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RESEARCH ARTICLE

Slowing in reading and picture naming: the effects of aging and developmental dyslexia

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Abstract We examined the slowing in vocal reaction times shown by dyslexic (compared to control) children with that of older (compared to younger) adults using an approach focusing on the detection of global, non-task-specific components. To address this aim, data were analyzed with reference to the difference engine (DEM) and rate and amount (RAM) models. In Experiment 1, typically developing children, children with dyslexia (both attending sixth grade), younger adults and older adults read words and non-words and named pictures. In Experiment 2, word and picture conditions were presented to dyslexic and control children attending eighth grade. In both experiments, dyslexic children were delayed in reading conditions, while they were unimpaired in naming pictures (a finding which indicates spared access to the phonological lexicon). The reading difficulty was well accounted for by a single multiplicative factor while only the residual effect of length (but not frequency and lexicality) was present after controlling for over-additivity using a linear mixed effects model with random slopes on critical variables. Older adults were slower than younger adults across reading and naming conditions. This deficit was well described by a single multiplicative factor. Thus, while slowing of information processing is limited to orthographic stimuli in dyslexic children, it cuts across verbal tasks in older adults. Overall, speed differences in groups such as dyslexic children and older adults can be effectively described with reference to deficits in domains encompassing a variety of experimental conditions rather than deficits in single specific task/conditions. The DEM and RAM prove effective in teasing out global vs. specific components of performance.

Keywords Dyslexia · Picture naming · Vocal reaction time · Difference engine model · Rate and amount model · Reading · Aging

Introduction

In the present study, we examined the speed of processing of dyslexic children and that of older adults to evaluate whether group slowing due to a learning deficit has different characteristics with respect to slowing due to aging. Comparing the speed of processing of groups or individuals may require a scale of analysis that goes beyond that of specific tasks (e.g., Cerella 1985). For example, reaction times (RT) of older adults are delayed as compared to those of younger adults across a large variety of experimental conditions, pointing to general, and non-task-specific slowing. Within a broad set of tasks, this delay can be expressed by one (or few) multiplicative factor(s) (e.g., Verhaeghen and Cerella 2002; Verhaeghen 2011). Namely, differences between younger and older adults grow multiplicatively as a function of the difficulty of the experimental tasks

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(defined as the amount of information to be processed for initiating a response; Faust et al. 1999). This multiplicative factor expresses an over-additive effect, such that more difficult conditions produce larger group differences than easier conditions over and above the specific characteristics of the conditions themselves (Faust et al. 1999).

While aging is a likely candidate for global slowing, the same logic may apply to several other group comparisons. Myerson et al. (2003) quote Alzheimer's disease, brain injury, depression, and multiple sclerosis as candidates for analysis of speed of processing in terms of global factors and refer to this approach as "*comparative human cognition*". If one (or few) global factor(s) is (are) sufficient to explain the data, this represents an important simplification. Thus, this approach is considerably more parsimonious than searching for deficient mechanisms based on the full range of tasks on which these patients show impaired performance. In previous papers, we examined the possibility of applying this approach to the study of developmental dyslexia (e.g., Zoccolotti et al. 2008). Namely, we observed that a model of multiplicative worsening as a function of condition difficulty fits well the observed slowing across tasks involving processing of letter strings, such as reading or lexical decision (e.g., Paizi et al. 2013).

In the present study, we compared the RT slowing shown by dyslexic children with that of older adults using an approach controlling for over-additivity and looking at global, non-task-specific effects. In previous work, we referred to two models which focus on global differences in timed tasks: the difference engine model (DEM) by Myerson et al. (2003) and the rate and amount model (RAM) by Faust et al. (1999). They present similar (though not identical) assumptions, and focus on different, but putatively complementary, aspects of performance. In this introduction, we will mainly focus on the DEM as our key interest is in understanding group differences in global components of performance. However, we will also examine whether specific factors (e.g., word length or frequency) may contribute to the group differences once over-additivity is taken into account, which is a core focus of the RAM model.

The DEM (Myerson et al. 2003) aims to show that a single speed factor can account for the diversity in performance between individuals and groups. Accordingly, RTs can be seen comprised two separate and independent components of response: a sensory-motor or non-decisional compartment (marking early sensory-perceptual components and late motor programming components) and a cognitive compartment (marking the processes concerned with the decisional components of a given task). The contribution of these two components can be estimated based on the relationship between condition means and standard deviations (SD); this is the key relationship that ties condition difficulty to inter-individual variation in speed. According to Wagenmakers and Brown (2007), the linear increase of SDs along with that of the mean can be regarded as a law that represents a critical constraint for models of RT performance. Across a large variety of tasks, Myerson et al. (2003) note that, as RTs grow (indicating differences in condition difficulty), so do SDs. This relationship is well expressed by a regression line with a beta coefficient of ca. .30. This indicates that an inter-individual variability grows multiplicatively as tasks become more difficult over and above their specific characteristics. The intercept on the *x*-axis of this linear regression represents an estimate of the average time spent for sensory and motor processing (sensory-motor compartment; about 300 ms according to Myerson et al. 2003) and is expected to be constant.

The relationship between means and SDs predicts performance not only across tasks but also across individuals having different levels of performance. Thus, even if the RTs of younger adults are faster than those of older adults, a single (i.e., the same) linear regression fits the data of both groups; in other terms, the condition means of older adults are generally slower but their associated SDs grow with the same multiplicative factor as do those of younger adults. Accordingly, the experimental points representing data of both younger and older adults are fit by the same regression line, but older adults' points are shifted with respect to those of younger toward the upper and rightward portion of the graph. Myerson et al. (2003) also note that delayed RTs in older adults predominantly depend on the slowing of the cognitive compartment while the sensory-motor compartment is only minimally affected.

Thus, the function relating SDs and means represents an invariant element across tasks and groups. However, this does not necessarily indicate that a given group is equally delayed on every task. For example, older individuals are much more delayed in visuospatial than in lexical/verbal tasks (Hale and Myerson 1996; Lawrence et al. 1998). Thus, plotting the condition means of the older group against those of the younger group (a procedure known as Brinley plot) yields a much steeper slope for visuospatial (3.11) than for lexical/verbal (1.35) tasks (Hale and Myerson 1996). According to Myerson et al. (2003), these different slopes indicate the severity of the impairment; i.e., a greater deficit in visuospatial with respect to verbal performance. To account for these results, Myerson et al. (2003) introduce the idea that deficits can be expressed in terms of separate "domains", i.e., large classes of tasks that share some inherent characteristics. Critically in the DEM, domains produce global effects across a variety of tasks but conform to the same general law underlying the variation in individual performance, i.e., the relationship between difficulty (as assessed by condition means) and inter-individual variability (as assessed by standard deviations of the corresponding conditions; Myerson et al. 2003; see also Chen et al. 2007). It is important to note that domains are empirically defined, i.e., they are not a priori assumed by the model. The studies by Hale and Myerson (1996) and Lawrence et al. (1998) indicate that envisaging verbal and visuospatial domains are the effective means for explaining the effect of aging. Other conditions may require different domains to be adequately defined; thus, this theoretical framework allows envisaging the possibility of global and yet partially distinct deficits. Indeed, effects such as those described by Myerson et al. (2003) in the elderly are global to the extent that they cut across a variety of tasks and yet they are not entirely general as they are selective only for some sub-set of tasks (i.e., visuospatial or verbal tasks). Thus, uncovering the structure of the impaired domain in a given group of subjects is a general aim of the *comparative human cognition* approach and one which has the potentiality to effectively describe a large variety of conditions (Myerson et al. 2003).

