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ARTIFICIAL LANGUAGE LEARNING

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Resumo. Neste artigo fazemos uma revisão breve de investigações actuais com técnicas comportamentais e de neuroimagem funcional sobre a aprendizagem de uma linguagem artificial em crianças e adultos. Na secção final, discutimos uma possível associação entre dislexia e aprendizagem implícita. Resultados recentes sugerem que a presença de um défice ao nível da aprendizagem implícita pode contribuir para as dificuldades de leitura e escrita observadas em indivíduos disléxicos.

***Palavras-chave*:** RMF; TMS; linguagem natural; sintaxe; região de Broca; aprendizagem de uma linguagem artificial; aprendizagem de uma gramática artificial.

Abstract. This paper briefly reviews some recent behavioral and functional neuroimaging work on artificial language learning in children and adults. In the final part of the paper, we discuss reports of an association between dyslexia and implicit learning. Recent findings suggest that an implicit sequence learning deficit might contribute to reading and writing difficulties in dyslexic individuals.

***Keywords*:** FMRI; TMS; natural language; syntax; Broca’s region; artificial language learning; artificial grammar learning.

Introduction. Human languages are characterized by Hockett's "design features of language" [1, 2]: discreteness, arbitrariness, productivity, and the duality of patterning (i.e., elements at one level are combined to construct elements at another level). Somehow these properties arise from the way the human brain works, develops, and learns in interaction with its environment. This suggests that humans are equipped with learning mechanisms which shape the language acquired into a discrete system when the relevant communicative context is present (**Figure 1**). During the past decade, artificial language learning (ALL) paradigms have revitalized the study of language acquisition and language processing. The complexity of natural languages makes it exceedingly difficult to isolate factors responsible for language learning and language processing. For example, semantic-pragmatics, syntax, and phonology operate in parallel and in close spatial and temporal contiguity. Because of this, ALL paradigms have been developed with the objective to control the influence of the various elements of natural language. Language researchers have thus turned to artificial languages as a means of obtaining better experimental control over the input to which learners are exposed. For example, the use of artificial languages makes it possible to control for prior learning experience of the learner. Moreover, it is critical to understand what children can learn in order to specify possible language acquisition mechanisms. More importantly, the identification of such acquisition mechanisms will allow researchers to evaluate their degree of domain-specificity as well as possible inherent constraints. The basic assumption in artificial language learning research is that some of the learning mechanisms are shared between artificial and natural language acquisition [3-5].

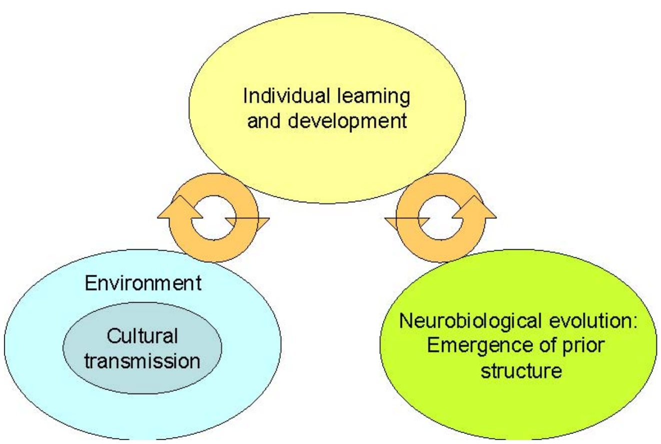

Figure 1. An adaptive cognitive system situated in the context of its evolutionary history and its current environment [for further discussion see 6]

Implicit Learning. Humans are equipped with acquisition mechanisms that extract structural regularities implicitly from experience without the induction of explicit models [5, 7, 8]. This human capacity was explored in the seminal work of Reber [5], which showed that humans can successfully classify sequences generated from an implicitly acquired formal (artificial) grammar. He proposed that this implicit acquisition process is intrinsic to natural language acquisition. Reber [5] also suggested that humans can acquire implicit knowledge of the underlying structure of grammar through a statistical learning process and that the acquired knowledge is put to use during grammaticality classification. Reber [5] argued that implicit learning mechanisms abstracted ‘rule-based’ knowledge and more recent studies seem to suggest that dual mechanisms might be engaged [9-11]. Moreover, it has been argued that artificial grammar learning (AGL) is a relevant model to investigate aspects of language learning with in infants [3], to explore differences between human and animal learning relevant to the narrow faculty of language [12], and to investigate language learning in adults [4, 13].

