemes within the sequence (e.g., *the consonant /f/ always appears as an onset if*

the medial vowel is /a/, but as a coda if the medial vowel is /e/), learning was slower and less robust than with the first-order constraints. Later, this finding was replicated in subsequent work by Warker and colleagues (Warker & Dell, 2006; Warker et al., 2008). These authors demonstrated that adult speakers were in fact able to learn new second-order constraints, but not until the second day of learning. More precisely, the effect occurred after an exposure of 144 sequences, and the effect was most substantial after an offline consolidation period involving sleep (see also, Gaskell et al., 2014; Warker, 2013). The dissociation in time course with first-order constraints is explained within a self-interfering principle (for computational evidence, Warker & Dell, 2006; Warker et al., 2008): due to dependence on the characteristics of other phonemes within the sequence, similar inputs do not always lead to similar outputs. As an example, the consonant /f/ is sometimes associated with a /f/-onset output and sometimes with a /f/-coda output depending on the medial vowel. This results in interference that does not occur in first-order constraints (in which /f/ is always associated with a /f/-onset output or a /f/-coda output). As a result, more exposure, and a consolidation period with sleep is needed to overcome interference and learn the contextual associations between syllable structures and phoneme position.

In some interesting developmental work, Janacsek and colleagues tested nine different age cohorts from age 4 to age 84 on the ability to implicitly learn sequential regularities (Janacsek et al., 2012). She showed superior performance for children that were between seven and twelve years of age. Phonotactic constraint learning is an important aspect of novel word(-form) learning that relies on implicit sequential learning abilities (Gupta & Tisdale, 2009b; Ullman, 2004). Word-learning is an activity that does not end and even accelerate at school age (Altman, 1997; Pinker, 1994). In light of the ongoing debate about age-sensitivities in different aspects of language-learning (Kennedy & Norman, 2005; Newport et al., 2001; Werker & Hensch, 2015), it is important to investigate children on the ability to rapidly acquire novel phonotactics.

There has been some relevant work within the comprehension domain showing that young infants are able to learn (and generalize) novel second-order phonotactic constraints quickly after a short auditory exposure to a small set of input exemplars (e.g., Chambers, Onishi, & Fisher, 2003; Gerken & Knight, 2015). However, experiments testing children's ability to learn novel phonotactics through speech production are entirely missing. In the current study, we were interested in investigating children's ability to rapidly pick up novel phonotactic constraints by looking at their speech errors. With this aim, and with respect to Janacsek's developmental findings on implicit learning skills, we tested a group of nine-year-old children on Dell's phonotactic constraint paradigm. The main focus of the study concerned the time course of the phonotactic learning patterns in the speech error data of the children. A group of Dutch-speaking adults was also tested to see whether the (slowly developing) speech error patterns for second-order constraints

found in previous studies could be replicated in a group of Dutch speaking adults. All participants returned to the lab on four consecutive days for production of sequences of CVC syllables that were constrained with language-wide, experiment-wide and unrestricted consonants. Similar to previous work, half of the participants were informed about the constraints and half were told nothing about the crucial manipulations. This was done to investigate whether phonotactic learning indeed develops under incidental learning conditions, which would indicate that it is not dependent on explicit information and therefore on implicit statistical learning (Warker & Dell, 2006).

Methods

1. Participants

Twelve young adults between 18 and 25 years old (M = 21.42, SD = 2.27; 2 males), and twelve 9-to 10-year-old children (M = 9.74, SD = .37; 5 males) participated in the study. The children were recruited from three different schools. Adults were recruited by advertising. Testing took place individually in a testing room at Ghent University for the adults and in a secluded classroom at school for the children. All participants were native Dutch speakers and none of them suffered from any developmental or neurological disorder. Half of the participants were assigned to the informed condition and were briefed about the experiment-wide constraints in the task. The other half of the adults remained uninformed. Participants in the informed and uninformed groups were matched for (age-adjusted) percentile scores on the Raven's Progressive Matrices (Raven, Raven, & Court, 2000) and for performance on the Digit Span subtest of the WISC-III-NL (Kort et al., 2005). Percentile scores on the Raven's Progressive Matrices were comparable between children and adults. This was done to assure that the groups were comparable for general cognitive abilities. All adults completed informed consent and received financial compensation for their time at the end of the experiment. Parental consent was obtained for the children and they were compensated with sweets.

2. Materials

Each participant received a set of 96 sequences on each day. Each sequence contained four novel word-forms of the structure CVC (e.g., *kieng nief siet hiem*). In total, eight different consonants (i.e., /k/, /ŋ /, /n/, /f/, /s/, /t/, /h/ and /m/) were used. Each consonant appeared once per sequence. These consonants belonged to three different constraint groups: language-wide (/h/, /ŋ/), experiment-wide (/t/, /k/), and unrestricted (/m/, /n/, /f/, /s/). The vowels were either /i/ (as in the English word

"deep" or the Dutch word "fiets") or /øː/ (as in the Dutch word "deur")[8], and this alternated between sequence-trials. This means that half of the trials contained sequences with solely /i/-vowels and half with solely /øː/-vowels. All sequences were constructed so that in each sequence /h/ was always an onset and /ŋ/ was always a coda in accordance to Dutch phonotactics. The consonants in the unrestricted groups appeared both as coda and as onset throughout the experiment (also in accordance to Dutch phonotactics). The consonants appeared equally often at both positions across the entire experiment. The positions of the consonants in the experiment-wide groups are unrestricted in the Dutch language but appeared restricted within the setting of the experiment. Half of the participants experienced the experiment-wide constraint */t/ is an onset and /k/ is a coda if the vowel is /i/; /k/ is an onset and /t/ is coda if the vowel is /øː/.* We call this the "tiek-keut" restriction. The other half of the participants experienced the reverse constraint. We call this the "kiet-teuk" restriction.

Four lists of 96 sequences were randomly generated for each participant by use of a computer program. Letter combinations that resulted in existing words were avoided. The sequences were printed in 80-point bold Courier New and white font on a black background. The sequence appeared in one line and remained on the screen until reciting was finished, after which a new sequence line was presented. Because the main focus of the study was to test children, the sequences were also presented auditorily in support of reading ability. Each CVC syllable (or word-form) was recorded separately by a male voice and noise-cancelled. During sequence presentation, the syllables were presented at 60dB using headphones (Sennheiser PC 131) at a rate of one syllable per second.

3. Procedure

Half of the participants were first informed about the experiment-wide constraints. This was done step-by step using a Powerpoint presentation. Each experiment-wide constraint was accompanied by two examples, one that followed and one that violated the constraint. The children and adults in the uninformed condition were not informed about the constraints. After task instructions, all participants were presented with four practice sequences to familiarize themselves with the task. Participants first heard the sequence once (together with the visual presentation on the screen), and were then asked to recite the sequences in time with a metronome. They first recited the sequence slowly at a rate of one syllable per second (in time with the metronome) and subsequently repeated this sequence three times without pause at a faster rate of 2.53 syllables per second (in time with the

[8] We avoided the vowels /ae/ and /I/ that were used in Dell et al. (2000) and in Warker and Dell (2006) as these vowels resulted in too many existing words in the Dutch language during sequence generation.

metronome). The sequence remained on the screen until reciting was finished. In total, one set of 96 sequences was completed per day. Each session was digitally recorded using a head-mounted microphone and a computer-built recorder.

Results

Before analysis, speech errors were transcribed from the digital recordings. Consonants that moved position in a particular sequence were either coded as same-position or other-position, depending on the position they moved to. For the experiment-wide consonants, this was coded with respect to the medial vowel within the sequence-trial and the restriction that the participant was experiencing (i.e. "tiek-keut" or "kiet-teuk"). For example, if the target sequence is *kieng nief siet hiem* and a participant (who is experiencing the "kiet-teuk" restriction) recited this sequence as ***h****ieng* ***t****ief* ***n****ie****s*** ***k****iem*; five errors would be coded (in bold): One same-position error for the language-wide constraint (i.e., /h/ switched from onset to another onset), one other-position error for the experiment-wide constraint (i.e., /t/ switched from coda to onset), one same-position error for the unrestricted constraint (i.e., /n/ switched from one onset to another onset), one other-position error for the unrestricted constraint (i.e., /s/ switched from onset to coda), and one same-position error for the experiment-wide constraint (i.e., /k/ switched from onset to another onset). For cutoff errors (e.g., *s…keut*), only the first uttered consonant was coded. Substitutions (i.e., consonants that were replaced by other new consonants) and omissions or indistinguishable phonemes were not included for analysis. A second coder who was blind to the manipulations and the aim of the study transcribed 12 sessions (randomly distributed across group and training day) in order to test for inter-rater reliability. Overall, coding reliability was very good: For the 18 432 syllables that were doubly transcribed, both coders agreed there was no error on 17 760 syllables and on the presence and nature of 414 errors. The agreement was 98.6%. For those syllables in which the original coder found an error (512 errors), the conditionalized agreement rate was 75%. These values are comparable to previous studies (e.g., Warker et al., 2008). Therefore, the original coding of the first coder was not changed.

