Language, Reading, and Motor Control: Get Rhythm!

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1. Introduction

Biological Foundations of Language already included a discussion of the role of temporal structural regularities and rhythm as organizing principle in language (see chapter 3 in Lenneberg 1967). In this article, we rely on Lenneberg's biological notion of language and related ideas like rhythmicity and temporal structural regularities in order to show that individuals with developmental dyslexia (DD) are less efficient than control individuals in using structural regularities during handwriting and some language activities. Consequently, they cannot fully exploit (temporal) structural representations to process oral language, to execute handwriting movement and to read, although they have developed compensatory mechanisms to understand language, perform motor activities, and read. This proposal is based on findings collected in a varieties of studies conducted in our lab.

First, we show that children with DD, who do not fail standardized language tests, but do not process oral language in the same ways as age-matched peers, as evident through ERP measures. They are also less efficient than control peers in morphologically manipulating non-words. Second, we show that children with DD are impaired in complying with two rhythmic principles governing handwriting considered in its motor dimension (not spelling), although they do not meet the criteria for disgraphia. Thus, children with DD have subtle oral language problems and motor disorders, beyond clear reading difficulties.

Although we are aware of the great genetic and phenotypic heterogeneity of dyslexia and language disorders, we would like to conjecture that there might be a common source to language, motor and reading difficulties. This lies in the efficient use of the temporal structural regularities underlying these three behaviors. The possibility of a common source does not preclude the existence of different phenotypic manifestations, as the way to compensate for the difficulties may vary across individuals.

2. Heterogeneity in Development Dyslexia

DD is usually defined as a specific difficulty in learning to read accurately and fluently. Many researchers agree on the notion that DD is the expression of a core deficit in phonology (Ramus, Pidgeon & Frith 2003, Snowling 2000) rather than in visual processing or in attention (Vellutino et al. 2004). As such, it is a language-related disorder (Vellutino 1977). The complex and variable neuropsychological profiles of individuals with DD have promoted other hypotheses, and have led

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to the notion that there exist different types of DD. For example, Wolf & Bowers (1999) suggested that there are three types of DD. One whose core deficit is phonology, a second one caused by a timing deficit that impairs temporal integration of the letters' forming words (Bowers & Wolf 1993) and prevents children with DD to recognize and represent orthographic patterns and a third one caused by the combination of the preceding two types. Other subtypes of DD, resulting from the breakdown of component processes involved in reading, are discussed in Zoccolotti & Friedmann (2010) and Friedmann & Coltheart (in press).

Beyond the heterogeneity in the profiles of individuals with DD, another dimension of variation is the fact that often children with DD display difficulties with language before their exposure to literacy, which are expressed in delay of language onset and of development. Among others, McArthur et al. (2000) reported that 55% of the children with DD scored more than one standard deviation below the mean on CELF-R, a test measuring oral syntactic and morphosyntactic skills. In other words, DD often co-occurs with language difficulties.

In addition to language problems, some studies revealed that children with DD experience fine and gross motor problems (Cappellini, Coppede & Valle 2010, Cheng-Lai et al. 2011, Thompson et al. 2015). It should be pointed out that, with few exceptions, motor skills in children with DD have rarely been investigated. These exceptions include Nicolson & Fawcett 1990 (see also Nicolson & Fawcett 2011), who formulated the Automatisation Deficit Hypothesis, according to which children with DD have difficulties in automatizing skills, including reading and motor skills. This hypothesis has been further developed into the Cerebellar Deficit Hypothesis. In this theory, the co-occurrence of reading and motor problems finds its root in a dysfunction at the level of the cerebellum, that blocks the automatisation of skills (e.g., reading, motoric skills, rules of language; see e.g., Stoodley & Stein 2013, Stoodley 2014 for a critical view of this hypothesis). Other exceptions are studies in which the tapping activity in synchrony with an isochronic-pacing metronome was investigated. In particular, Wolff (2002) found that, in a tapping task, students with DD anticipated an isochronic-pacing metronome signal much more than control children did and had some difficulties in reproducing patterned rhythms. Extending this line of research, Thomson & Goswami (2008) asked 10-year-old children with DD to tap in time/synchrony with a metronome beat. They found variability within individuals in the paced inter-tap intervals, suggesting that these children were not constant in their tapping rate within a given condition. In addition, association between motoric and auditory rhythmic skills, on the one hand, and literacy measures, on the other, were found. Other studies supported the relevance of the link between rhythm perception and literacy (Flaugnacco et al. 2014) and between rhythmic skills and grammar (see Gordon et al. 2015) and led to the conclusion that rhythmic timing may be crucial for language, motor skills and reading. Overall, these findings suggest that there is a lot of heterogeneity in individuals with DD and that DD often co-occurs with language problems and with motor deficits. They also revealed a special role for rhythmic timing.