Following Reber [5] and Seger [14], Forkstam & Petersson [15] adapted four defining characteristics of implicit learning: (1) limited explicit access to the knowledge acquired; subjects typically cannot provide an explicit account for either the process or the outcome of acquisition; (2) the nature of the knowledge acquired is more complex than simple associations or simple exemplar-specific frequency counts; (3) implicit learning does not involve explicit hypothesis testing, and is an incidental (automatic) consequence of the type and amount of processing performed on the stimuli; and (4) implicit learning does not rely on declarative memory mechanisms that engage the medial temporal lobe memory system.

Artificial Syntax Learning in Children. The difficulty of acquiring a language is related to the fact that the internal mental structures that represent linguistic information are not directly expressed in the surface form of a language (e.g., in the utterance). The question of if, and how, these structures are acquired, is the question of how a learner transforms the language input ("primary linguistic data") into phonological, syntactic, and semantic knowledge [16]. On the traditional Chomskyan view, the input underdetermines the linguistic knowledge of the adult grammar. The dilemma of generalizing beyond the stimuli encountered without over-generalizing, in combination with the absence of certain generalization errors during child language acquisition, suggest that the learning mechanisms involved are constrained by prior knowledge or constraints. For example, it appears that children never consider rules solely based on linear order in sentences [3]. This, and similar, observations, was one of the fundamental reasons that led Chomsky to propose the existence of a specific language acquisition device [17-19]. Thus, the acquisition of a grammar is not only based on an analysis of the linguistic input, but depends on an innate structure that guides the process of language acquisition [20]. The current lack of knowledge concerning the actual acquisition mechanisms involved during early childhood makes it difficult to determine the relative contributions of innate and acquired knowledge in language acquisition, and more importantly how these factors interact during ontogenetic development. One approach to these issues, exposes infants to artificial languages and this has resulted in a number of discoveries regarding the learning mechanisms available during infancy [3]. We note here that the ALL paradigms that have been investigated so far in both adults and children generally report similar, or "equivalent", findings for both adults and children.

Acquisition of Structured Sequence Knowledge. In this section we review some results on *pattern-based abstraction* and *category-based generalization* in the acquisition of sequence structure, but first we make a brief summary of earlier results. In an early study, Gómez and Gerken [21] showed that after brief exposure to a simple artificial grammar, 12-month-old children could distinguish new grammatical from non-grammatical sequences, suggesting that learners were able to generalize the acquired knowledge to new sequences with familiar co-occurrence patterns. Gómez and Gerken [21] also showed that children were able to discriminate grammatical and non-grammatical sequences in a transfer version of their artificial language learning paradigm (i.e., despite a change of vocabulary). Gómez and Gerken [3] argued that their findings suggest that the infant brain supports abstraction processes for the acquisition of sequence structure, consistent with the infant capacity for rapid rule-abstraction [22]. Subsequently, Marcus and colleagues [23] showed that infants might not be able to do this for certain types of non-linguistic stimuli (e.g., tones and shapes), and they suggested that this type of rule-abstraction therefore is specific to language. However, it was recently shown that infants can acquire these rules with familiar, salient non-linguistic material, like familiar animals [24]. Interestingly, cotton-top tamarin monkeys were also able to acquire the rules used by Marcus and colleagues [22] using linguistic stimuli [25].