The interest here is in examining whether the large-scale impairments evident in the case of aging can be effectively distinguished from that observed in the case of dyslexia. Aging and dyslexia are clearly widely different conditions; yet, they also share some features. In particular, neither condition seems easily accommodated within a single task deficit: furthermore, both are characterized by widespread slowing in a variety of cognitive tasks. Therefore, it seems instructive to more explicitly define these two conditions in terms of affected domains.

As stated above, in the case of aging, deficits have different severity in the visuospatial and in the verbal domains. Likewise, for developmental dyslexia, studies taking into account global components of performance help delineate the specific domain of impairment in these children. Thus, children with dyslexia show the same severe impairment when reading words or non-words (Paizi et al. 2011; Martelli et al. 2014; Zoccolotti et al. 2008) and when performing a lexical decision task (Marinelli et al. 2014; Paizi et al. 2013), the slowness being linearly proportional to task difficulty. By contrast, no (or very limited) deficit is present when dyslexic children read (or discriminate between) single letters (De Luca et al. 2010), name figures (Zoccolotti et al. 2008), perform a lexical decision task in the auditory modality (Marinelli et al. 2011), or repeat words and non-words (Marinelli et al. 2011). Also of note is that the deficit in dyslexic children is limited to the cognitive compartment of these tasks; in fact, no corresponding delay is observed in the sensorimotor compartment (as assessed by the intercept on the *x*-axis; Martelli et al. 2014). Based on these results, the area of impairment concerns the processing of visually presented strings of letters (independent from being words or non-words). In this vein, we have proposed that dyslexic children suffer from a deficit at the pre-lexical "grapheme description", independent of case, font, location or orientation (Marsh and Hillis 2005).

In the present study, we evaluate deficits in speed of processing of such different groups, as dyslexic children and older adults. To address this aim, we manipulated the type of stimuli to be decoded (orthographic strings vs. pictures) as well as various parameters known to influence reading and naming performance, including word length, frequency and lexicality. First, based on the DEM we expected that the same linear relationship between means and SDs would hold for children (with and without dyslexia) and adults (younger and older) across all tasks. Second, we hypothesized that the slowing of dyslexic children and older adults could be better described referring to different domains in which performances operate (see below for specific predictions). Finally, we also evaluated whether specific factors modulate the slowness of dyslexic children and older adults over and above the global slowing within a domain; in particular, we checked for the possible selective influence of factors, such as frequency, lexicality and length (see "Data analysis" for details). Overall, based on the *comparative human cognition* approach by Myerson et al. (2003), the general aim of the study was to demonstrate that a combination of distinct but partially overlapping global and specific factors may effectively characterize the cognitive impairment of different groups of individuals.

Based on the hypothesis of a deficit in the pre-lexical grapheme description, we expected dyslexic children to be impaired within an orthographic domain, defined as a class of tasks requiring the processing of grapheme strings. Accordingly, they should be impaired in word and non-word reading. By contrast, based on previous research we expected dyslexic children not to be delayed in picture naming (Zoccolotti et al. 2008; see also Trauzettel-Klosinski et al. 2006). Notably, this expectation is at variance with the proposal that the core deficit of dyslexic children includes access to the phonological lexicon (Nation et al. 2001; Swan and Goswami 1997), a hypothesis based on their impairment in tests of confrontation naming of pictures. Thus, our experimental conditions should allow us to determine whether dyslexia is accounted for by a deficit in a graphemic domain or in a more general verbal domain. Within the orthographic domain, slowing should be accounted for by a single multiplicative factor with no additional influences of factors such as lexicality and frequency (Paizi et al. 2011, 2013; Zoccolotti et al. 2008). Predictions were more mixed for length because in some previous studies we found a residual effect of length even when the over-additivity effect was controlled for (Paizi et al. 2013; Zoccolotti et al. 2008).

As to older adults, based on previous research showing a moderate slowing in the lexical/verbal domain (Hale and Myerson 1996; Lawrence et al. 1998), we expected to confirm such slowing in all our tasks (which involve verbal processing, namely both reading and picture naming) independent of the orthographic/non-orthographic nature of stimuli; to the extent in which this slowing is global it should be accounted for by a single multiplicative factor.

In Experiment 1, we compared dyslexic children with age-matched controls on reading and picture naming tasks, as well as older adults with younger adults. In Experiment 2, orthographic and non-orthographic conditions were tested on another sample of children with and without dyslexia (motivations for this experiment are presented below).

Experiment 1

Method

Participants

Italian typically developing children, children with dyslexia, younger adults and older adults took part in the study. All had normal or corrected-to-normal visual acuity. Both 12 children with dyslexia and their 17 controls (see Table 1) attended 6th grade. The two groups were comparable for age ($t = .05$; $p = .48$) and gender ($\chi^2 = .81$, $p = .37$). All children scored within the normal limits (according to Pruneti et al. 1996) at the Raven's Coloured Progressive Matrices, a measure of non-verbal intelligence. As recommended by the Consensus Conference on learning disabilities (2011), reading deficits were identified based on a standardized test considering both speed and accuracy measures. Dyslexic children scored at least 1.65 SDs below the norm for either speed or accuracy on a standard reading test (MT Reading test, Cornoldi and Colpo 1995). In this test, the child reads a text passage (comprising a total of 271 words or 592 syllables) aloud with a 4-min time limit. Speed is measured in seconds/syllable. The average reading time (raw data) was .31 s/syllable for children with dyslexia and .23 for typically developing readers ($t = 5.51$; $p < .0001$), that is, a slowing of 35% in the former (see Table 1). Accuracy is measured in terms of number of errors. Scoring takes into account the functional meaning of errors. Each word with an elision, substitution, insertion or inversion of letters is scored as 1 error, while changes in stress assignment, spontaneous self-corrections, errors that do not change the meaning of text, repetitions of the same errors and hesitations are given a ½ score. If the child does not complete the text passage reading, the number of errors adjusted for the amount of text read is scored. Raw and z scores are presented in Table 1.

The study was carried out according to the principles of the 2012–2013 Helsinki Declaration. Informed consent to participate in the study was obtained from the parents of the children. The study was approved by the IRCCS Santa Lucia Ethics Committee (Prot. CE/PROG.480 of 20/02/2015).

Twenty-five younger adults and 22 older adults took part in the study. The two groups were comparable for gender ($\chi^2 = .63$, $p = .20$). All participants scored within the normal limits for adults at the Raven's Standard Progressive Matrices (Spinnler and Tognoni 1987). All adults reported the absence of reading problems or history of language delay. Both groups were given the same reading test used with children (MT Reading test, Cornoldi and Colpo 1995). The average reading time of the two groups was .18 ± .02 for the younger adults and .21 ± .03 s/syllable for the older adults ($t = 3.45$; $p < .001$); thus, older adults were ca. 14% slower than younger adults. Informed consent was obtained from all participants.