3. Morphological Rules in Children with Developmental Dyslexia

As outlined in the previous section, several studies have demonstrated that children with DD have problems with oral language. For example, Joanisse et al.

(2000) reported that English-speaking children with DD have difficulties in the use of past verb marking (*-ed*); Bar-Shalom, Crain & Shankweiler (1993) showed that 7- to 8-year-old English-speaking children with DD have severe difficulties in comprehending relative clauses (see also Robertson & Joanisse 2010). In addition, individuals with DD, who do not fail on standardized oral language measures or behave as controls in behavioural tasks, may display subtle morphosyntactic problems evidenced through the event related potential (ERP) technique. Rispens, Been & Zwarts (2006) showed that Dutch-speaking adults with DD exhibit ERP anomalies during the processing of oral sentences including a subject-verb agreement violation (equivalent to *the child speak* or *the children speaks*; see also Rispens, Roeleven & Koster 2004).

In a similar vein, Cantiani et al. (2015) found that 8–10 year old Italian-speaking children with DD, who did not differ from controls on an Italian standardized test for grammatical comprehension, manifested an atypical ERP response during the processing of oral sentences including a subject-verb agreement violation. Specifically, whilst in control children the subject-verb agreement violation elicited the expected P600, in children with DD the same violation provoked a N400, suggesting that the two groups did not process this morphosyntactic violation in the same way (see also Rispens, Roelevan & Koster 2004). Interestingly, the two groups did not differ in the behavioural task consisting of judging the grammaticality of the sentences.[1] However, the two groups differed on a behavioural task requiring the morphological manipulation of non-words. In this task, children were given a legal non-word and were asked to produce the diminutive, the augmentative, or they had to derive the infinitive from when given a finite invented verb, or derive the noun from a given verb. In other words, children had to use their implicit knowledge of various morphological rules, whose application is very common in Italian. The results showed that children with DD scored significantly lower than control children.

Cantiani et al. (2013) interpreted these findings in the light of the Declarative/Procedural model (Ullman 2001, Ullman & Pullman 2015) and suggested that the N400 response found in children with DD reflected the use of a lexical-semantic compensatory strategy or the use of an explicit rule. Children with DD have difficulties in forming or using implicit morphological rules stored in the procedural memory and rely on explicit rules or on lexical forms stored in the declarative memory. Otherwise put, children with DD process subject-verb agreement violations through a lexical-semantic route, rather than a structural syntactic dependency applied at the hierarchical level between a constituent and an inflectional head hosting the inflected verb (Guasti 2017). Consistent with this view, children with DD were unable to use implicit morphological rules to modify non-words and to the extent that they succeed, they likely used processes like analogy to existent words memorized in the declarative memory. This conjecture is supported by the fact that the higher the negativity of the N400 in the ERP task, the greater the accuracy in the morphological manipulation of non-words.

[1] Similar behavioural and ERP evidence was gathered by Cantiani et al. (2013) with well-compensated adults affected by DD, who were followed in the same clinic from their childhood and never received a diagnosis of specific oral language impairments.

All in all, these findings suggest that children with DD exhibit subtle problems in oral language, which are not necessarily evident in standardized behavioural task and in everyday life, because they are very well compensated. However, these problems are very relevant to understand the nature of the difficulties, which affect individuals with DD. Whether oral language problems in children with DD results from comorbidity with Specific Language Impairment (SLI) or are the sign of a deeper relation between the two disorders is an open question. What we can conclude is that these language deficits seem to be located in the rule-governed component of language and are compensated through lexical-semantic processes, whose nature requires further investigation.

4. Motor Rhythmic Difficulties in Children with Developmental Dyslexia

While the association between DD and motor skills deficit is generally seen as a case of comorbidity, the works by Wolff (2002) and Thomson & Goswami (2008) put forward the possibility that rhythmicity plays a crucial role in these two disorders. According to Llinás (1993) "rhythmicity is the ability to generate a sequence of rhythmic events that are time-locked to each other" (Pagliarini et al. 2015: 162). Furthermore, Llinás (1993) noticed that individuals with DD, beyond linguistic deficits, had difficulties in generating fast sequential movements. Inspired by these observations, and based on the hypothesis that rhythmicity may be impaired in individuals with DD, Pagliarini et al. (2015) studied handwriting in children with DD and in control children.