Pattern-based abstraction can be described in terms of relations over surface (e.g., physical) characteristics of the stimuli. A relation is abstracted by comparing the perceptual characteristics of elements in a sequence [3]. Infants are sensitive to such pattern-based abstraction [21, 22]. Saffran and collegues [24] provided evidence that this type of rule learning is not domain-specific, that is, limited to linguistic stimuli, but also holds for non-linguistic material (e.g., sequences of dog pictures). Consistent with this, cotton-top tamarins also master this type of rule learning [25]. These rule-learning tasks are more than simple sequence learning. The learner must, for example, detect the same/difference relationships within sequences, and this requires that the learner can represent and categorize sequence tokens as being of the same or different type. Thus, factors such as stimulus familiarity, categorizability, ease of representation, are important factors that likely modulate acquisition [24]. Saffran and colleagues [24] suggested, more generally, that pattern learning is facilitated when the perceptual information presented matches the relevant learning mechanism, and, in this sense, learning mechanisms are constrained by the nature of the information acquired. Gerken [26] provides interesting results in this context. Gerken [26] replicates the findings of Marcus and colleagues [22] in two experiments in which infant learners were exposed to different acquisition sets, generated from the same artificial grammar, and with several plausible generalizations possible. The results showed that one group of learners generalized in one direction, while the other did not, and this depended on the structure of the acquisition set. Gerken [26] suggested that learners behave conservatively and do not generalize too far beyond the regularities present in the input. This suggests that the structure of the acquisition set, or stimulus domain, influences the type of regularities that the learner will be tracking and acquiring [26]. Similarly, the results of Saffran and colleagues (2005) suggest that the structure of the input determines the primitives over which generalizations are made, which presumably are part of either an innate endowment, or previously acquired, or both. This type of research, in which the generalization properties of the acquisition machinery is characterized as a function of the input data, is of critical importance and harbors the potential to distinguish between theories of language development.

In contrast to pattern-based abstraction, *category-based generalization* involves operations over abstract rather than perceptually grounded variables [3]. Gómez and Gerken [3] illustrate the point by comparing the pattern-based representation ABA with the category-based representation Noun-Verb-Noun. Recognizing ABA and Noun-Verb-Noun both involve identity. In the ABA case, the relation is surface bound and related to the identity of two tokens of the same type (A = A), while in the Noun-Verb-Noun case, the identity relation holds over categories (Noun = Noun). In the latter case, the learner has to identify the first and third elements as members of the category Noun. The ability to abstract over categories is fundamental to natural language acquisition/processing. One hypothesis is that a learner who identifies a novel word as belonging to a particular category has immediate access to all of the rules involving that category. Category-based abstraction and the problem of how learners acquire relations between grammatical classes are therefore central to understanding language acquisition. While arbitrary abstract dependencies are difficult to acquire in general, if a subset of category members are conceptually or perceptually marked, the acquisition task might be simpler – abstraction seem to occur when there is sufficient evidence to distinguish the relevant categories [3]. Again, this suggests that there are constraints on the learner and the nature of the acquisition mechanisms [27]. Finally, there is one important domain, the mapping of developmental trajectories under experimental control, in which infant research on ALL cannot be replaced by corresponding adult research. An interesting example was recently reported by Gómez and Maye [28], who investigated the acquisition of simple non-adjacent dependencies in infants. The results suggested that 15-month-old children were able to acquire a simple non-adjacent dependency structure, while this was not the case for 12-months-olds. This developmental dissociation might be understood in terms of, for example, differences in the size of on-line processing windows, modulated by attention and working memory capacities, differences in representational capacities, or innate developing biases – all topics for future research.