Stimuli, apparatus and procedure

Stimuli were 96 pictures of objects, 96 words corresponding to the object names, and 96 non-words. Objects were selected according to the following criteria: their corresponding names were 4-, 5-, 6-, and 7-letters long; the frequency of half of the object names (separately

Table 1 Summary statistics for typically developing children, children with dyslexia, younger and older adults of Experiment 1: mean age (in years, with range in parentheses); N of female and male participants; mean raw scores (and SDs in parentheses) on Raven's Coloured Matrices; mean raw scores and z scores (and SDs in parentheses) on speed and accuracy measures of the MT Reading test (the same passage was used for all groups; z scores were not computed for adults since normative data for the passage are available only for 6th grade children)

	Age	Male	Female	Raven test	Reading speed (s/syllable)	Reading accuracy (errors)	Reading speed (z score)	Reading accuracy (z score)
Typically developing readers ($N = 17$)	11.5 (11.0–12.4)	7	10	33.6 (2.8)	.23 (.03)	7.3 (2.3)	.59 (.29)	.19 (.31)
Children with dyslexia (N = 12)	11.5 (10.9–12.2)	3	9	33.0 (1.9)	.31 (.05)	21.3 (1.3)	−.26 (.53)	−1.95 (.46)
Younger adults ($N = 25$)	23.9 (19.0–26.8)	13	12	51.0 (6.9)	0.18 (.02)	4.5 (2.6)	–	–
Older adults ($N = 22$)	69.1 (65.2–77.2)	14	8	43.0 (9.0)	0.21 (.03)	2.4 (1.5)	–	–

for each word length) was high and it was low for the other half (2.28 and 1.48 mean log word frequency for high and low frequency, respectively; Marconi et al. 1993). Pictures were selected from three standardized image sets: Snodgrass and Vanderwart (1980), Peabody Test (Dunn and Dunn 1981), and Boston Naming Test (Kaplan et al. 1983). Objects whose correspondences with the word name proved ambiguous or whose images determined high error rate in a pilot study were excluded. There were 24 words per length condition (12 for high and 12 for low frequency), matched for word frequency, bigram frequency and initial phoneme across all lengths. Non-words were derived from words by changing one (or two) letter(s) except the first one, and were matched to words for bigram frequency.

Stimuli were displayed on a white background at a 57 cm viewing distance. Pictures were black line drawings subtending about 7.0°. Letter font was black lowercase Times New Roman; horizontal center-to-center letter distance subtended .4°.

Each stimulus was singly displayed on a PC screen controlled by DMDX software (Forster and Forster 2003). Each trial sequence consisted of a 15-ms acoustic tone, a 400-ms blank and a 250-ms fixation cross followed by presentation of the target. The stimulus disappeared at the onset of pronunciation or after 4000 ms. Separately for pictures, words and non-words, the 96 stimuli appeared in four blocks of 24 trials each; blocks were matched for length, frequency (number of high and low frequency items), and initial phoneme (high and low frequency items were counterbalanced within a block, independent of length). Block composition was different across stimulus types, i.e., the content of a block of pictures was not replicated in a block of words, to avoid association of same items. Stimulus order was randomized within each block; block order was randomized across participants.

The first block of each stimulus type was preceded by a brief practice (five 6-letter items different from the experimental stimuli) and followed by a short pause. Participants were instructed to name the picture or to read the word (or non-word) aloud as fast and accurately as possible. A voice key connected to the computer recorded vocal RTs at the onset of pronunciation. The vocal response was also digitally recorded from onset to check for response accuracy. Participants were tested individually in a quiet room (children, at their school). Pictures and non-words were administered on the same day, along with standard testing, with a long pause after each condition; order of stimulus type was counterbalanced across participants. Words were administered after at least one week. The experimenter noted pronunciation errors.

Data analysis

Vocal RTs were manually detected using Check Vocal software (Protopapas 2007). Only RTs to correctly responded items were considered for the analyses. Invalid trials due to technical failures accounted for 4.5 and 3.2% of responses for control and dyslexic children, respectively, and were discarded from the analyses. Invalid trials were 3.2 and 4.4% in younger and older adults, respectively. The error rates were 4.6% for control readers, 7.9% for dyslexic children, 2.4% for younger adults and 4.0% for older adults. As we were interested in time measures, we did not analyze accuracy data further.

To detect global components, we tested the prediction of a linear relationship between the condition means of two groups hypothesized to vary in overall information-processing rate; this was done by plotting the mean RTs of one group against those of the other group obtaining the so-called Brinley plot. This relationship is diagnostic of the presence of over-additivity, that is, the tendency for group differences to be larger in more difficult conditions over and above the effect of specific experimental manipulations (Faust et al. 1999). We were interested in examining whether word/non-word and picture conditions could all be accounted for either by a single global factor or by two separate factors. To this aim, a regression analysis with task (words/non-words and pictures) coded as a dummy variable (1 and 0, respectively), group (participants' performance) and task by group interaction as predictors was carried out. The presence of a significant task by group interaction would indicate that separate regression lines are appropriate for the orthographic and pictorial conditions, whereas the absence of the interaction is in keeping with the idea that a single regression line may account for the RT slowing.

Then, we tested the DEM prediction of a linear relationship between the overall group RT means and the SDs of the same conditions. The DEM predicts that the same relationship will hold for different groups even though they may be different in processing speed (e.g., young vs. older adults; Myerson et al. 2003). Therefore, the plot was done considering together the four groups of participants. The DEM also assumes the sensory/motor component to be small and constant across experimental conditions and individuals; its value is estimated by the intercept on the *x*-axis of the linear relationship between the RT condition means and the corresponding SDs.

Over and above large-scale effects, contributions of specific variables could also be envisaged (Faust et al. 1999). To this purpose, linear mixed effects models with random intercepts as well as random slopes were used (Baayen et al. 2008; Snijders and Bosker 2012). With respect to traditional (ANOVA) analyses, this type of models is able to establish whether group differences in sensitivity to psycholinguistic variables hold true after controlling for the presence of individual differences in the modulation of these variables. In the case of reading, a mixed effects model was carried out on raw RT data to examine the effects of group, length, lexicality, and frequency, as well as their interactions (in a full factorial model), as fixed factors. In interpreting the effect of frequency it must be noted that words actually varied for frequency, while in the case of non-words, the frequency effect merely marked the origin of the base words. In the case of picture naming, the mixed effects model considered the effects of group, length and frequency as fixed factors. For all analyses, items and participants were entered as random effects, to control for deviations by subjects or by items in slopes of fixed effect. This allowed the evaluation of fixed effects taking into account the error variance due to deviations from the average slopes of the length (frequency and lexicality) by participants effects, as well as from the average slope of the age and group effect by items (i.e., random slopes). Furthermore, error variance due to deviations from the average RT (when fixed effects are 0) by participants and by items was also considered in the analysis (random intercepts). By taking into account not only differences in RTs due to random variations but also by random differences in the slope of effects, the presence of global components in data can be controlled for. In this way, it is possible to detect the specific components contributing to the group differences, independent of the contribution of global components (i.e., the presence of over-additivity). Analyses were performed with the SPSS software.