Handwriting is a motor activity which requires the generation of a rapid sequence of movements governed by two rhythmic principles: Isochrony and homothety. These two principles, which govern different types of movement, are here explained in relation to handwriting. According to the principle of isochrony, the absolute writing duration of a word (or generally of a movement) remains more or less invariant irrespective of its size (Freeman 1914, Lacquaniti, Terzuolo & Viviani 1983, Viviani & Terzuolo 1983). This invariance is guaranteed by the existence of a compensatory mechanism that guides the writer in modulating writing speed as a function of the size of the word being written (Binet & Courtier 1893, Stetson & McDill 1923, Viviani & Terzuolo 1982). For example, if the size of a word increases, the speed of handwriting will also increase, that is, one writes faster. The principle of homothety (Lashley 1951, Viviani & Terzuolo 1982) asserts that the relative duration of the writing of the single letters of a word will remain the same across changes in the writing duration of the whole word. In order to exemplify, let us consider an example. When writing the word *cat*, if the time spent on writing the letter 'c' is 50%, the letter 'a' is 20% and the letter 't' is 30% of the total writing duration of the entire word, the same relative durations are maintained across different total writing durations (as a consequence of writing faster or slower).

Thus, the isochrony principle rules the absolute duration of the whole word (which tends to remain more or less constant under different writing conditions) and the principle of homothety rules the relative duration of single letters, which does not vary despite the variations of the duration of the whole word. Notice that the two principles are independent and a violation of one does not requires a violation of the other.

As we said, Llinás (1993) pointed out that individuals with DD experience difficulties in generating fast sequential movements. Pagliarini et al. (2015) went further and hypothesized that children with DD struggle in complying with the two principles of rhythmic organization of handwriting. Furthermore, the authors conjectured that if rhythmicity is problematic for these children, correlations between handwriting, language, and reading measures should be found, as all these activities involve a rhythmic component. To test these hypotheses, Pagliarini et al. (2015) asked 9-year-old children with DD (scoring -2 SD below the mean on accuracy or speed in a standardized reading task) and same age typically developing (TD) children to write the Italian word *burle* (English: *jokes*) with a wireless pen on a digitizing tablet. Children were asked to write the target word in both cursive and all-capital block scripts, and for each script, children were asked to write the target word in three conditions: Spontaneous, that is, as they usually write, bigger, and faster with respect to the spontaneous condition. A number of kinematic measures (duration, velocity, disfluency) of writing were collected and analyzed.

The results showed that TD children complied with the principle of isochrony, meaning that they wrote faster when they had to write the word bigger (so that the absolute duration of the word remained constant). They also complied with the principle of homothety, meaning that they were able to keep constant the relative writing duration of individual letters across changes in the total word duration. By contrast, children with DD struggled in obeying the two principles. Although children with DD somewhat changed their handwriting behavior across conditions, they did not increase the writing speed adequately when they had to write bigger. In other words, these children had difficulties in modulating their handwriting movement as a function of the size of the word, thus failing to fully comply with the principle of isochrony. They tried, but they did not increase their handwriting movement enough. Children with DD were also less able to keep the relative writing duration of single letters constant across changes in size: For example, they were poor in rescaling the duration of single letters when they had to write bigger. Again, they tried and did some rescaling, but they did not maintain the relative duration constant. These results support the hypothesis that children with DD have difficulties in keeping the rhythm of writing across changes in the size of words.

Furthermore, Pagliarini et al. (2015) also demonstrated that there were correlations between reading, writing, and language (vocabulary and non-word repetition) measures, thus supporting the hypothesis that reading, writing, and language are mediated by rhythmic competence. In a following study, Pagliarini and colleagues (Pagliarini et al. 2017) investigated the development of the rhythmic principles of handwriting by testing typically developing (TD) children from the first to fifth grade of primary school (i.e. from age 6 to 10). The authors found that children with TD were already perfectly able to comply with the principle of isochrony and homothety in their first grade of primary school (i.e., at age 6) and only after a few months of formal education (and of learning to write).[2] They also found that, from age 6 to 10, children complied equally well with these two principles. In other words, TD children do not need a lot of training to comply with the rhythmic principles of handwriting, a fact that is compatible with the idea that

[2] Notice that these children were on average 2–3 years younger than children with DD in Pagliarini et al. (2015).

the two principles are already available before schooling. As a consequence, the difficulties experienced by children with DD in obeying the rhythmic principles of handwriting cannot be due to a lack of training, as already at age 6 TD children comply with them as well as 10-year-old children do.