Artificial Syntax Learning in Adults. A crucial assumption in research on artificial language learning and structured sequence processing is of course that the mechanisms involved are shared with natural language acquisition and processing. A growing body of evidence suggests that this is indeed the case. This includes evidence from studies using functional magnetic resonance imaging

[FMRI, 4, 9, 29], electro-encephalography [EEG, 13, 30], and transcranial magnetic stimulation [TMS, 31, 32]. Furthermore, behavioral investigations also suggest that artificial language learning/processing is relevant to natural language learning/processing, including parallel developmental trajectories mapped with artificial [28] and natural language material [33], as well as brain lesion studies suggesting that language processing deficits are paralleled by impairment in structured sequence learning/processing [34-39]. The acquisition of knowledge of sequence structure in adults is typically investigated in various artificial grammar learning (AGL) paradigms. The implicit AGL paradigm provides one approach to systematically investigating aspects of structural (i.e., syntactic) acquisition from exposure to grammatical (i.e., positive) examples alone, without explicit feedback, teaching instruction, or engaging subjects in explicit problem solving by instruction [4]. In certain important respects, these acquisition conditions resemble those found in natural language development. Generally, AGL consists of acquisition and test phases. In the acquisition phase, participants are exposed to an acquisition set generated from a formal grammar. In the standard version, subjects are informed after acquisition that the sequences were generated according to a complex set of rules (but they are not told about the actual rules), and are asked to classify novel sequences as grammatical or not, based on their immediate "gut feeling". A robust finding is that subjects classify well above chance, both for regular [e.g., 4, 8, 40, 41] and non-regular sequential dependencies, including context-sensitive non-adjacent dependencies [42].

An alternative way to assess implicit artificial syntax acquisition is the structural mere exposure version of AGL, in which participants are never informed about an underlying generative mechanism [40, 41]. This version is based on the "mere exposure effect", which refers to the finding that repeated exposure to a stimulus induces an increased preference for that stimulus compared to novel stimuli [43]. In structural mere exposure AGL, participants are asked to make preference judgments on novel sequences (like/prefer or not), based on their immediate intuitive impression. Folia and colleagues [40] investigated both grammaticality and preference classification after five days of implicit acquisition on sequences generated from a simple right-linear unification grammar [cf. e.g., 29]. The grammaticality task was administered after the last preference classification on the last day of the experiment. The results showed that the participants performed well above chance on both preference and grammaticality classification. In addition to the factor *grammaticality status*, we also manipulated a measure of local subsequence familiarity, *associative chunk strength*, [high/low ACS, cf., 9, 11, 40, 44]. The effect of local subsequence familiarity on endorsement rates were small compared to the effect of actual grammaticality status. These results suggest that structural knowledge, independent of ACS, is used to classify novel sequences and provides support for the notion that syntactic structure, other than local subsequence regularities, is used for both preference and grammaticality classification. Subjective reports also showed that the participants did not utilize rule-searching or other explicit problem solving strategies but that their classification decisions were reached by guessing based on "gut feeling". Moreover, the subjective ratings of perceived performance did not correlate with the actual performance. Very similar results were found in another preference/grammaticality study of adult learners [41].

Uddén and colleagues [42, 45] investigated the implicit acquisition of nested and crossed non-adjacent dependencies (corresponding to context-free and context-sensitive grammars, respectively), while controlling for local subsequence familiarity. In contrast to many AGL studies, we used an implicit learning paradigm over nine days – long enough to allow for both abstraction processes and knowledge consolidation to take place. This is important in implicit AGL because sleep has a significant effect on classification performance in adults [46]. This is also consistent with results that naps promote abstraction processes after ALL in 15-month-old infants [47]. In a first experiment, Uddén and colleagues directly compared the acquisition of regular and non-regular syntax (i.e., nested dependencies) in a within-subject design. We found that subjects implicitly acquired knowledge about the non-regular nested structures. However, the acquisition of non-regular aspects was harder than regular aspects of the underlying grammar.