Results

RT data for word and non-word reading (orthographic conditions) and picture naming (non-orthographic conditions) are presented in Fig. 1 (separately for the four groups of participants). The figure shows several general trends in the data: (a) responses to words (and non-words) are generally faster than responses to pictures; (b) lexicality and frequency effects are apparent for orthographic materials; (c) length effects are clear for non-words but smaller or absent in the case of words; (d) in the case of pictures the frequency effect appears detectable while the effect of length is unstable. Comparisons between matched groups indicate that (a) children with dyslexia are consistently slower than the control children across orthographic materials but not on pictures; (b) dyslexic children show greater length effects the case of words; (c) older adults are consistently slower than younger adults across orthographic and picture conditions.

Analysis of global components

Figure 2 shows the Brinley plots comparing dyslexic to control children (Fig. 2a) and older to younger adults (Fig. 2b) across experimental conditions.

Various observations can be derived from Fig. 2a. First, dyslexic children are slower across all orthographic conditions (empty circles). In fact, data points are all well above the dashed diagonal line; this indicates a slope of 1, i.e., equal RTs for dyslexics and controls. By contrast, dyslexic children name pictures with similar

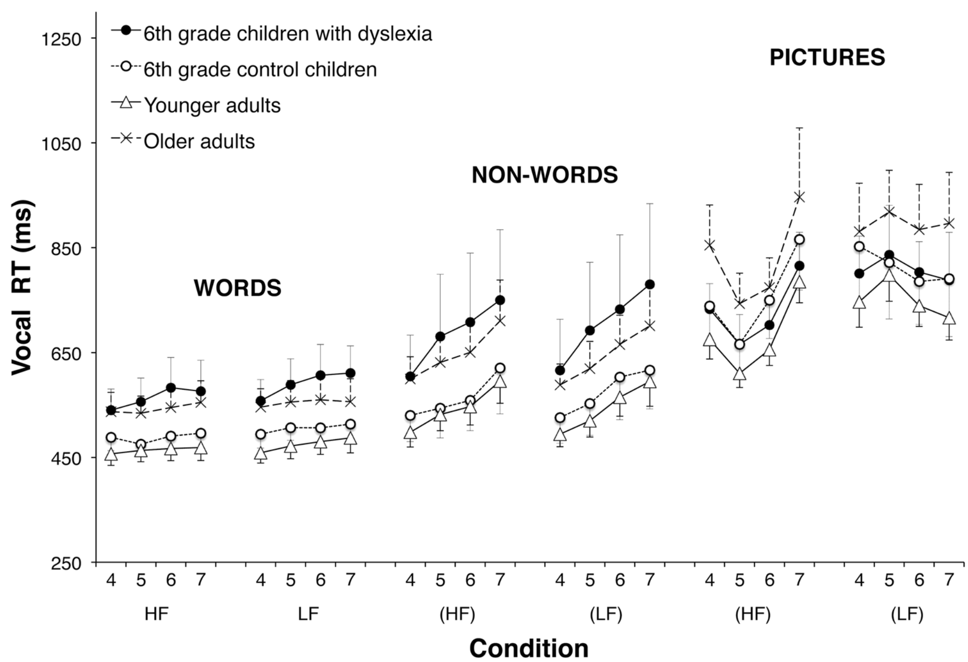

Fig. 1 Mean raw RTs for word and non-word reading and for picture naming as a function of the length of the orthographic string, or of the length of the name of the picture. *Different symbols* report data separately for the four groups of participants in Experiment 1. HF and LH indicate high and low frequency, respectively. *Error bars* represent confidence intervals ($\alpha = .01$)

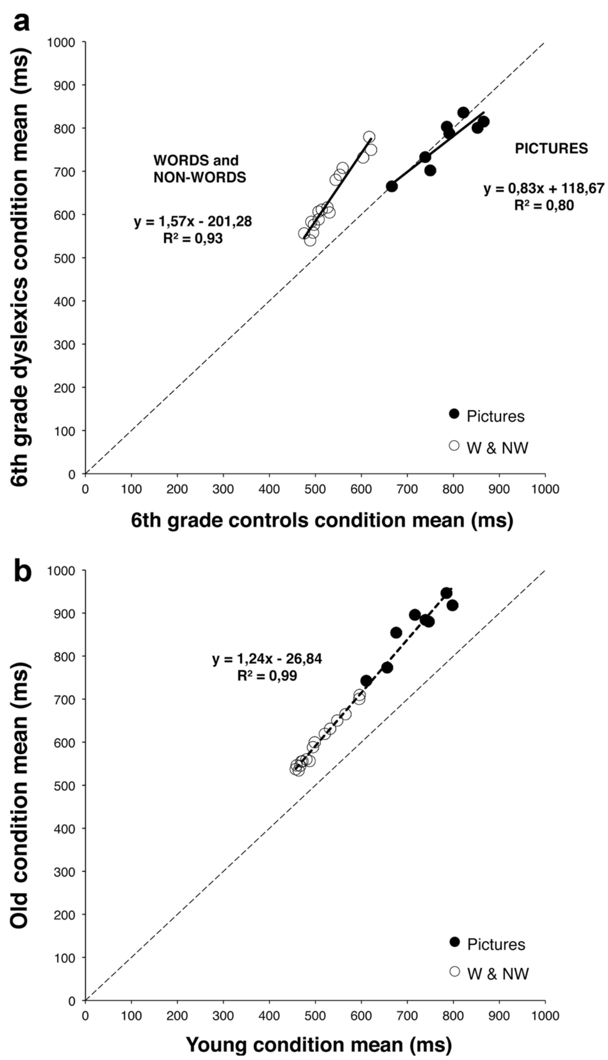

Fig. 2 Brinley plots reporting mean RTs for **a** children with dyslexia vs. typically developing children in various conditions, and **b** older adults vs. younger adults in the same conditions (*open circles* word and non-word reading; *closed circles* picture naming). The *dashed line* indicates equal performance between two groups. The equations of the linear fit are also reported

RTs as control children; i.e., most filled circles lie close to the diagonal line marking iso-performance. Second, a two-line regression solution explains the best performance of the two groups. All orthographic conditions (whether words or non-words) are well fitted ($r^2 = .93$) by a regression line with a 1.57 slope, while all picture data points are fitted ($r^2 = .80$) by a regression line with a .83 slope. Alternatively, a solution with a single regression line for all experimental conditions provides a less effective explanation of data ($r^2 = .78$). A regression analysis yielded a significant task by group interaction [$t_{(1)} = 4.14$, $p = .001$], confirming that the beta coefficients for the bivariate regression for the words/non-word and picture tasks were indeed different.

Inspection of Fig. 2b indicates two main findings. First, older individuals are slower than younger individuals across all orthographic and non-orthographic conditions. Second, a one-regression line solution explains quite well the differences between the two groups ($r^2 = .98$); the slope of this regression is 1.24. A regression analysis yielded no significant task by control interaction [$t_{(1)} = -.648$, $p = .52$], indicating that the beta coefficients for the bivariate regression for the words/non-word and picture tasks were not different.

Figure 3 illustrates the prediction of the DEM of a linear relationship between the RT group means and the corresponding SDs for the tested conditions. Data for the four groups of participants are presented with different symbols. Note that, independent of the specific experimental manipulation, longer RTs tend to be associated with greater inter-individual variability. To explain the experimental data, a two-regression line solution seems preferable, with one regression for the orthographic ($y = .50x - 202.91$; $r^2 = .86$) and one for the non-orthographic ($y = .45x - 235.59$; $r^2 = .67$) stimuli. By contrast, a solution with a single regression line for all conditions provides a lower determination coefficient ($r^2 = .60$). The two regression coefficients are similar for the slope (.50 and .45) while they are different as it regards the *x*-axis intercept (i.e., the estimate of the sensory/motor component according to the DEM): these are 402.6 and 524.6 ms, for orthographic and non-orthographic stimuli, respectively. Thus, there is a 122 ms delay associated with the response to pictorial stimuli.