To measure the effect of novel phonotactic learning, the same analyses were used as in Dell (2000), Warker and Dell (2006) by using non-parametric Wilcoxon matched pair tests. We were specifically interested in the percentage of same-position slips for experiment-wide versus unrestricted consonants on each day/training session (see also, Warker and Dell, 2006). The percentage of same-position slips for the experiment-wide consonants should be significantly above that of the unrestricted consonants, if learning occurs.

1. Children

The language-wide constraints were never violated: children's errors containing /h/ and /ŋ/ were legal 100% of the time (SE = 0, based on a total of 926 errors). The raw number same-position and different-position errors on each day for both the experiment-wide and unrestricted consonants can be found in Table 1. On the first day, there was already evidence for learning (**Day 1**, Z = -2.98, p = .003 with only 1 of 12 participants having a mean difference in the unexpected direction)[9]. The effect was significant on all subsequent days (**Days 2-4**, Z = -3.06, p = .002; separately per day, **Day 2**, Z = -2.98, p = .003 with 1 participant in the wrong direction; **Day 3**, Z = -2.76, p = .006 with 1 participant in the unexpected direction; and **Day 4**, Z = -2.82, p = .005 with 2 participants in the wrong direction). Additionally, a Mann Whitney U test was performed to test for differences between the informed and uninformed children. Overall, the learning effect was not significantly different between groups (Z = -1.54, p = .12; nor for each day separately, ps > .05). Finally, the 96 sequences from day 1 were broken down into four sets of 24 sequence trials to more precisely determine when learning began to manifest itself in speech errors. Although there was no significant difference for the first 24 sequences (i.e., **1-24**, Z = -1.61, p = .11), the restricted constraints were picked up significantly in the subsequent sequences (i.e., **25-48**, Z = -2.16, p = .031; **49-72**, Z = -2.67, p = .008; **73-96,** Z = -3.06, p = .002). The pattern of speech errors during the first day is visualized in Figure 5.1.

Table 1. Number of consonant movements (i.e., same-position and different-position) obtained from the children.

	Experiment-wide			**Unrestricted**			
	same	**different**	**% same**	**same**	**different**	**% same**	**Learning (%)**
Day 1	314	39	89	456	260	64	25**
Day 2	250	8	97	367	127	74	23**
Day 3	269	21	93	417	216	66	27**
Day 4	260	8	97	314	188	63	34**

**p < .01

[9] On the first day, there were two empty data cells, one for the experiment-wide errors and one for the unrestricted errors because there was one child who did not make any errors involving the experiment-wide and unrestricted consonants. As in Warker (2013), these empty data cells were estimated for analyses using the mean for experiment-wide errors and unrestricted errors for that day respectively.

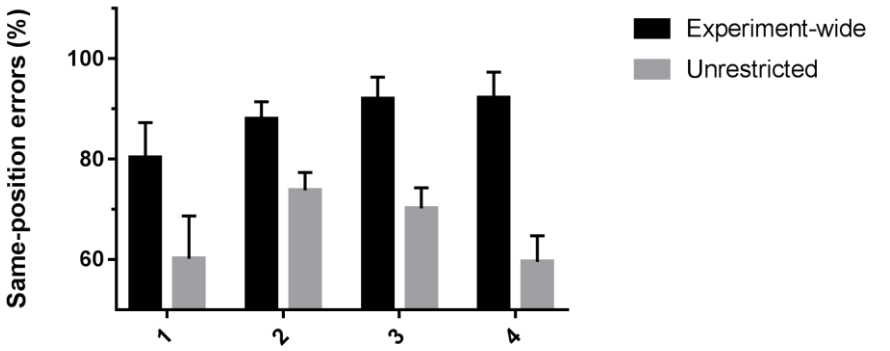

Figure 5.1. Mean legality (same-position) percentages and standard errors across the four sets of 24 trial sequences in **day 1** in the group of children.

2. Adults

The language-wide constraints were never violated: adult's errors containing /h/ and /ŋ/ were 100% legal (SE = 0, based on a total of 354 errors). The raw number of same-position and different-position errors that were made on each day, for both the experiment-wide and unrestricted consonants, are reported in Table 2. On the first day, there was no significant difference between experiment-wide and unrestricted errors (**Day 1**, Z = -.80, p = .42 with 4 of 12 participants having a mean difference in the unexpected direction). However, the difference emerged on the subsequent days (**Days 2-4**, Z = -2.3, p = .019; separately per day, **Day 2**, Z = -1.96, p = .05 with 2 participants in the unexpected direction; **Day 3**, Z = -.11, p = .92 with 3 participants in the wrong direction; **Day 4**, Z = -2.19, p = .028 with 1 participant in the wrong direction)[10]. Additionally, a Mann Whitney U-test was performed to test for differences between informed and uninformed adults. Overall, the learning effect was not significantly different between groups (i.e., across all days, Z = -.943, p = .35). In a further analysis, the second day for which the learning effect appeared (i.e., sequences 97 to 192) was broken down in four sets of 24 sequence trials to more precisely determine when learning began to manifest itself in speech errors during this session. The analysis revealed a learning effect that emerged significantly from the second quartile of sequence-trials: **97-120**, Z = -1.60, p = .11; **121-144**, Z = -2.67, p = .008; **145-168**, Z = -2.25, p = .024; **169-192** set, Z = -2.81, p

[10] On the fourth day, there were four empty data cells for the restricted errors and one empty data cell for the unrestricted errors because four participants did not make any errors involving the restricted (or unrestricted consonants). As in Warker (2013), all empty data cells were estimated for analyses using the mean for the restricted (or unrestricted) errors for the appropriate day.

= .005). The pattern of speech errors revealing learning during the second day and across other days is visualized in Figure 5.2.

Table 2. Number of consonant movements (i.e., same-position and different-position) obtained from the adults.

	Experiment-wide			**Unrestricted**			
	same	**different**	**% same**	**same**	**different**	**% same**	**Learning (%)**
Day 1	85	10	89	193	29	87	2
Day 2	55	2	96	149	18	89	7*
Day 3	50	3	94	116	12	91	3
Day 4	30	1	97	96	17	85	12*

*$p < .05$

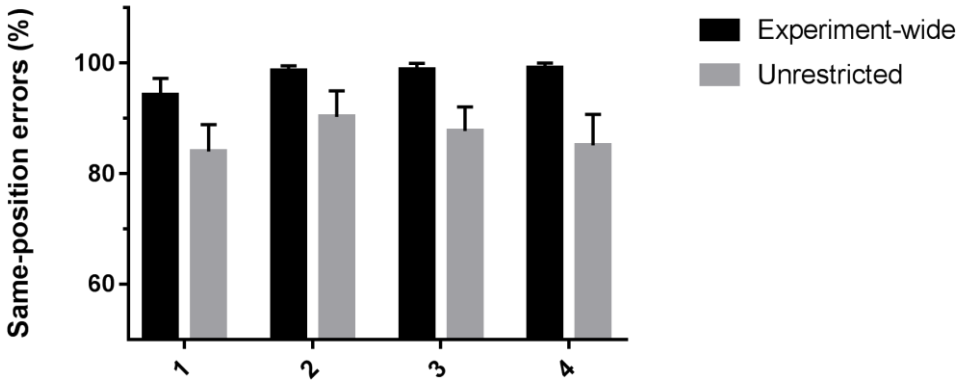

Figure 5.2. Mean legality percentages and standard errors across the four sets of 24 trial sequences in **day 2** in the group of adults.