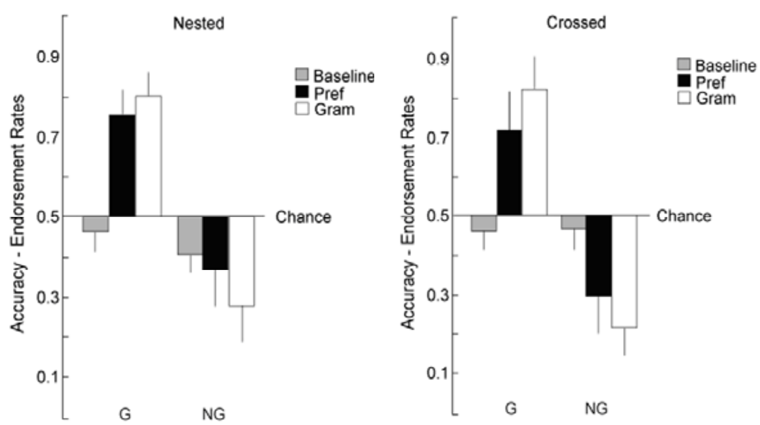

Figure 2. Classification performance in endorsement rates. Pref = preference classification, which was also in the baseline test. Gram = grammaticality classification. Error-bars indicate standard deviations.

In a second experiment, we investigated an agreement structure which generated context-sensitive, crossed dependencies. The non-grammatical sequences consisted of two violation types: *category violations* ($A_1A_2A_3A_4B_2B_1$) and *agreement violations* (e.g., $A_1A_3A_2B_3B_2B_1$). The results of the second experiment replicated the finding from the first that participants implicitly acquire non-regular structure. In addition, the results showed that agreement violations were significantly harder to acquire than category violations. In the final experiment, we employed a between-subject design to compare the implicit acquisition of context-sensitive, crossed dependencies (e.g., $A_1A_2A_3B_1B_2B_3$), and the more commonly studied context-free, nested dependencies (e.g., $A_1A_2A_3B_3B_2B_1$). The results showed robust classification performance, equivalent to the levels observed with regular grammars, for both types of non-regular dependencies (**Figure 2**). The post-experimental questionnaire showed, as in the previous experiments, that there was little evidence for any explicit knowledge of the underlying grammar, supporting the notion that structural knowledge was implicitly acquired. Similar findings have also been reported by others [48]. In particular, de Vries and colleagues [48] showed that learning of non-adjacent dependencies can be facilitated by perceptual cues that make the non-adjacent dependencies more salient. Taken together, these results strongly support the notion that humans can implicitly acquire knowledge about complex systems of interacting rules by mere exposure to the acquisition material. Moreover, the results show that if given enough acquisition exposure, participants demonstrated robust implicit learning of non-adjacent dependencies of both context-free and context-sensitive type at levels comparable to simple right-linear structures.

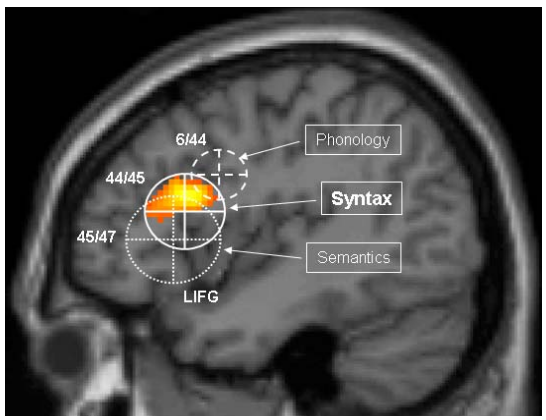

Figure 3. Regions related to phonological, syntactic, and semantic processing (cf., Bookheimer, 2002, and Hagoort, 2005). Left: Activation related to artificial syntactic violations (Petersson et al., 2004).