5. Language, Reading and Motor Skills: What do they Have in Common?

The data reviewed on handwriting suggest that children with DD have troubles with the rhythmic principles of writing movements, that is, with the temporal structure that underlies the production of sequential movements. Let us consider more thoroughly what it means to comply with the principles of isochrony and homothety, which govern the rhythm of writing. To keep the absolute duration of the whole word and the relative duration of single letters constant across changes in size, one needs to have an abstract temporal representation (independent of the specific script), that is, the temporal structure of the whole handwriting movement (of the word) and of its components before starting to write. In this way one can modulate the velocity appropriately for writing the whole word and for rescaling the relative duration of single letters when the total duration changes. This representation is hierarchical in that the time allocated to each component unit (letters and, below letters, strokes) of the word depends on the duration of the whole word. There are two key aspects that are worth to be emphasized further. One is that to behave adequately and efficiently during handwriting, one needs to have an abstract hierarchical representation of the movements; the second is that one employs this temporal representation to anticipate changes in velocity and in rescaling the duration of components movements. Based on the findings we discussed, different options are open to characterize the difficulties experienced by children with DD. We could say that children with DD do not have the abstract representation underlying the execution of movement or have a different representation (e.g., with less details) than TD children. They could also have the same representation as TD children, but cannot exploit it as efficiently as TD children to modulate their handwriting movements.

Let us now consider the data reviewed about oral language problems in children with DD. These also point toward a problem having to do with the abstract representations or with the rules underlying word formation or sentence formation. Children with DD are less efficient than TD children in applying morphological rules to non-words to obtain other non-words with for example specific suffixes. They also do not process the subject-inflected verb agreement dependency via an abstract morphosyntactic rule, according to which agreement holds between a constituent located in a certain hierarchical configuration in the clausal structure and the verbal inflection. In this case, it was found that at the behavioural level children with DD were as good as TD children in judging the grammatical violations.

The ERP data shed light on this aspect by revealing that they did so in a different way than TD children. What can this different way be? One possibility is to assume that, on the basis of a morphosyntactic rule, children can predict the inflection on the verb by having extracted the inflection of the subject constituent. Another way consists in processing the subject constituent, processing the inflected verb and verify that their agreement suffixes match. The first mechanism is more efficient than the second one, because it is based on prediction and consists in temporally anticipating something that has still to come. If the prediction is met, as happens in most of the cases, nothing has to be done. The second mechanism does not predict: It checks that the linguistic features of two items match. It is obvious that children who use the second mechanism to process language are less efficient in reading or read slowly, since reading also takes advantage of the ability to predict. Based on this, two alternatives can be drawn: Children with DD perform language tasks and process language by basing themselves on different representations or rules than TD children. Alternatively, the mechanisms that they use are less efficient than the mechanisms used by TD children. Cantiani et al. (2015) conjectured that children with DD used lexical-semantic rules stored in declarative memory rather than morphosyntactic rules stored in the procedural memory.[3] If this is so, we have to conclude that the former types of rules may lead to less efficient linguistic behaviours than the latter ones, e.g., in the case of the morphological manipulation of non-words, but not in judging grammatical and ungrammatical sentences.

Our data on handwriting (Pagliarini et al., 2015, Pagliarini et al., 2017) and oral language processing (Cantiani et al., 2015) in children with DD leave open some options concerning what may get awry, but somehow these options turn around the notion of abstract hierarchical representation, abstract temporal representation and prediction. In fact, having an abstract representation or a rule is used for predicting incoming input. Children with DD might be able to extract some sort of abstract representation, but this is less detailed than that of TD children or is of a different nature and its use is less efficient than that of the representation that TD children can avail themselves of. Alternatively, the abstract representation can be the same in children with DD and in children with TD, but the mechanisms that use this representation are less efficient in children with DD.