Comments The Brinley plots indicated two different patterns of slowing in dyslexic children and in older adults. The former were impaired for all orthographic materials with performance showing clear over-additivity over and above the influence of frequency, length and lexicality. Furthermore, dyslexic children showed an essentially spared performance on picture naming. By contrast, older adults were delayed in comparison to younger adults across orthographic and non-orthographic tasks.

The magnitude of the slope of the line fitting older vs. younger adults means (1.24) indicated a moderate slowing which is coherent with previous data on lexical/verbal tasks (Hale and Myerson 1996; Lawrence et al. 1998). Lawrence et al. (1998) reported a slope of 1.18 for individuals between 60 and 69 years of age and one of 1.43 for individuals in 70–79 age range. Note that this decay is generally smaller than that reported for visuospatial tasks (e.g., 3.11; Hale and Myerson 1996).

The slope for the contrast between dyslexic and typically developing children (1.57) confirms previous data on similar materials, although it is smaller than that reported in previous studies (e.g., Zoccolotti et al. 2008). Since the

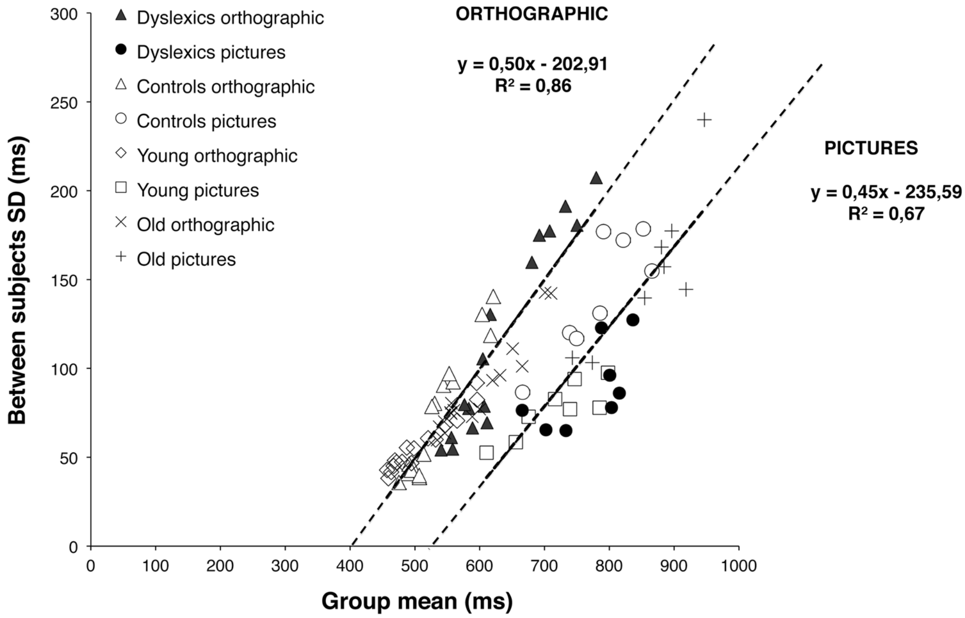

Fig. 3 SDs for each group and condition of Experiment 1 are reported as a function of the corresponding means. *Different symbols* refer to data of different groups and conditions in the orthographic and non-orthographic domains. According to the DEM prediction, linear regression lines fit well the data: the best fit is obtained when separate regression lines are used for the two domains (as indicated by the determination coefficients)

slope is one general indication of the severity of the reading deficit, different groups of children may display different values depending on their severity. As presented below, in Experiment 2, we replicated these observations on a different sample of dyslexic and control children, and found a steeper slope.

Some features of the data appear compatible with the DEM, while others require some additional considerations. The present data confirm the presence of a clear increase in variability (SDs) as a function of condition difficulty. However, reading words (and non-words) and naming the corresponding pictures generated two partially separated factors differing substantially in terms of the x-intercept marking the non-decisional sensory/motor component (and much less in terms of the slopes of the regression marking the decisional components of the tasks).

Because words and pictures share the same vocal output, it seems unlikely that the intercept difference is due to the motor component of the task and an interpretation in terms of different visual requirements between orthographic strings and pictures seems in order.

Analyses of specific factors

Comparison between children with dyslexia and typically developing children *Word and non-word reading* The linear mixed effects model showed the main effects of frequency [$F_{(1,4898)}$ = 11.14, p < .001], lexicality [$F_{(1,4898)}$ = 13.81, p < .0001] and length [$F_{(3,4898)}$ = 28.91, p < .0001]. Longer RTs were present for low- (594.1) than high-frequency (575.3 ms) words, for non-words (632.3 ms) than words (537.1 ms), and for longer stimuli (with RTs longer of ca. 25.3 ms for each additional letter, at least p < .01).

The group effect was significant [$F_{(1,4898)}$ = 16.79, p < .0001]: dyslexic children employed 636.5 ms to read words while controls 532.9 ms. Group interacted with length [$F_{(3,4898)}$ = 3.89, p < .01]: larger and significant length effects for children with dyslexia (mean of RT increase per letter = 33.2 ms, at least p < .05) than for controls (mean increase = 17.3 ms; for which significant differences were reported only between 4- and 6-letter stimuli and for 7-letter stimuli that had longer RTs than all other lengths, at least p < .05).

The lexicality by length interaction [$F_{(3,4898)}$ = 17.44, p < .0001) highlighted larger length effects for non-words than words: the mean RT increase per letter was 40.8 ms for non-words (at least p < .0001) and only 9.7 ms for words.

Among random effects, the subject by length (Z = 4.76, p < .0001), subject by lexicality (Z = 5.00, p < .0001) and item by group (Z = 8.24, p < .0001) interactions were significant while the subject by frequency interaction was not (Z = .90, p = .37).

Picture naming The linear mixed effects model showed the main effect of frequency [$F_{(1,2375)}$ = 5.82, p < .05]: low-frequency pictures (809.7 ms) were named more slowly than high-frequency pictures (742.0 ms).

Neither the effect of group was significant [$F_{(1,2375)}$ = 0.01, p = .93] nor were all interactions with this factor: dyslexic children employed 768.0 ms for naming pictures while controls 783.7 ms. Groups were modulated in near identical ways by stimulus length and frequency.

The analysis also showed the significance of the frequency by length interaction [$F_{(3,2375)}$ = 7.44, p < .0001]: a length effect was present for high-frequency pictures (mean RT increase per letter = 87.4 ms, at least $p < .05$; except for 4-letter stimuli that had comparable RTs to 5- and 6-letter stimuli) but not for low-frequency pictures. The frequency effect was detectable only in 4- and 5-letter stimuli (at least $p < .05$) but not for longer ones.

Among random effects, the subject by frequency ($Z = 4.73$, $p < .0001$) and item by group ($Z = 6.98$, $p < .0001$) interactions were significant while the subject by length interaction was not ($Z = .16$, $p = .87$).