FMRI Findings in Adults. In a recent FMRI study of implicit AGL [49], we investigated a simple right-linear unification grammar [cf., 50, 51, 52] in which subjects were exposed to grammatical sequences in an immediate short-term memory task with no performance feedback. Implicit acquisition took place over 5 days. On the last day a grammaticality test was administered with the factors grammaticality and local subsequence familiarity [technically, associate chunk strength (ACS), cf., 11, 44]. In addition, natural language data from a sentence comprehension experiment had been acquired in the same subjects in a factorial design with the factors syntax and semantics [for details see 53]. The main results of this study [49] replicate previous findings on implicit AGL in detail [4, 9]. First, in contrast to claims that Broca's region, in the context of language processing, is specifically related to syntactic movement [54-56] or the processing of nested dependencies [57-59], we found the left inferior frontal region centered on Brodmann´s area (BA) 44 and 45 to be activated during the processing of well-formed (grammatical) sequence from a simple right-linear unification grammar independent of local subsequence familiarity. Second, Broca's region was engaged to a greater extent for artificial syntactic violations, that is, when the unification of structural pieces becomes more difficult or impossible [cf., 50] and that the effects related to artificial syntactic processing in Broca's region were essentially identical when we masked these with activity related to natural syntax processing in the same subjects [53]. We note here that the unification operator in any unification grammar is an *incremental and recursive* process [see 49 for details]. Thus, our results were also highly consistent with functional localization of natural language syntax in the left inferior frontal gyrus [Figure 3, 50, 60]. Interestingly, the medial temporal lobe was deactivated during artificial syntactic processing, consistent with the view that implicit processing does not rely on declarative memory mechanisms that engage the medial temporal lobe memory system [11, 61, 62].

Given the findings of Folia and colleagues [40] as well as Uddén and colleagues [42, 63] that grammaticality and preference classification are essentially equivalent at the behavioral level after implicit acquisition, we decided to investigate this issue with FMRI. Participants were exposed to a simple right-linear unification grammar in an implicit AGL paradigm during 5 days. On day 1, FMRI data was acquired during a baseline preference task in which the participants had to classify sequences as likable/preferable or not based on their immediate "gut-feeling". There were no significant effects of grammaticality status or local subsequence familiarity on day 1, neither at the brain nor the behavioral level. On day 5, the participants classified new sequences as likable/preferable or not. In contrast to the baseline preference classification, the preferences of the subjects now correlated significantly with the grammaticality status of the sequences both at the behavioral and brain level (**Figure 4**).

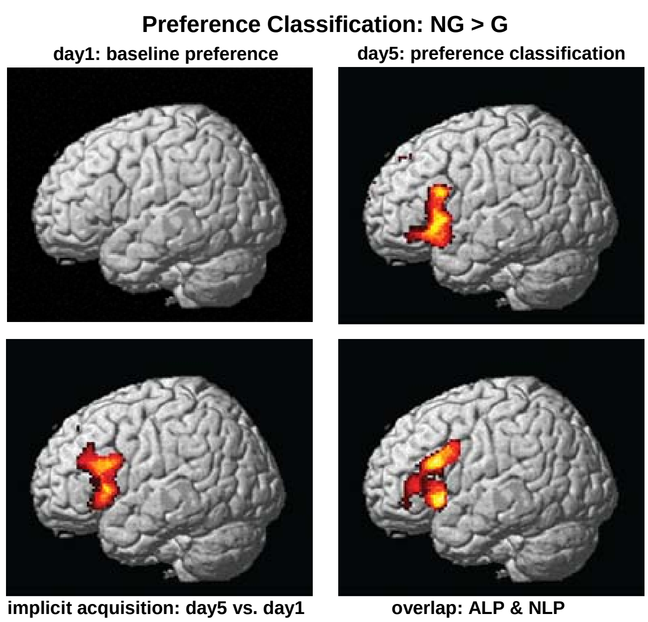

Figure 4. Brain regions engaged during correct preference classification. The main effect non-grammatical vs. grammatical sequences on day 1, baseline (preference) classification (**top left**); on day 5, preference classification after 5 days of implicit acquisition (**top right**); the effect of implicit acquisition (**lower left**); and the main effect non-grammatical (NG) > grammatical (G) during grammaticality classification (**lower right**), here masked with the syntax related variability [49].

Based on these, and previous findings, Petersson and colleagues [29] concluded that the left inferior frontal region is a generic on-line sequence processor that unifies information from various sources in an incremental and recursive manner, independent of whether there are requirements for syntactic movement or processing of nested non-adjacent dependencies, or not.