3. Group Comparison

To further investigate child-adult differences for phonotactic constraint learning early in training, a hierarchical logistic regression model was fit to the speech-error data on Day 1, using the lme4 package in R (R Development Core Team, 2011). The dependent variable was Position, or whether phonemes move to the same or different position. There were two predictor variables or fixed effects, i.e., Restrictedness (experiment-wide vs. unrestricted) and Age Group (children vs. adults). Maximal inclusion of random slopes for the within-participants variables (i.e., 1 + Restrictedness| ppn) was strived for (Barr, Levy, Scheepers, & Tily, 2013). However, due to convergence issues, the random slope for Restrictedness was discarded from the model, and only a random intercept for subject was included. The p-values were calculated using Wald-z. The analysis revealed a significant two-way interaction between Restriction and Group (β=1.23, *SE*=.44, z = 2.79, p<.01), as well as an effect of Restriction (β=-1.50, *SE*=.19, z= -7.89, p<.001). Planned comparisons showed a significant phonotactic learning score for the children (β=-1.5, *SE*=.19, z=-7.89, p<.001) but not for the adults (β=-.027, *SE*=.40, z=-.69, p=.90). The same-position percentage for the unrestricted condition was higher for the adults than for the children (β = 1.37, *SE*=.31, z=4.3, p<.001).

General Discussion

The current study demonstrated that both children and adults were able to pick up complex (second-order) phoneme combination rules. Speech errors for the experimentally-constrained consonants violated their original syllable position less often than for the unrestricted consonants, indicating that children and adults acquired implicit knowledge of the experimentally restricted phonotactics through exposure, above and beyond what can be explained by a syllable-position effect. Importantly, the speech error data revealed a different time course for phonotactic learning in children than in adults, with children showing evidence for learning already on the first day. We elaborate on these findings below.

First, and this was the focus of the current study, nine-year old children learned a set of second-order phonotactic constraints by producing novel word-forms containing that constraint. Remarkably, and in contrast to what has been observed with adults in previous studies, learning revealed itself in speech errors already on the first day of learning. When the first day was broken down into four sets of 24 sequences, results showed that the learning effect appeared reliably after an exposure of 24 sequences. This indicates that children are rapid learners of novel phonotactics and do not need a large amount of sequence trials (including a

consolidation period involving sleep) as was found in adults (Warker, 2013; Warker et al., 2008).

Second, an additional group of Dutch-speaking adults were exposed to the same set of second-order phonotactic constraints. Similar to what has been found in previous studies with English speaking adults, but in contrast to what we observed with the children in the current study, the adults showed a learning effect that emerged only from the second day of training. When the second day was broken down into four sets of 24 sequences, results demonstrated a significant effect above the unrestricted constraints from the second quartile of trials. In other words, adults learned the same phonotactic constraints after much more exposure to 120 trials. One must immediately consider, however, that the same-position percentage for the unrestricted condition was surprisingly high in our group of adults, i.e., 87.4%. This is about 11% higher than in previous adult studies (Warker and Dell, 2006), and about 14% higher than what we observed in our children. The high syllable-position effect in adults could be explained by the fact that the to-be-recited sequences contain four non-words, for both the children and adult group. This means that adults are reciting sequences that are two to three items below their working memory span ($M_{\text{forward span}}$ = 6, SD = .81) while this is not true for children (who perform conform their working memory span, $M_{\text{forward span}}$ = 4.8, SD = .37). The bimodal (written and spoken) stimulus sequence presentation in the current study, in contrast to previous studies with adults where the sequences were presented in a written mode only, could have further strengthened the adult's advantage for sequence-specific position labeling within each trial.

As far as we know, no previous studies have investigated children's time course of speech errors in phonotactic constraint paradigm. In contrast with speed of learning, there has however been some work investigating the strength of learning across groups. In 2014, Samara and Caravolas compared school-aged children with adults when learning graphotactic constraints (Samara & Caravolas, 2014). In their study, 7 years old children and adults were exposed to written sequences of three letters (e.g.,"des") that contained consonants constrained to a particular position (first-order), or depending on the vowel (second-order). After exposure to 144 (short exposure) or 288 (long exposure) trials, and a short distraction task, participants were tested for legality judgment on a set of novel strings. Signal detection analyses showed that both children and adults were sensitive to the two types of constraints but strength of learning was higher in adults than in children. Interestingly however, when existing words were removed from the stimulus set, children performed as accurately as adults. Moreover, reaction times analysis showed that adults were not faster than children in responding to test items that contained the complex constraints. So even though the 7-years-old children have just begun to receive formal literacy instruction, they show comparable acquisition of the constraints as adults after a relatively short exposure of 144 trials. The current study was not

designed for directly comparing the strength of learning in children and adults as this needs a different approach that controls for baseline differences in the syllable-position effect. The current study was able to demonstrate that children have an early time course for learning novel phoneme combination rules through speech production and are able to implicitly pick up the rule already on the first day of training. However, because of the significant baseline differences for the unrestricted constraints, we need to be cautious in making strong conclusions about potential child-adult differences without additional research.

A third observation is that both children and adults appear to learn implicitly. Even though half of the participants were told of the imposed constraints beforehand, the extent of learning was similar between instruction groups. This illustrates that primarily an implicit learning mechanism underlies performance in the constraint paradigm in both groups, and that speech errors denote a reliable measure of implicitly acquired knowledge.

Conclusion

We conclude that the apparently early time course for learning novel experimentally-induced phonotactics in children provides some intriguing insights into child superiorities in some aspects of language learning. It is widely accepted that children, before they reach adolescence, are faster in picking up certain novel linguistic patterns than adults, in particular for phonology (Newport et al., 2001). They do not need years of practice before mastering a native-like tongue compared with adults (Johnson & Newport, 1989; Lenneberg, 1967). According to some researchers, implicit learning theories can provide more insight in the sensitive period debate (e.g., Dekeyser & Larson-Hall, 2005; Lichtman, 2016; Paradis, 2009; Ullman, 2001). The current study corroborates the hypothesis that developmental trajectories for some aspects of language learning, such as phonology, have its basis in implicit learning abilities. Additional research that investigates implicit learning performance for linguistic materials (such as phonotactic constraint learning via speech errors) across multiple sessions and developmental age cohorts is needed to explore these assumptions further. It is important to acknowledge that the results in the current study are restricted to a small set of consonants (/t/ and /k/). Although, we do not have strong reasons to assume that the effects found in the current study are not generalizable to other consonants (e.g. Warker, 2013; Warker & Dell, 2015), further research is recommended to take different consonants into account.

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Supporting information

The across-data performance was additionally analyzed using a hierarchical logistic regression model. The dependent variable was Position, or whether phonemes moved to the same position or different position, There were three predictor variables, or fixed effects: Restrictedness (experiment-wide vs. unrestricted), Day (1, 2, 3 vs. 4) and Age Group (Children vs. Adults). We strived for maximal inclusion of random slopes of the within-subject factors (Day, Restrictedness, and their interaction). The best fitting model was one that included both an interaction between Restrictedness, Day and Age Group, and Subject as a random variable with a random slope of Day (Position ~ Age Group * Restrictedness * Day + (1 + Day | Subject)). The random slope for restrictedness was dropped due to convergence issues of the model. The output for the fixed effects is shown in Table 1.

Table 1. Logistic regression across groups

Predictors	Estimated Coeff.	SE	z-value
Intercept	1.82	0.30	5.99***
Age Group	0.07	0.64	0.11
Restrictedness	-1.01	0.28	-3.67***
AgeGroup*Restrictedness	1.21	0.67	1.80^{+}
AgeGroup*Day	-0.06	0.31	-0.20
Restrictedness*Day	-0.45	0.12	-3.76***
AgeGroup*Restrictedness*Day	-0.00	0.32	-0.01

Note. * indicates significance ($p < .001$); $^{+}$indicates marginal significance ($p < .07$)

CHAPTER 6

GENERAL DISCUSSION

« Education is an admirable thing but it is well to remember from time to time that nothing that is worth knowing can be taught. »

- Oscar Wilde

In this final **Chapter 6**, we start by summarizing the overarching goal of this thesis and the main findings that were obtained from the four empirical chapters. For each empirical chapter, we will also discuss what we consider as the main limitations of the study and the possible improvements that could be considered in future experimentation. The discussion is focused around three big themes. First, we will summarize our theoretical views on the central question of whether and why there may be critical/sensitive periods for language learning. Next, we will extrapolate these views to the implications for the role of human memory systems in adult second language learning and in developmental language disorders. Finally, we will try to explain our memory-based approach to sensitive periods in language acquisition from an evolutionary point of view. We will end the chapter with a discussion of some possible directions for future research.