How are these conjectures related to the defining problems of DD, that is, troubles in reading? First, reading is grounded on oral language (see Kovelman et al. 2008), both at the level of decoding and of comprehending written texts.[4] In fact, one hypothesis attributes the problems of children with DD to phonology. Second, reading also involves forming abstract orthographic representations (i.e., not specified in a particular script) of words or of units larger than graphemes (e.g., morphemes) that can be used to predict future words (for example on the basis of the first morpheme of a word, one can predict the rest of the word). It is known that the number of fixations (on a text) is higher for children with DD than for TD children. This fact suggests that children with TD can predict and thus skip frequent words or highly expected words, that is, to recognize words, they do not need to perceptually process them all; children with DD, instead, do not predict as efficiently as TD children and have to process all (or almost all) words to recognize them. This is precisely what we have conjectured above when we suggested that

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3 Ullmann & Pierpoint (2005) advance a similar hypothesis for children with SLI. They proposed the Procedural deficit hypothesis, whereby children with SLI suffer from atypical development of brain structures that subserve procedural memory. See also van der Lely & Ullman (2001) and van der Lely (2005).

4 Kovelmann et al. (2008) showed that 8-year-old children exposed to English after age 3 are weaker than monolingual and children exposed before age 3 on word reading and phonological awareness tasks.

there can be two mechanisms to perform linguistic tasks, one based on prediction and one not based on predictions. In ongoing research, we are exploring the possibility that the predictive mechanism is not efficient or is impaired in individuals with DD. Preliminary results show that individuals with DD are poor in anticipating future events, that is, they are not as efficient as TD children/adults in using an abstract representation to predict future events.

Although we left some options open, our proposal amounts to say that there is a common core underlying language (and reading being a language-related activity) and motor actions. It is possible that this common core consists in making efficient use of supra-modal abstract hierarchical representations to predict future events. The idea that the shape of linguistic rules is not domain-specific, but is shared, at least in part, with other cognitive systems converges with data from a fMRI study carried out by Tettamanti et al. (2009) on healthy adults. In this study, the authors extended to the visuo-spatial domain a previous fMRI study by Tettamanti and colleagues (Tettamanti et al. 2002) carried out with language stimuli (see also Tettamanti & Weniger 2002). In Tettamanti et al. (2002), the processing of non-rigid syntactic dependencies (NRSD; e.g., drop the subject of finite clauses) in the language domain was contrasted with the processing of rigid syntactic dependencies (RSD), that is, dependencies between items at fixed position (e.g., negation is the third element of a sentence). In Tettamanti et al. (2009), the same two types of rules (NRSD and RSD) were tested in the visuo-spatial domain (instantiated by sequences of symbols). During the training phase, participants were exposed to strings that obeyed either NRSD or RSD and had to discover the rules. During the testing phase, they had to judge whether given strings conformed or not to the learned rules. Tettamanti et al. (2009) hypothesized that "non-rigid" syntactic dependencies (NRSD)–that is, syntactic rules established between words at various positions, which "are the core type of dependencies found in all human languages", are not domain-specific, but are present in various cognitive domains (beyond language). The authors found that participants were able to learn both types of rules (NRSD and RSD) with great accuracy when presented in the visuo-spatial domain. However, learning RSD was slower than learning NRSD. In addition, the processing of NRSD in the visuo-spatial domain, as previously established for the language domain, activated Broadmann area 44 of the left inferior frontal gyrus.

The authors conclude that "in the human brain, one single 'grammar without words' [expressed by NRSD rules] serves different higher cognitive functions" (Tettamanti et al. 2009: 825). Our data based on language and motor skills in children with DD are compatible with the idea that this grammar may be less efficiently used by children with DD compared to children with TD and this may cause subtle deficits across different cognitive domains that may be very well compensated and hard to single out in everyday activities.

6. Conclusion

In this short article, we have seen that children with DD have difficulties in maintaining the rhythm of handwriting and have difficulties in manipulating words and sentences. On this basis, we have proposed that they exhibit deficits in making efficient use of abstract temporal representations or rules. Alternatively, we could suggest that they have difficulties in extracting abstract temporal representations or rules, or have less detailed abstract representations than TD children. At present, the data discussed do not allow us to decide between these hypotheses. Our conjectures converge with extant data showing that there are links between rhythm perception and literacy (Flaugnacco et al. 2014), between rhythmic skills and grammar (see Gordon et al. 2015). It is also consistent with the findings that there are non-rigid syntactic dependencies that are operative in different cognitive domains (Tettamanti et al. 2009). Although there are various pieces of data that go in the same direction, nevertheless our conjectures open a series of questions: Why is there heterogeneity among individuals with DD? Is the deficit we have uncovered present in populations with other language problems, like individuals with SLI? Since children with SLI and DD differ from children with a sole diagnosis of DD (even if language impairments are evident in these individuals; see Cantiani et al. 2015 and reference cited there), what makes them different?

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