TMS Findings in Adults. One way to test whether the neural correlates of artificial syntax processing observed with FMRI in Broca's region (BA 44/45) is causally related to classification performance is to test whether repeated transcranial magnetic stimulation (rTMS) to Broca's region modulates classification performance. We have previously shown that Broca's region is causally involved in syntactic processing of sequences generated from a simple right-linear regular grammar [31]. In a recent follow-up, Uddén and colleagues [64] investigated whether this was also the case for non-regular non-adjacent dependencies. More specifically, we investigated the same context-sensitive type of crossed dependencies as described above in an off-line 1 Hz rTMS paradigm in which the left inferior frontal region (BA 44/45) and the vertex (control region) were stimulated. We found a significant performance decrease after LIFG stimulation compared to vertex stimulation (a control region irrelevant to syntactic processing). Thus, the TMS results show that Broca's region is causally involved in artificial syntax processing.

Dyslexia: An Implicit Learning Deficit? In the final section of this review of implicit learning and artificial language learning, we present a brief but comprehensive review of recent findings of an association between dyslexia and implicit learning deficits. An important weakness of all studies of implicit learning in dyslexics to date is that they lack a developmental design [65]. Another weakness is that some of the studies report null-findings, while weak tendencies in the reported data suggest an implicit learning deficit in the dyslexics. Nevertheless, the conflicting literature on implicit learning and dyslexia might suggest that it is not enough to investigate simple implicit acquisition or just to contrast implicit and explicit learning.

Developmental dyslexia is commonly defined as a reading disability, a deficit in learning to spell and write, occurring in children despite normal intelligence, no sensory or neurological impairment and conventional instruction and socio-economic opportunity [66-68]. However, dyslexia is rarely studied in the framework of the contemporary learning literature [40, 69]. Learning to read involves both explicit as well as implicit processes; children initially learn the grapheme-phoneme correspondence explicitly, typically in a supervised manner, after which they apply and continue to learn them implicitly in an unsupervised manner [70].

Vicari et al. (2003) reported deficient implicit learning in dyslexic children in a visuo-motor serial-reaction-type task (SRT; sequences of colors). Their main finding suggests that individuals with developmental dyslexia are impaired in the acquisition of implicit sequence knowledge. In contrast, there was no significant difference between the dyslexic and control groups on explicit sequence learning. Other studies have reported null-findings on similar SRT-type tasks [71, 72]. However, Waber et al. [72] investigated a sample of children with ‘‘heterogeneous learning problems'', which make their findings difficult to interpret in the context of dyslexia. Rüsseler et al. [73] questioned the implicit learning deficit in dyslexia based on these and their own null-findings. However, although there was no significant learning difference between the dyslexic and normal readers, the dyslexic subjects showed consistently longer response times (RTs) on the SRT-task compared to the normal controls. This was also the case in Kelly et al. [71]. Importantly, in a follow-up study, Vicari et al. [74] used the classical SRT-task as well as an implicit mirror drawing test, and showed that the children with developmental dyslexia were impaired on both tasks. Their SRT results suggest a deficit in sequential learning and that the deficit does not depend on the material being learned, but only the implicit character of the task. These behavioral findings were further replicated in an FMRI study of adult dyslexics [75]. Both Stoodley et al. [76] and Howard et al. [69] provided further evidence that the implicit learning deficits observed in dyslexic individuals can be narrowed down to paradigms that involve sequential processing.