Comparison between older and younger adults *Word and non-word reading* The mixed effects model showed the main effect of lexicality [$F_{(1,8509)} = 34.46$, $p < .0001$] and length [$F_{(3,8509)} = 43.42$, $p < .0001$]: non-words (594.7 ms) produced longer RTs than words (509.1 ms) and RTs were longer of about 20.4 ms for each additional letter. The main effect of frequency was not significant [$F_{(1,8509)} = 1.40$, $p = .24$], with similar RTs for low-frequency words (554.1 ms) and high-frequency words (549.6 ms).

The effect of group was significant [$F_{(1,8521)} = 33.05$, $p < .0001$]: young participants employed 506.4 ms for reading words/non-words while older participants 597.3 ms. However, group did not interact with any variable examined.

Lexicality interacted also with frequency [$F_{(1,8509)} = 5.73$, $p < .05$] and length [$F_{(3,8509)} = 35.20$, $p < .0001$]: larger length effects were reported for non-words (mean increase = 35 ms; at least $p < .0001$) than words (mean increase = 5 ms; not significant except for the passage from 4- to 7-letter stimuli that was significant, $p < .05$). Frequency effects were present only in the case of words ($p < .01$) but not in the case of non-words ($p = .54$).

Regarding random effects, the subject by length ($Z = 5.76$, $p < .0001$), subject by lexicality ($Z = 6.48$, $p < .0001$) and item by *group* ($Z = 9.84$, $p < .0001$) interactions were significant, while the subject by frequency interaction was not computed as it proved redundant in the model.

Picture naming The analysis showed the main effects of frequency [$F_{(1,3628)} = 6.48$, $p < .01$] and length [$F_{(3,3628)} = 4.46$, $p < .01$]: low-frequency pictures were named more slowly (822.4 ms) than high-frequency pictures (755.6 ms) and 7-letter stimuli produced longer RTs with respect to all other lengths (at least $p < .0001$).

The effect of group was significant [$F_{(1,3628)} = 25.74$, $p < .0001$], but did not interact with any other variable. Young participants showed shorter RTs for naming pictures with respect to older participants (715.8 ms vs. 862.1 ms, respectively).

The frequency by length [$F_{(3,3628)} = 7.32$, $p < .0001$] interaction was significant: stimuli of different length had similar RTs in the case of low-frequency pictures; for high-frequency pictures a length effect was present (mean RT increase per letter = 94.5 ms, at least $p < .001$), except for 5-letter stimuli that had RTs comparable to 6-letter stimuli.

Regarding random effects, the subject by frequency ($Z = 6.05$, $p < .0001$) and item by group ($Z = 7.89$, $p < .0001$) interactions were significant while the subject by length interaction was not computed since it proved redundant in the model.

Comments As for the reading tasks, the roles of stimulus length and lexicality were compatible with previous findings both in the analyses on children and on those on adults. In particular, as frequently reported in the literature (e.g., Weekes 1997) length effects were larger in the case of non-words than words. Results on the effect of frequency were somewhat more mixed. In particular, we expected a frequency effect for words but not for non-words (where frequency only indicated the origin of the base words); however, the frequency by lexicality interaction was significant in the analysis comparing older and younger adults but not in that comparing dyslexic and control children.

The focus here is on the possible differential effects of these factors in the two tested group comparisons (dyslexic children vs. controls, and younger vs. older adults). In general, the interactions with the group factor were limited. As for children, only the group by length interaction was reliable in the reading task. Consistent with previous research (Spinelli et al. 2005; Zoccolotti et al. 2008), children were particularly sensitive to the effect of length; notably, this group difference was present in an analysis which controlled for the over-additivity effect indicating its specificity. The group by frequency and the group by lexicality interactions failed to reach significance. This is in keeping with the idea that the slowing shown by dyslexic children is best accounted for by a deficit at a pre-lexical level which affects performance across orthographic conditions (see Marsh and Hillis 2005). However, as stated above, it is conceivable that these findings may be at least partially due to lack of sensitivity of the measures, with children with dyslexia being only moderately impaired. A check of this possibility will be carried out in Experiment 2 where the role of frequency and length will be tested on another group of children with a more severe reading difficulty. It should also be noted that the samples of words (and corresponding non-words) was not very large and this may have contributed to the obtained results.

As for the two groups of adults, no group by condition interaction was detected. This finding is in keeping with the idea that the reading slowing of older adults is general, cutting across all experimental conditions tested.

The general pattern of results was somewhat less clear-cut in the case of picture naming. The expected effect of frequency was confirmed but did not interact with group either in the analyses on children or in those in adults. The effect of length was somewhat more erratic with some unexpected variations particularly in the case of high-frequency pictures. Notably, in this case the group effect was present in the case of the age comparison indicating a slowing in older individuals but not in children with dyslexia who showed an essentially spared performance in picture naming.

Experiment 2

The aim of Experiment 2 was to confirm the dissociation between orthographic and non-orthographic processing on a separate group of children with dyslexia and chronologically age-matched children. We examined older children with dyslexia presenting more severe difficulties at standard reading tests than those of Experiment 1. This may be instrumental in verifying the selectivity of the deficit in the orthographic domain in dyslexic children.

Method

Participants

Fifteen dyslexic children and 15 controls (see Table 2), all attending 8th grade, took part in the second study. The groups were comparable for age ($t = 1.14$; $p = .14$) and gender ($\chi^2 = .60$, $p = .44$). The dyslexic children scored at least 1.65 SDs below the norm for either speed or accuracy on the MT Reading test (Cornoldi and Colpo 1995; see Table 2). The average reading time (raw data) was .27 s/syllable for children with dyslexia and .18 for typically developing readers ($t = 3.89$; $p < .0005$), that is, a slowing of 51%. All participants had normal or corrected-to-normal visual acuity. However, due to time limitations, we could not administer the Raven's Coloured Progressive Matrices in this sample.

Informed consent was obtained from the parents of the children.

Stimuli, apparatus, and procedure

Stimuli were 140 pictures of objects and the 140 words corresponding to the object names. Based on the set of stimuli used in Experiment 1, a set of pictures with 8-letter names (selected from the same databases of images as in Experiment 1) and the corresponding words were added to the original set of stimuli to have a greater range of response variability. Moreover, to match targets for critical variables, a slightly larger set of items was used. Overall, there were 28 words per length condition (14 for high and 14 for low frequency), matched for word frequency, bigram frequency and initial phoneme across all lengths (2.24 and 1.48 mean log word frequency for high and low frequency, respectively; from Marconi et al. 1993). Procedure and device for RTs recording were the same as in Experiment 1.

Non-words were not used to shorten the length of the recording sessions, and because we did not intend to further explore the role of lexicality.

Data analysis

Scoring of RTs was carried out as in Experiment 1. Invalid trials due to technical failures accounted for 6.1 and 5.0% of the responses of typically developing readers and children with dyslexia, respectively, and were discarded from the analyses. The error rate was 3.8% for typically developing readers and 7.1% for children with dyslexia.

Analysis on global components was carried out along the same lines of Experiment 1.

Linear mixed effects models were carried out to examine reading and naming RTs. In particular, the effect of group, length and frequency, as well as their interactions, were entered as fixed factors. Items and participants were entered as random effects to control for deviations by subjects or by items in slopes of fixed effects. Furthermore, error variance due to deviations from the average RT by participants and by items was also considered in the analysis (random intercepts).