Goal and findings

The overarching aim of this doctoral thesis was to gain better understanding of the different learning and memory processes that children versus adults use when learning novel words, and whether, because of these processes, children outperform adults on novel word-learning. In the literature, it is shown that children are generally considered to be good at language learning, while adults often struggle with reaching a high proficiency. The oldest account of children's superior language learning skills was provided by Lenneberg's critical-period hypothesis. Lenneberg argued that maturational constraints exist for the period during which a first language can be acquired. If acquisition does not occur by the time of adolescence, full mastery can never be obtained. Later, it became clear that critical periods were not observed for all aspects of language learning. For some aspects, such as lexico-semantic learning that benefits from attention and cognitive effort, adults were found to be equally as good, or even better at learning than children. This has led most researchers to adopt the alternative terminology of a "sensitive period" (SP) hypothesis. This describes the widely observed phenomenon that it seems easier to learn novel (first/second) linguistic representations early in life, preferably before the age of twelve, although it remains possible to reach a certain proficiency level after this age. Today, it remains poorly understood *what* adults experience as being particularly difficult in language acquisition, and also *why* they find these aspects difficult. Most controversy in the sensitive-period debate exists around the aspect of word-learning. Most researchers believe that everyone, at whatever age, has the capacity to learn novel words. While there might be some grain of truth in that, the question remains whether adults learn words in the same way, and at the same rate as children. The seemingly simple process of word-learning is actually a complex task: at the minimum, it involves learning phoneme combination rules or

phonotactic constraints, memorizing lexical forms and associating these forms with semantics.

In **Chapter 1**, we elaborated on the complexity of word-learning by showing that many memory processes are involved, from short-term memory to procedural memory and declarative memory processes. These memory-processes and related cognitive functions all follow their own developmental trajectories, and interact during learning. Most empirical evidence for this interaction comes from the domain of motor-skill learning. Based on this knowledge, it was shown that children excel in procedural memory or implicit sequence learning (using similar cognitive processes as in motor skill learning), while adults shift to explicit memory mechanisms for learning. This latter process appears to interrupt automatic skill learning in procedural memory, making automatic learning less used in adult learning. In four empirical chapters, we investigated whether children outperform adults on procedural word-learning.

In **Chapter 2**, we compared eight-year-old children and adults on long-term phonological sequence (novel word-form) learning, under implicit and explicit task instructions. We found that although children initially started at a lower memory level (due to the fact that the length of the sequences exceeded their verbal short-term memory capacity more than that of the adults), they outperformed adults for offline retention of the sequences, up to one year after initial training. This age-effect was found for the implicit sequence, but disappeared when attention was explicitly allocated to the learning materials (i.e., in the explicitly instructed sequence). Moreover, we found that learning and offline retention of the implicit sequences was positively correlated with vocabulary development in our group of children. This indicates that children's word-learning abilities rely on implicit serial-order learning mechanisms. In our group of adults, initial learning and offline retention of the implicit sequences was positively correlated with task awareness and working memory. This suggests that whether sequential learning plays a role in adult word-learning depends on other cognitive resources, such as attention. Our findings overall suggest that a (domain-general) early-maturing procedural learning mechanism (i.e., an implicit learning mechanism) that interacts with late-maturing explicit learning mechanisms, may account for child-adult differences in skill learning related to language, such as word-form learning.

In **Chapter 3**, we investigated how children's advantage for implicit learning of phonological sequences was modulated by the type of item presented in the sequence (sublexical or syllables versus lexical or words), and what effect the occurrence of item-overlap between the to-be learned sequences had on learning. Sublexical sequences resembled more natural word-learning circumstances than lexical sequences, and item-overlap undermined the serial-order learning process that we considered underlie word-learning. We observed that children outperformed

adults for learning novel syllable-sequences, but not for learning word-sequences, and only if the syllable-sequences did not fully overlap. In an additional experiment in Chapter 3, we showed that when adults were forced to break down the phonological (sublexical) sequences into smaller two-syllable structures; thereby the experiment simulating children's smaller working memory and/or chunking capacities, adult's learning ability on the task increased to the same level as children. Overall, these findings (again) show that children outperform adults on procedural learning mechanisms that play a role in word-learning, and indirectly suggest that the effect is modulated by developmental differences in chunking capacity.

In **Chapter 4**, we temporarily disrupted activity (using Transcranial Magnetic Stimulation) within the left dorsolateral prefrontal cortex (DLPFC) prior to learning overlapping and non-overlapping syllable-sequences in adults. We found that learning of the non-overlapping sequences was significantly enhanced in the DLPFC-disrupted group compared with a control group. We additionally found a negative correlation between learning and executive function abilities (tested in a separate session) in the control participants. These results confirm the competitive relationship between late-developing frontal-dependent cognitive functions that support declarative memory and implicit learning related to word-learning.

Finally, in **Chapter 5**, we investigated the ability of children and adults to rapidly learn novel phonotactic constraints hidden in novel words through production experience. We used speech errors as a tool to investigate implicit acquisition of the constraints. Previous work with adults showed that speech errors did not reveal constraint learning until the second day of training. Here, we showed that children's speech errors provided evidence of learning already on the first day of training, which was clearly earlier than adults. This finding suggests that children are rapid implicit learners of new phoneme combination rules that are inherent to the process of word-form learning.

Altogether, our findings corroborate the hypothesis that children exceed adults in (long-term) implicit sequence learning in procedural memory that underlies certain aspects of word-form learning. Adults have more difficulties with this aspect of word-learning because they shift to better-developed cognitive functions that support the declarative memory system, but that impair learning using the procedural memory system.

Memory for order: a unifying mechanism

Just as there is little value in remembering the digits of a phone number without also remembering the serial order in which the numbers appear, there is little value in remembering the allophones or phonemes of a novel word without memorizing their serial order. Throughout this thesis, we argue that serial-order memory is as much important for motor skill learning (e.g., riding a bicycle) as it is for certain aspects of language learning. As we explained in the introductory Chapter 1, within the theoretical framework of Page and Norris (2008, 2009), verbal short-term memory directly relates word-form learning to serial-order learning. Also, many other researchers have similarly highlighted the importance of the verbal short-term memory system for word-learning or vocabulary development (for instance, Baddeley et al., 1998; Gathercole, 2006), though not in the context of a specific computational model.

It does not suffice to remember the sequence of digits in a phone number just for a couple of minutes in short-term memory, at least not if we want to memorize it by heart. This is especially true when we consider the task of acquiring a new word. According to the dual-store memory by Atkinson and Shiffrin (1968), memories are first stored in short-term memory, and subsequently, due to limited capacity of short-term memory as new memories are formed, transferred to the long-term memory system. Each time the memory stored in the short-term system is rehearsed it is strengthened in the long-term memory system. Hebb (1961) studied this transfer from short-term to long-term memory and argued that the simultaneous activation of cells leads to an increase in synaptic strength between those cells: "*neurons wire together if they fire together*" (Lowel & Singer, 1992). The persistence in this activation, due to repetition, induces lasting cellular changes that make the memory pattern more stable for long-term memorization.

In this thesis, we have proposed that learning new words can be understood as the acquisition of ordered allophone/phoneme sequences that transfer from a representation in short-term memory to a long-term memory representation due to repeated exposure. The central assumption put forward in this thesis is that the link between memory and language learning can be operationalized using Hebb-learning principles in a Hebb-learning paradigm. In earlier work, it has been empirically shown that verbal Hebb repetition learning, or the repeated recall of a particular sequence of syllable items (Hebb, 19661), can be considered as a laboratory analogue of acquiring new phonological word-forms (Szmalec et al., 2009, 2012).

Our data across the four chapters show that children outperform adults in long-term serial-order syllable sequence learning, even when controlling for initial differences in short-term serial-recall ability (see for instance Chapter 2). As presented in Chapter 1, within the computational model of Page and Norris (2008, 2009), learning a new word depends on two independent parameters: the short-term order representation of a phoneme sequence (i.e., the primacy gradient), and the long-term weight-change process through repeated exposure (i.e., learning rate). The ability to learn sequences by their repeated presentation and recall (the second parameter in the model) can be seen as one of the abilities that differ between individuals: some people are quick learners, while others need more exposure and practice to learn.

Developmental work by Mosse and Jarrold (2008) showed that learning new words is significantly correlated with children's general ability to immediately recall verbal sequences in short-term memory. Word-learning is however also significantly correlated with the long-term magnitude of both verbal and spatial Hebb learning. These findings suggest that, while the first parameter (the primacy gradient in short-term memory) of the model of Page and Norris (2008, 2009) might play a domain-specific role in word-learning, the second parameter (the learning rate) acts as a domain-general mechanism. Interesting work by Van Dijck and colleagues showed that retaining serial order in working memory draws upon spatial attentional mechanisms, even for retaining the order of verbal and/or non-spatial-dependent items (van Dijck, Abrahamse, Majerus, & Fias, 2013). In other words, when facing a laboratory task, such as the Hebb-learning task or the Serial Reaction Time task, both memorizing the serial-order of the items, as memorizing or attending to the perceptual alignment of these items across space and/or time (i.e., visuospatial attention processes), interact with skill learning. These aspects that are inherent to using laboratory tasks need to be taken into account when modeling skill learning in the natural environment.