Sperling et al. [77] argued that poor implicit learning could hinder the establishment of good phonological processing as well as learning orthographic–phonological representations, while Gombert [70] proposed that children with dyslexia have a phonological deficit that prevents normal implicit learning of linguistic regularities and, hence, interferes with reading development. Howard et al. [69] showed that adult dyslexics are impaired on implicit acquisition in an alternating (higher-order) SRT-task in which sequential dependences exist across non-adjacent elements. Their results suggest that college students with a history of dyslexia are impaired in implicit higher-order sequence learning but unimpaired on spatial context learning. They argued that evidence from patient, functional neuroimaging, and transcranial magnetic stimulation suggest that sequence learning depends on fronto-striatal-cerebellar brain circuitry and that the acquisition of non-adjacent, higher-order, sequential regularities calls on fronto-striatal-cerebellar circuitry whereas spatial contextual learning depends on medial temporal lobe structures [69, 78, 79]. Howard et al. [69] also reported significant positive correlations between measures of reading ability and accuracy-based implicit acquisition measure. Importantly, they were able to rule out several non-specific explanations for their results, including a general cognitive or attention deficit, task difficulty, or age, and established that deficits in implicit sequence learning occur even when explicit learning can be ruled out. Howard et al. [69] emphasize that dyslexics might not suffer from a general implicit learning deficit, but that this is specific to sequence processing, highlighting the importance of sequence complexity (i.e., the level of structure present in the sequences), consistent with the findings of Vicari et al. [74, 80].

Much less is known about the implicit acquisition of artificial grammars in dyslexics. To date only four studies on dyslexia have been conducted using this paradigm. Rüsseler et al. [73] used a short acquisition session and report null-findings for correct responses on the grammaticality task; no baseline classification was included in the experiment, and they did not control for local subsequence regularities. Although there was no significant difference between the dyslexic and normal readers, the dyslexic subjects performed at a lower level on the classification task. Pothos and Kirk [81] used the artificial grammar of Knowlton & Squire [11] in two AGL tasks with different stimulus format in a between-subject design: in the geometric-shapes-embedded task, the stimuli were created to encourage whole stimulus perception, de-emphasizing the constituent elements, while in the geometric-shapes-sequential task the constituent elements were emphasized by presenting them serially. Pothos and Kirk [81] controlled for local subsequence regularities. The dyslexic group performed equally well on ‘’grammaticality’’ classification in both tasks. The non-dyslexic group performed as well as the dyslexic group on the visual-embedded but less well on the visual-sequential task. Pothos and Kirk [81] argued that the dyslexic participants were less able to process the individual stimulus elements and proposed that competent real world learning is achieved via an interaction of implicit and explicit learning processes. Finally, Pavlidou and colleagues [82, see also 83] investigated a group of typically developing and developmental dyslexic primary school children on a modified AGL task in which grammaticality status and local subsequence familiarity was manipulated. Interestingly, the dyslexic group showed no significant effect of either grammaticality status or local subsequence familiarity, while the normal controls did. Based on these findings, they argued that developmental dyslexia is associated with an impaired implicit rule abstraction mechanism.

In summary, there is a growing series of studies of implicit learning in dyslexia. Taken together, these studies suggest that there are aspects of implicit learning that might operate at sub-normal levels in dyslexic individuals. The lack of a developmental design in these studies [65] prevents us from making any conclusions concerning the causal role of an implicit acquisition deficit in dyslexia. It might be an outcome of dyslexia rather than a cause, similar in character to the many parallel findings between the dyslexic and illiterate brain [84-86]. A few tentative conclusions are warranted, however: (1) dyslexia does not seem to be associated with a general implicit learning impairment; (2) the implicit learning impairment observed does not seem to be related to non-specific factors such as general cognitive or attention deficit, task difficulty, or age; (3) the implicit acquisition deficit seems to be related to sequence processing, modulated by sequence complexity (i.e., the level of structure present in the sequences, for a short review see Petersson [87] and a comprehensive review see Davis et al. [88]); and (4) the implicit learning deficit in dyslexia can be observed when explicit learning is intact.

Conclusions. A growing body of empirical evidence suggests that the mechanisms involved in artificial language learning and structured sequence processing is shared with natural language acquisition and natural language processing. This includes evidence from functional neuroimaging studies using MRI, EEG, and TMS. In addition, we reviewed the literature on implicit learning and dyslexia, which seems to suggest that dyslexia is associated with a specific implicit learning impairment related to sequence processing and sequence complexity.

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