Table 2 Summary statistics for typically developing children and children with dyslexia of Experiment 2: mean age (in years, with range in parentheses); *N* of female and male participants; mean raw scores and *z* scores (SDs in parentheses) on speed and accuracy measures of the MT Reading test

	Age	Male	Female	Reading speed (s/syllable)	Reading accuracy (errors)	Reading speed (*z* score)	Reading accuracy (*z* score)
Typically developing readers (*N* = 15)	13.3 (12.7–13.9)	9	6	.18 (.02)	4.2 (2.3)	.63 (.32)	−.11 (.63)
Children with dyslexia (*N* = 15)	13.4 (12.9–14.4)	11	4	.27 (.09)	18.3 (5.5)	−1.21 (1.79)	−3.93 (1.48)

Results

Experimental data on word reading and picture naming are presented in Fig. 4 separately for dyslexic and control children. Data indicate faster RTs for words than pictures. Length effects are clear for dyslexic (but not control) children in reading words; the effect of length is less clear in the case of pictures. Small frequency effects are detectable for both picture and orthographic stimuli.

Analysis of global components

Figure 5 shows the Brinley plots comparing dyslexic and control children across experimental conditions. The pattern of results is similar to that of Experiment 1. Dyslexic children are slower across all orthographic conditions while they name pictures with a similar speed as controls. A two-regression line solution explains the best difference between the two groups with all orthographic conditions fitted by a regression line with a 3.59 slope; the determination coefficient is not very high ($r^2 = .68$) possibly due to the limited range of variability across orthographic conditions. All picture naming conditions are well fitted ($r^2 = .89$) by a regression line with a .92 slope. A regression analysis yielded a significant task by group interaction [$t_{(1)} = 3.03$, $p < .01$], confirming that the beta coefficients for the bivariate regression for the words/non-word and picture tasks were different.

Figure 6 shows the relationship between the RT group means and the corresponding SDs separately for the two groups, and the orthographic and pictorial conditions. As in Experiment 1, a two-regression line solution fits well the experimental data, with one regression for the orthographic ($y = .63x - 247.12$; $r^2 = .89$) and one for the non-orthographic ($y = .40x - 210.45$; $r^2 = .72$) stimuli. A solution with a single regression line for all experimental conditions does not provide a good fit of the data ($r^2 = .39$). The intercepts on the x-axis were 392.5 and 524.3 ms for the orthographic and the non-orthographic stimuli, respectively. Therefore, there is a 131.8 ms delay associated with the response to pictorial stimuli.

Comments For dyslexic children, the results generally confirmed those of Experiment 1. This group of children showed a generally more impaired performance, an effect marked by a steeper slope in the Brinley plot (3.59) as compared to the children examined in Experiment 1 (1.57). However, in spite of this generally more impaired performance, these children still did not show a deficit in naming pictures as indicated by a slope for these stimuli near (and in fact below) unity. Thus, results confirmed the selectivity of the deficit for the orthographic domain found in Experi-

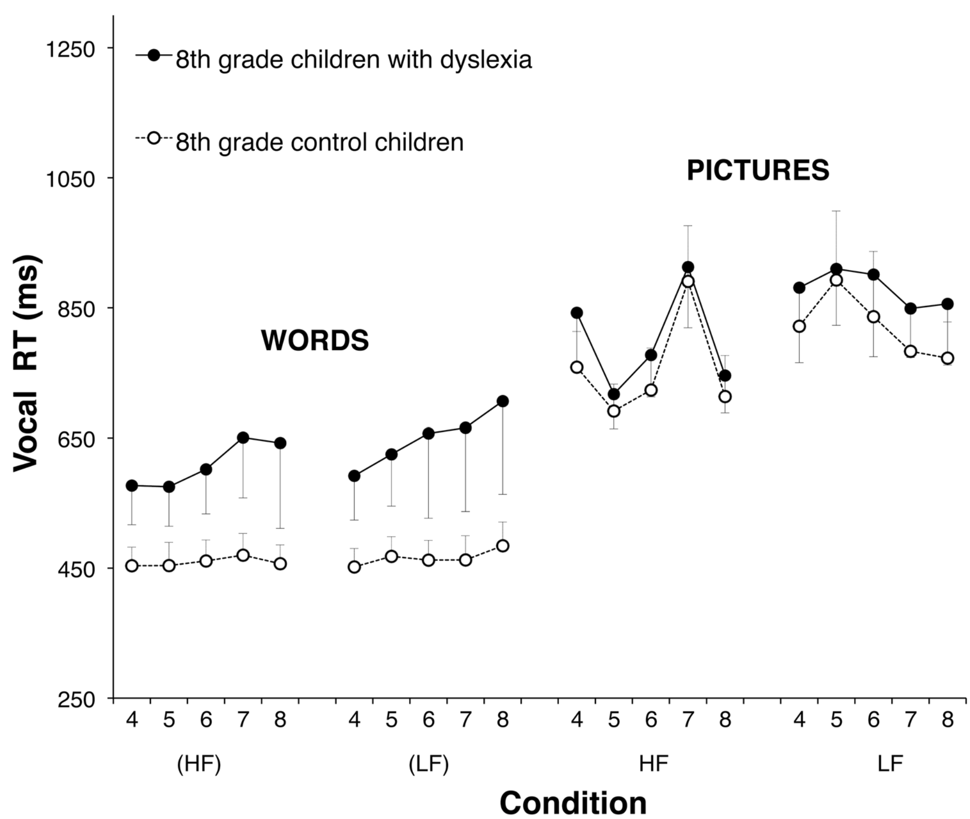

Fig. 4 Mean raw RTs for word reading and for picture naming as a function of the length of the orthographic string, or of the length of the name of the picture. *Different symbols* report data separately for the two groups of children in Experiment 2. *Error bars* represent confidence intervals ($\alpha = .01$)