Hence, and this is the hypothesis that we wanted to pursue in the thesis, long-term memory for serial order (identified as procedural memory) is a theoretical and domain-general (i.e., modality-independent) construct that can offer a very useful framework for understanding developmental sensitivities in the acquisition of various sorts of skills that we encounter across the life-span, from perceptual or motor skill to aspects of language.

Is there a critical period for language learning?

It is widely believed that the ability to learn language decreases with age. But are there good evidential grounds for believing that our brain is prewired to acquire language only during a certain period in life, in the same way that the chaffinch's brain is constrained to learn songs in the first 15 days of its life? The critical-period hypothesis is the subject of a long-standing debate in the study of language. The evidence is limited and stems mainly from theoretical arguments and analogies to other critical periods in biology. Nonetheless, the phenomenon itself is widely accepted; children appear to pick up linguistic structures, whether in their first or a second language, with more ease than adults, and they ultimately attain better proficiency.

It is often hard to disentangle the environmental factors that may play a role when observing child-adult differences in language learning. This issue was already evident in the case of Genie, the feral girl who was deprived from normal language development and who was never able to acquire language normally after her isolation. For many proponents of the critical-period hypothesis, this case-study was regarded as prominent evidence for a biologically determined critical period for (first) language acquisition, together with Lenneberg's observation that language abilities recover from damage to the left-hemisphere in young children, but not or to a lesser extent, in adults. However, the lack of language acquisition in Genie's later life might have been due to her exposure to a generally abusive environment, or to the lack of exposure to other social and cognitive factors, rather than to insufficient exposure to language-specific input. Another example that illustrates the complexity of the critical-period hypothesis is when considering adults who learn a second language. Although, adults often struggle with syntax and phonology of the second language, they are still able to acquire it (often despite the foreign accent). How can this be reconciled with a strict biological view of a critical period for language learning ability? Moreover, adults often do not struggle with acquiring words. Perhaps the brain preferably lateralizes formal properties of language, such as phonology and grammar, but not the more idiosyncratic properties, such as the lexicon? Moreover, rather than any dramatic discontinuity in language-learning sensitivity, the age-dependent decline seems rather gradual even after the brain has lateralized (Birdsong, 2006). There is, furthermore, also a great deal of individual variability in language acquisition. Some adults are capable of attaining near-native fluency at a second language, whereas some children are less successful (Harley & Wang, 1997). This latter effect, in particular, suggests that other factors, such as motivation or the time and effort that is put at learning, could potentially modulate

language learning. Also, when learning a second language as a child, one on average spends more time in learning the language than when learning it later as an adult (Snow & Bornstein, 1987). Finally, children compared to adults, possess less prior linguistic knowledge, and are less exposed to explicit teaching instruction in the environment. How do these factors impact upon differences in language-learning sensitivity?

It is very difficult to provide a clear-cut answer to the question whether a strict biologically-determined period exists for language or not. There seems to be a well-accepted age-dependent sensitivity for syntactic development and, even more strongly, for phonological development (Newport et al., 2001). However, other factors, such as time spent at learning, prior linguistic experience and teaching methods, also potentially interact with learning. Most researchers today agree that Lenneberg's original view on critical periods (i.e., hemispheric lateralization that completes around puberty) is an unwarranted stretch in explaining the phenomenon that children seem to be better at language learning than adults (unless perhaps we assume that the brain does not completely lateralize; i.e., it lateralizes for some aspects of language and for some children, but not for all). From this discussion, we can conclude that general language research has failed to support the critical period hypothesis in its strongest form. Today, it is more accepted to use the terms sensitive periods or "younger-is-better" when talking about child-adult differences in language learning (Singleton & Lengyel, 1995). Although the sensitive-period hypothesis softens the strong claim to some extent (i.e., it concedes that language acquisition is still possible beyond puberty), it has also saddled us with other – and perhaps more important – unanswered questions: Why are children better at some, but not all aspects of language? Why do adults perform badly at learning language, while they are generally very good at memory tasks? Why are adults not only less proficient at language learning, but also at learning other skills such as motor learning? How can individual variabilities in second-language-learning sensitivity be explained? And so on.

The linguist Chomsky (1975) argued that language is a special human feature that is innate, species-specific and biologically pre-programmed (and therefore, cannot be reduced to learned cognitive processes). But to what extent is language an autonomous function that does not interact with other cognitive processes? We will not go into too much detail about Chomsky's nativist view on language. Even if we assume that language is a module on its own, in cognitive psychology and psycholinguistics, it is accepted that language does interact with the cognitive system (Harley, 2013). The psychologist Piaget (1923), more strongly claimed that there is no special faculty of language. He proposed that we process language using the same sort of cognitive processes as we use in the other domains of cognition. Within his view, language is learned using general cognitive processes rather than language-specific ones. Our linguistic development might therefore

depend on our general cognitive development. Twenty years ago, Elissa Newport proposed an alternative maturational view on the sensitive-period hypothesis in line with this cognitive view (Newport, 1990). The age-dependent decline in language learning, as she argued, coincides with maturational changes for other cognitive abilities such as working memory capacity. Hence, an immature cognitive system in children could perhaps paradoxically lead to superior language learning (Elman, 1993; Newport, 1990). At these times it was often couched in the terms "less is more" (Newport, 1990) or "starting small" (Elman, 1993). Due to the fact that children can only process limited amounts of stimuli in the environment at a time, they better get the small segments right before they go on to more complex units. This is advantageous in language in the sense that they are not overwhelmed by complexity. They learn in a more analytic way, and this gives them more flexibility to regularize/generalize to new contexts (e.g., assembling the newly acquired words into new sentences), and to create more stable representations in long-term memory (i.e., less to forget).

The less-is-more hypothesis has the potential, in contrast to the strict biological account on hemispheric lateralization, to answer the question why adults often show an advantage at the initial stage of performing a language learning task, while they seem to fall back at later stages of learning (e.g., for long-term retention or for generalization to new contexts). Because adults learn language in a more holistic way, they process the new information much faster than children. But this is not the most efficient strategy in the long term. This is an important observation: It is not clear that because older learners perform the task as well as, or even better than younger learners, they are actually processing the language in the same efficient way. This is also what we proposed in Chapter 2 where we found that children were disadvantaged at an initial stage of learning, due to their smaller memory capacities, but eventually outperformed adults when retaining the sequences across offline periods. Also, in Chapter 5, we found that adults were better able to memorize or associate the positions of the consonants that were restricted at trial-level. They failed, however, to rapidly learn the positions that were restricted at the level of the experiment (long-term).

Although we believe that what Newport proposed with her less-is-more hypothesis is a very interesting framework for understanding child-adult differences in language learning, we also see a few shortcomings in its explanatory potential. First of all, we have some difficulties in understanding what is meant by "limited cognitive (memory) resources". Research in the literature often refers to limited working memory capacities, where young children can only perceive and remember small segments of the language (e.g., Kersten & Earles, 2001). Working memory is however, a complex construct that contains several subcomponents, such as an executive control system that controls the operation of the phonological and visuo-spatial subsidiary systems (Baddeley, 1992). The executive component uses

different prefrontal-dependent functions such as attention and shifting strategies to perceive and update the information that is temporarily stored in the short-term subsystems (Baddeley et al., 1996). Do all of these subcomponents interact with language learning? In fact, storage capacity is known to play a supporting role in language learning, in particular in the acquisition of vocabulary in early childhood (Baddeley et al., 1998), as well as in motor learning (Janacsek & Nemeth, 2013). Other researchers prefer using the term "limited processing capacity" when describing the less-is-more hypothesis (e.g., Cochran et al., 1999). However, we learned from Jones (2012), who was introduced in Chapter 3, that differences in processing capacity do not necessarily mean differences in memory capacity. Differences can also be caused by other factors. For instance, prior experience with the material (an environmental factor), cause children to chunk, and process sequences in smaller parts than do adults. Second, the empirical evidence is scarce and mainly limited to grammar learning studies (Conway et al., 2003). And third, some studies found a positive effect of limited cognitive capacities in language learning while others found a negative, disrupting effect (Conway et al., 2003), even within the same aspect of language learning (Finn et al., 2014). In sum, we believe that the less-is-more hypothesis is, in its current state, not able to fully answer the question of why adults have difficulty learning some, but not all, aspects of language.

To answer the thesis question, we need to take a broader neurocognitive memory approach in the study of language learning, by accepting that different aspects of language rely on the dynamical relationship between the procedural and declarative memory systems. The declarative/procedural model of language was first proposed by Ullman (Ullman, 2001, 2015). Within his view, the development of the lexicon (i.e., the memorization of words) and the development of grammar (i.e., the rule-governed sequential combination of lexical forms in complex words, e.g., walk + ed, or in phrases and sentences) depend on two well-studied brain memory systems. Lexical memory depends on declarative memory, which underlies the learning and use of fact and event knowledge. Declarative memory may be computationally specialized for learning arbitrary relations, and is rooted largely in temporal lobe structures. Aspects of grammar involve procedural memory. This distinct brain system subserves the acquisition and expression of motor and cognitive skills (e.g., riding a bicycle), and may be specialized for sequences; rooted largely in basal-ganglia structures (Ullman, 2001, 2015).

In the introductory Chapter 1, we proposed that the distinctive memory systems also play a role in lexical learning, which is an aspect of language that is (or was) less well understood in the sensitive-period debate. In fact, many aspects of word-learning are governed by rules and sequential combinations, such as phonotactic learning and memorizing the serial order of phonemes, while other aspects rely on arbitrary relations, such as learning the semantic meaning of a word

(Gupta, 2012). A procedural/declarative memory view on the study of word-learning can help us better understand why adults are found to be less proficient at learning some aspects of language but not others. By analogy with the developmental differences in motor skill learning, we corroborate the hypothesis that children are generally good at learning language because this mainly relies on the procedural memory system that develops early in life. Adults however, shift to declarative memory processes, as these are more readily available, not only in terms of maturation, but also in the environment (i.e., through teaching methods). Declarative memory and its related cognitive functions, in particular attention and executive functions, compete with the neural resources in procedural memory systems, therefore disrupting the procedural aspects of language learning. In other words, we propose the procedural/declarative model, an expanded variant of the less-is-more hypothesis, as a promising model to investigate child-adult differences in language learning.

We illustrated this by showing that children outperform adults on word-learning processes by focusing on the implicit/procedural memory basis of them (Chapter 2, 3 and 5). If we focus on the declarative aspects of words (i.e., when attention is explicitly allocated to the task or when learning is semantic/arbitrary; Chapter 2), the child advantage disappears. Procedural learning is a slow process (Ellis, 2005), and therefore it is more likely that age-differences are not revealed until later during learning (Chapter 2). Learning in declarative memory might reveal some advantages in the short term (Chapters 2 and 5), but is more likely to impede the formal properties of language learning in the long-term. In Chapter 3, we showed that children seem to use different chunking strategies than do adults when memorizing phonological sequences, and that this might help them to learn the sequences better than adults. The different chunking strategy could be caused by differences in working memory capacity, or by differences in prior knowledge. Based on our findings in Chapter 4 that followed-up on Chapter 3, we argue that working memory capacity, and in particular executive functioning that is rooted in the late-maturing dorsolateral prefrontal cortex, could explain the child-advantage for phonological sequence learning.

In sum, we conclude that the critical-period hypothesis lacks sufficient support in its strongest form. This may be due to a rather "isolationist" view on language learning which is actually a very complex process that also interacts with other cognitive processes. We showed in this thesis how an approach that examines the link between language and memory has the potential to advance our understanding of one of the basic questions of science; to explain why children learn language more easily than adults, even for aspects that do not seem to be restricted by age at first sight (i.e., word-learning). It also brings novel theoretical insights into the interaction between memory and language, which can be further applied to better understand the cognitive basis of normal and pathological language development,

and individual differences in the language learning ability. We will go deeper into these topics below.

First versus second language learning

During the early critical-period debate, some researchers argued that as long as adults have acquired a first language during childhood, the capacity to acquire other languages later in life remains intact (Harley, 2013). This is also called the "exercise" or "use-it-or-lose-it" hypothesis (Birdsong, 1999). Adults are often able to attain good to native proficiency in a second language as long as they receive enough time to practice. This lead many researchers to believe that adults' second language learning is not restricted to a biologically determined critical period (Loewen & Reinders, 2011). In this section, we will report some evidence suggesting that proficient adult second language learners come to rely on native-like brain mechanisms, even though they have processed the foreign language qualitatively differently than children (i.e., by using different neural memory processes). As reported below, the attainment of native-like proficiency depends on some crucial factors like time-on-task, instruction under which the second language is learned, and (dis)similarity with the native language.

In different studies, Morgan-Short and colleagues trained adult participants on an artificial second language, called Brocanto2, while recording the electrophysiological brain activity related to cognitive processes (using Event-Related Potentials; Morgan-Short, Finger, Grey, & Ullman, 2012; Morgan-Short, Steinhauer, et al., 2012; Morgan-Short, Sanz, Steinhauer, & Ullman, 2010). Across several sessions, participants were trained to speak and understand a novel language that helped them to play a chess-like computer game. The grammar of this language fully complied with the grammar of a natural language, but with fewer rules and vocabulary items (so that learning could be accomplished within hours). This artificial language enabled the researchers to control for a few important factors that are not controllable in natural learning conditions, such as timing and type of exposure (i.e., implicit/immersion-like versus explicit/classroom-like). Behaviorally, the authors found no differences in task performance between implicitly and explicitly instructed training conditions. However, remarkable differences were obtained in the neural activity of the participants. Early in training, at a low proficiency level, both the implicitly and explicitly trained participants showed an N400 component in response to syntactic violations of the novel language. The N400 component is thought to be associated with lexical/semantic processing in the first language and with declarative memory processing (Ullman, 2015). Later in training, however, the implicitly trained participants elicited a pattern that was typical of native speakers, and procedural memory processing (i.e., an anterior

negativity followed by a P600). Explicit training, by contrast, yielded an anterior positivity at a low proficiency level followed by a P600 at high proficiency. However, this shift in processing occurred much more slowly, and with much more variability, than in the implicitly trained group. These findings suggest that the "proceduralization", and hence native-like proficiency of grammar, benefits more from learning under implicit, immersion-like conditions. The attainment of native-like ERP components by the implicit group did not appear to be compatible with the view that adult's second language learning relies on entirely different mechanisms than first language learning in children.

At first sight, these data might question the "critical period" in second-language learning. The N400 displayed by the adult groups at low proficiency did however suggest that adults initially do not use the same neurocognitive mechanisms as children when acquiring a first language. The lack of a clear shift to a proficient P600 in the explicitly trained group suggests that the provision of explicit information may impede the development of native-like processing. In other words, despite the initial advantages, adults' declarative memory processing may not be as efficient in the longer term as procedural memory processing. Also, similar task performance between groups (or conditions) does not necessarily imply reliance on similar underlying (neural) mechanisms.

In the studies of Morgan-Short and colleagues, the second language differed from the first language in some crucial respects (i.e., word-order and gender agreement). Some studies have suggested that the more a second language is structurally similar to the first native language, the more likely that native-like mechanisms are involved (Sabourin & Stowe, 2008). As discussed earlier, the documented decline in adult's language achievements with increasing age of acquisition may be, in part, due to the level of prior language experience. This is often attributed to "entrenchement" mechanisms in the sensitive period literature (Birdsong, 2006). In this case, prior language experience places the system into a non-optimal state to acquire the novel language, because it takes time to reconfigure the native system for the new task, and therefore learning takes longer. The more the second language differs from the first language, the more interference and time that is needed to overcome the interference, and the more adults struggle with attaining proficiency as good, or as fast, as that of children.

In the present thesis, children and adults were presented with novel linguistic structures that were legal with respect to the first language. Because of that, it is difficult to draw strong conclusions on child-adult differences in natural second-language learning circumstances, where violations with the native language often occur. The amount of (dis)similarity between the novel linguistic structures and one's native language might be an important factor that needs to be considered in further work. It is possible that differences in first language knowledge partly

drive initial child advantages in second language learning. In that case, adults' explicit learning capacity has then the potential to help (but not overcome) acquiring the second language with the same apparent proficiency as children do.

Developmental language disorders

As well as in the current thesis, an increasing amount of research is starting to use the procedural/declarative model to explain pathological language development. For instance, research has shown that children with a Specific Language Impairment (SLI) and/or dyslexia have a significant deficit in sequence-specific procedural learning- and retention (Hedenius et al., 2011; Hedenius, Ullman, Alm, Jennische, & Persson, 2013; J. H. Howard, Jr., Howard, Japikse, & Eden, 2006; Hsu & Bishop, 2014), and try to compensate these impairments with other more declarative-driven memory processes (Lukács, Kemény, Lum, & Ullman, 2017; Lum, Conti-Ramsden, Page, & Ullman, 2012; Lum, Gelgic, & Conti-Ramsden, 2010). In our lab (and not reported in this thesis), we collected some preliminary data showing that children with SLI have more difficulty with the implicit learning of verbal and visuospatial sequences through Hebb-repetition learning compared with typical age-matched children. Moreover, in a word-associate learning task, children with SLI attained the same level of performance when visual semantic cues (i.e., using gestures) were additionally provided during training. Other work has similarly found a Hebb-learning impairment in children and adults with dyslexia (Bogaerts et al., 2016; Bogaerts et al., 2015; Szmalec et al., 2011). Hebb-learning performance in first grade children has also been shown to predict individual differences in later reading skills; thus offering a tool to diagnose dyslexia early in development (Bogaerts et al., 2016).

An evolutionary perspective

Many people assume that language evolved as a beneficial adaptation, shaped by Darwinian natural selection, to communicate existing cognitive representations, and therefore enhance our chance for survival (although, some also assume that language evolved as a side-effect; Harley, 2013). From an evolutionary perspective, why is it that a memory system that makes learning language less efficient, develops across age? In Chapter 3, we briefly commented on the argument that limited memory resources might only be beneficial for children who experience the world as "unorganized". Procedural memory recruits early-developing phylogenetic brain structures. There might be a strong evolutionary advantage for this that helps us focus on the formal properties of language, enough to communicate, and therefore enhance our chances for survival, before moving on to

acquire more complex language properties. For complex properties, the early brain structures, provided that they have accomplished their goal of acquiring basic survival functions (motor learning, basic communication), need to make room, in terms of neural resources, for the development of higher-order cognitive functions to further improve quality of life.

The declarative memory system is more flexible, and therefore can, and often does, learn a wide range of new strategies that help us to overcome, at least partially, numerous types of impairment (see above), as well as help us dealing with other obstacles in the environment, such as the urge to rapidly acquire novel second languages to communicate. For the latter, more explicit and faster strategies are needed (e.g., teaching methods at school) that appeal to a different memory system. In this situation, the procedural memory system would put us in a disadvantageous position because it is slow, too analytical and cannot take prior stored semantic knowledge into consideration. In other words, in some circumstances, and this is not only restricted to language, the development of declarative memory mechanisms might actually turn out to be advantageous in the complex environment that we typically encounter when growing older.

Limitations to the studies

In this section, we summarize what we consider as the main limitations for each empirical chapter. We also discuss the possible improvements that could be considered in future experimentation.

Starting with **Chapter 2**, we presented pictures (aliens) with the phonological sequences. Although the pictures were presented to make the task more attractive to children, we were also aware that the pairings might have induced explicit associative processes that are typical for semantic learning (another important aspect of word-learning). In the introductory Chapter 1, we argued that, because of its reliance on attention and other declarative associative memory processes, semantic learning might actually be better in adults than in children due to its declarative nature. It would have been interesting, therefore, to dissociate child-adult differences for the long-term retention of phonological form versus long-term retention of semantic pairing. At the end of the Hebb-learning task in Session C, we asked our participants, on an exploratory basis, whether they could *name* the aliens that they had seen during the experiment. Although this was not an ideal test to measure semantic learning (because participants also had to recall the correct phonological form), the data provided an indication of what was learnt by the children and adults. During this explicit recall task, all aliens presented during Hebb learning were randomly presented and participants were asked to recall their names. A logistic

regression was performed to determine the effects of Group and Instruction and their interaction on explicit naming ability (correct or incorrect) at the end of the experiment. The three aliens that were presented together with the filler sequence were never correctly *named*, which is not surprising given the fact that the order of the nine syllables of the filler sequences changed every trial. These null scores were excluded for analysis. The more relevant analysis on the remaining data revealed a significant main effect of Group, $\chi2(1) = 10.5$, $p = .001$ with adults showing overall better naming of the aliens than children. This effect disappeared when recall accuracy for the Hebb sequences at the end of learning (i.e. the last trial of session C) was entered as covariate in the model, $\chi2(1) = .186$, $p = .66$. If we additionally investigated naming abilities depending on the order of the alien within the sequence, we only observed a group effect for naming the last alien of the sequence, $\chi2(1) = 8.2$, $p = .003$ and not for naming the first two aliens; $\chi2(1) = 2.2$, $p = .13$ and $\chi2(1) = 1.05$, $p = .30$ respectively. This indicates that the apparent superior naming ability for adults was more likely driven by differences in immediate serial recall capacity and the ability to attend to all nine syllables in the sequence.

It is hard to draw firm conclusions from this supplementary investigation as it was presented immediately after the HRL task (session C) without further theoretical motivation. If we control for performance at the end of Hebb learning, it does suggest that children and adults do not fundamentally differ in acquiring sequence-picture pairings. This contributes to the debate about sensitive periods in vocabulary acquisition, or the lack thereof. However, we are rather careful in drawing strong conclusion from this data as we cannot rule out other episodic and working memory effects. Future studies should delineate the likely differential age-sensitivity for different components of word-learning by testing both the long-term memorization of form and long-term memorization of semantic association in a proper longitudinal design.

An additional limitation in Chapter 2 is that the length of the Hebb sequences was matched to a typical adult working memory span. This means that we initially put adults in an advantageous position when engaging in the laboratory task. This might explain why no child advantages are observed during the initial training session. Although this difference in baseline capacity (i.e., higher cognitive capacities for adults) reflects natural differences, it would have been interesting to explore whether we can see child advantages for implicit Hebb-learning capacities already early-on when controlling for differences in baseline (or starting) performance. This is exactly what we did in the subsequent Chapter 3, where the length of the sequences was matched to the typical memory span of the age groups. Despite equal performance on the filler sequences, performance on the Hebb sequences now improved more in children than in adults during initial training. This strengthens our conclusions about a maturational difference for implicit learning mechanisms that underlie language.

In **Chapter 3**, we hypothesized that encoding of chunks within the sublexical Hebb task takes place at different grain sizes in children compared with adults, with children using a larger number of *small chunks* and adults using a smaller number of *large chunks.* We provided initial evidence supporting this distinction in a third experiment by forcing adults to chunk the syllable sequences in small two-syllable chunks, and observing similar Hebb learning effects to those found in the children participants. However, further work is needed to investigate the modulatory role of increasingly larger chunks, and the extent to which the differently sized chunks then interfere with prior existing linguistic structures. This would enable us to examine the role of memory capacity versus prior knowledge in sequence learning across age.

In addition, it would be interesting to investigate whether children also potentially outperform adults for learning overlapping sequences. We explained in the chapter that full overlap in the input materials does not likely resemble natural word-learning conditions. However, it would be exaggerated to claim that overlap does not occur at all in real life. Children are sometimes exposed to word anagrams in the learning environment (e.g., "pots" vs. "stop"). A better illustration of natural word-learning conditions could hence be made operational through conditions of semi-overlap (i.e., some items are unique to the Hebb sequence whereas other items are shared with the filler sequences). A previous motor-learning study found that children were more resistant to interference caused by subsequent exposure to a sequence that contains the same items but in a different serial-order than at training (Adi-Japha et al., 2014). This effect was however only revealed after a period of offline consolidation (across wake) indicating more stable memory in children (Adi-Japha et al., 2014). This would be an important follow-up to the study presented in Chapter 3. Overall, it would suggest that children are actually better word-learners, even for conditions of overlap, but we need to look at performance in the long-term, i.e., after an offline consolidation period. An offline consolidation period may provide the necessary time course to deal with potential interference during daytime learning.

Another important condition to explore, and related to the issue above, is the effect of sleep during the offline consolidation period. Overall, it is accepted that declarative memory is more dependent on sleep than procedural memory, to prevent catastrophic interference during learning (Diekelmann, Wilhelm, & Born, 2009). In line with our working hypothesis that adults rely more on declarative memory processes than children, it would be interesting to test whether offline learning gains are more sleep-dependent (over wake-dependent) in adults than in children, especially when interference/overlap occurred during initial Hebb training.

Chapter 4 was limited in the extent that no stringent test of lexicalization of the phonological sequences was provided after learning. In the introductory Chapter 1 (p. 20, section 2.2.1), we showed that previous experimental work using the Hebb learning paradigm tested the idea that phonological chunks within the Hebb sequences, were integrated in the mental lexicon like novel words (Szmalec et al., 2009; Szmalec et al., 2012). This was investigated using lexical decision or pause detection tasks presented after an offline consolidation period. In 2010, Galea and colleagues found that Transcranial Magnetic Stimulation to the Dorsolateral Prefrontal Corte immediately *after* training on a motor sequence learning task facilitated learning across an offline period of wakefulness. A similar approach in the current study would greatly contribute to the current debate about the need of complementary learning systems in adult lexical learning, and in particular, the needs for offline consolidation periods involving sleep (see section 2.4, p. 26 of Chapter 1). Testing for lexicalization would need a slightly adapted design in which more Hebb sequence trials are presented (to increase power), and in which the phonological sequences are presented in a chunked manner (so that they are actually learned as isolated lexical units). Additionally, it would be interesting to add a stimulation group in which the primary motor cortex, which is a region related to procedural memory, could be found to disrupt implicit sequence learning (Wilkinson, Teo, Obeso, Rothwell, & Jahanshahi, 2009), or to add a group for which the left DLPFC is actively stimulated (instead of lesioned) using excitatory TMS stimulation. In these conditions, we would predict that Hebb repetition learning (and/or subsequent lexicalization of the Hebb-learned forms) would be abolished instead of enhanced.

Another question that needs further work is the importance of the laterality of stimulation. Language and motor skill abilities are assumed to be left lateralized, while visuospatial and attentional processes are right lateralized in the brain (Gotts et al., 2013). In the present study, we stimulated the left DLPFC. However, within our argument of the domain-generality of the underlying learning mechanism, and potential interactions with perceptual or spatial aspects of the Hebb task, it would be interesting to find similar enhanced learning effects when stimulating the right DLPFC (though, perhaps in a weaker extent). In their motor skill learning study, using the SRT task, Galea and colleagues (2010), disrupted both the left and right DLPFC and found enhanced motor skill learning within both laterality conditions (although the right stimulation resulted in the largest effect, potentially due to the nature of the SRT task). This suggests that the serial-order mechanism underlying skill learning might interact with visuospatial attention processes inherent to the task that is used.

Finally, in **Chapter 5,** our data were not sufficient to be able to draw strong conclusions on differences in the strength of learning between children and adults. In order to show these differences, a different approach and experimental design is

needed in which we would control for baseline differences on the syllable position effect (i.e., correctly associating the position of the unrestricted consonants at trial-level, which in the present study was high in the adults). On an exploratory basis, we selected a subset of five adults that showed the lowest syllable-position effect (averaged across days; *M*adults = 80.2%, SD = 3.5) and compared their learning with a subset of five children with a comparable syllable position effect (averaged across days; *M*children = 79.6%, SD = 5.6, Z = -1.27, p = .20). Their performance is illustrated in the Figure 6.1 below. When, in this small sample set, children and adults are directly compared for their performance on the experiment-wide constraints compared with the unrestricted constraints, children outperform adults on the experiment-wide constraints on the first day (**Day 1,** Z = 2.26, p = .024), but not on the unrestricted constraints (i.e., the syllable position effect; **Day 1,** Z = .593, p = .553). The child-adult difference disappears on subsequent days (all ps > .05) (all participants perform close to 100%). This provides some initial evidence for the hypothesis that children not only learn quicker, but also stronger (more robustly) than adults, provided that we correct for baseline differences in correctly labeling the syllable positions within the sequence. This latter finding however needs further experimental evidence using an appropriate design.

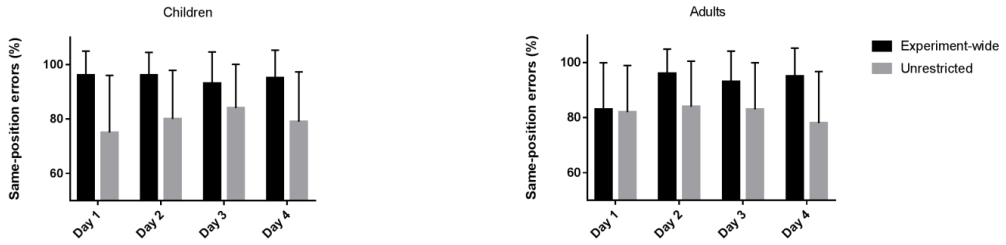

Figure 6.1. Mean legality (same-position) percentages and standard errors across the four days in a subset (n = 5) of the tested group of children and adults.

Future perspectives

We will end the section by providing the broader limitations of the thesis.

First, the studies in the thesis are limited, when compared to other studies of language and memory-related development abilities (e.g., Janacsek et al., 2012), which test a larger range of ages. The current study provides a snapshot of ability at age eight, nine or eleven, and at adult ages. Though there are many studies investigating just two ages in the literature (e.g. Bishop et al., 2012), claims about developmental trajectories consequently need to be interpreted with some reserve.

Although the child-adult comparison does provide some important insights into maturation differences by showing a clear childhood advantages in long-term learning, further research needs to take into consideration a wider age range across development.

Another limitation is the extent to which the Hebb-learning task is any closer to language learning than previous studies using Serial Reaction Time tasks. We have argued that HRL is mediated by implicit serial-order learning mechanisms (in procedural memory; Gupta & Tisdale, 2009b) that are the same as those underlying word-form learning. We believe that it is a domain-general serial-order learning mechanism that links performance in the Hebb task with performance in other procedural learning tasks, like SRT. To support this, it would therefore be interesting to investigate correlations between performances on both motor –and language tasks across development, or to try to dissociate the contribution of the serial alignment of items across space and/or time, also affecting perceptual skills, to language-learning.

Although we believe that artificial learning tasks are important to control for factors that can otherwise not be controlled in natural learning conditions (e.g., prior knowledge), they underestimate the truly complicated nature of real languages (and so the real task that learners face). The correlation between learning and vocabulary scores on these tasks are found in present and previous studies, and does provide some support for the claim that the tasks resemble natural language learning. However, the inclusion of more ecologically valid tasks, each covering different aspects of language, is needed.

The fact that we asked people questions about whether they noticed anything beyond the sequences also means participants were cued in to the fact that there might be something else going on within the study. Therefore, we cannot be 100% confident, therefore, that the children (who are more than old enough for self-directed attention), maybe have also engaged in more explicit processes. In other words, the explicit/implicit learning contrast was not always clean, and this could have masked other important differences. However, this would then be a shortcoming of every study using awareness reports.

Finally, there is still some uncertainty about the exact role of the prefrontal cortex and/or working memory in sequence learning. As we explained earlier, many functions are related to the prefrontal cortex, and working memory is in itself a complex construct with some of the subcomponents having a supporting role in implicit sequence learning. It is therefore important to dissociate these different roles. At first glance, it seems counterintuitive that learning improves by disrupting an area known to support memory. The DLPFC could have direct inhibitory connections with brain areas that are critical for learning in procedural memory.

Disruption would then directly disinhibit procedural memory and therefore enhance learning. The alternative is that the DLPFC might directly support declarative memory that has some overlapping areas with procedural memory. Recruitment of these multifunctional brain areas by the declarative memory system might compete with the adjunctive demands of the procedural memory system during learning. Disrupting the DLPFC would then reduce its impact as a competitor for overlapping resources, hence, leaving more resources to be allocated to the procedural memory system. Distinguishing between these explanatory modulatory (neural) mechanisms need further experimentation.

In addition to this, it would be interesting to clarify the exact psychological processes that underlie the neurobiological procedural/declarative model. In the current work, we argue that attentional control, or executive functions, is the process that interacts with implicitly picking up regularities in language and or other skills. Adults are putting too much conscious effort and control in acquiring a language, which is most often learned unconsciously. Due to this, they focus on inappropriate aspects of the language structure. This results in overload and superficial learning while missing the basic properties or the overlaying structure. Additionally, they focus on, or relate the novel input to prior internal models of what they already know (for instance, direct translation from the first language), causing entrenchment or interference during learning. This is an interesting question with broad implications for the educational setting that needs further testing, perhaps also in the classroom (i.e., the effect of immersion schools).

CONCLUSION

In four chapters, we have shown that human-memory theories and, in particular, theories about implicit serial-order learning, have the potential to improve our understanding of the cognitive processes that underpin various aspects of language acquisition across life. We have demonstrated that children outperform adults on the offline retention of phonological sequences, and rapidly integrate new phoneme-combination rules in their speech production system. We also showed that late-developing executive functions in working memory, supported by the left dorsolateral prefrontal cortex, impair long-term serial-order learning of phonological sequences in adults. Overall, the findings presented in this doctoral thesis contribute to a growing body of evidence regarding the involvement of two long-term memory systems in skill acquisition, both across normal development, as well as across pathological development. As such, we have succeeded in our aim to adopt a serial-order framework from the memory literature, into the study of language development.

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