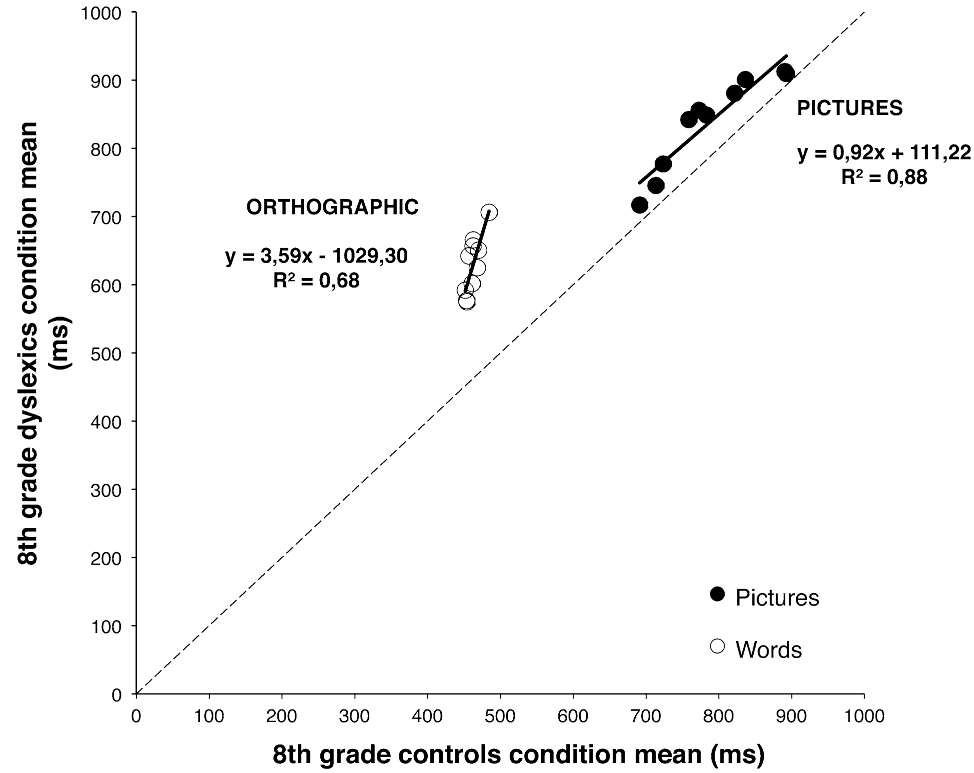

Fig. 5 Brinley plot reporting mean RTs for children with dyslexia vs. typically developing children across experimental conditions, similar to Fig. 2a (*open circles* word and non-word reading; *closed circles* picture naming). The *dashed line* indicates equal performance between two groups. The equations of the linear fit are also reported

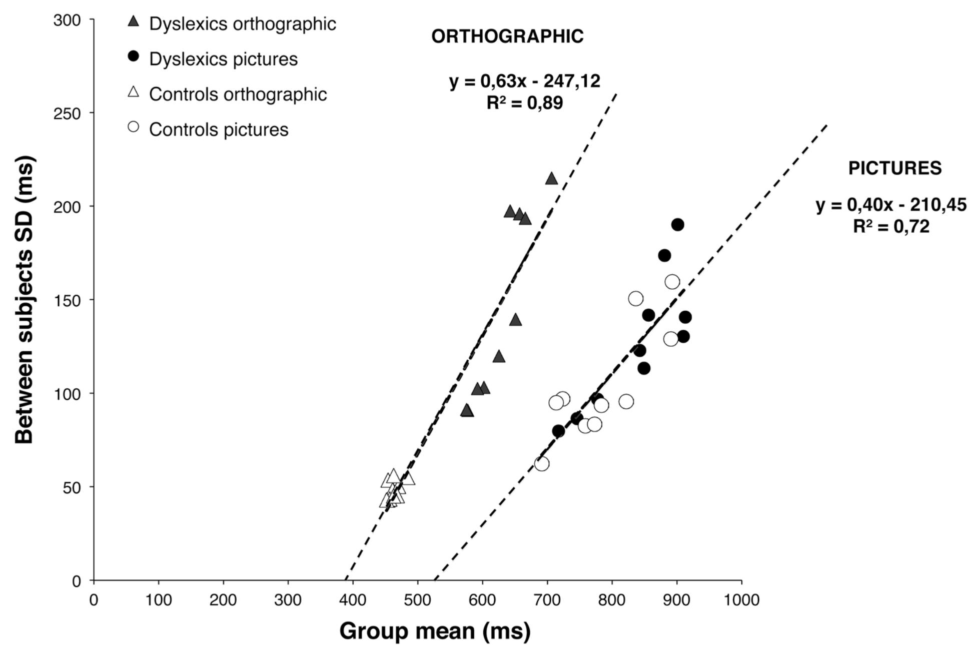

Fig. 6 SDs for each group and condition of Experiment 2 are reported as a function of the corresponding means. *Different symbols* refer to data of different groups and conditions in the orthographic and non-orthographic domains. According to the DEM prediction, linear regression lines fit well the data: the best fit is obtained when separate regression lines are used for the two domains (as indicated by the determination coefficients)

ment 1 as well as in previous research (Zoccolotti et al. 2008).

Also, results concerning the relationship between means and SDs were similar to those of Experiment 1. In particular, a two-line solution seemed to account best for the data. The critical difference between these two lines was in terms of intercepts on the *x*-axis with a 131.8 delay for pictorial stimuli. Since the output for words and pictures was the same for these two types of stimuli (i.e., it involved the pronunciation of the same words), according to the DEM, the difference between intercepts presumably lies in the different times necessary for processing figures with respect to letters strings, pointing to the role of early visual analysis of the targets.

Analyses of specific factors

Word reading The mixed effects model showed the main effects of length [$F_{(4,3825)} = 9.85$, $p < .0001$]: RTs were longer of about 13.5 ms for each additional letter. The main effect of frequency [$F_{(1,3825)} = .82$, $p = .36$] was not significant (557.6 and 534.3 ms for low and high-frequency words, respectively).

The effect of group was significant [$F_{(1,3825)} = 43.08$, $p < .0001$]: dyslexic children employed 629.4 ms for reading words while controls 462.5 ms. Group interacted with length [$F_{(4,3825)} = 5.08$, $p < .0001$]. RTs of dyslexic children were modulated by length (RT increase of about 22.5 ms per letter; except between 4- and 5-letter stimuli and between 7- and 8-letter words each difference was significant at least $p < .01$), while for controls length effects (RT increase per letter = 4.5 ms, n.s.) were negligible.

The analyses also showed the significance of the frequency by length interaction [$F_{(4,3825)} = 4.29$, $p < .01$]: length effects were larger for low-frequency words (RT increase per letter = 18.4 ms) than for high-frequency words (RT increase per letter = 8.6 ms).

All random effects were significant: the subject by frequency ($Z = 5.12$, $p < .0001$), subject by length ($Z = 3.06$, $p < .01$) and item by group ($Z = 5.51$, $p < .0001$) interactions were all significant.

Picture naming The analyses showed only the main effect of frequency [$F_{(1,3502)} = 6.78$, $p < .01$]: low-frequency pictures were named more slowly (850.3 ms) than high-frequency pictures (777.3 ms). The main effect of *length* was not significant [$F_{(4,3502)} = 1.62$, $p = .17$].

The effect of group was not significant [$F_{(1,3502)} = 2.64$, $p = .10$], nor were the interactions involving this factor: dyslexic children employed 839.2 ms for naming pictures while controls 788.4 ms. Groups were modulated in a near identical way by stimulus length and frequency.

The frequency by length interaction was significant [$F_{(4,3502)} = 4.08$, $p < .01$]: length effects were negligible among low frequency pictures. For high-frequency pictures, some differences were detectable as a function of length: in particular, 5-letter stimuli produced shorter RTs than all other stimulus lengths, except for 8-letter stimuli (at least $p < .05$), and 8-letter stimuli were named faster than 7-letter stimuli ($p < .001$). Low-frequency pictures were named more slowly than high-frequency pictures in the case of 5- and 8-letter stimuli (at least $p < .05$).

Among the random effects, the subject by frequency ($Z = 4.71$, $p < .0001$), and item by group ($Z = 8.27$, $p < .0001$) interactions were significant while the subject by length interaction was not ($Z = .00$, $p = 1.00$).

Comments For the orthographic conditions, results indicated the role of length as well as of its interaction with frequency; thus, as frequently reported, the length effect was greater for low- than for high-frequency words (Coltheart et al. 2001). As in Experiment 1, length interacted also with group, with the length effect detectable only among dyslexic children but not control readers.

General discussion

The results support the idea of the *comparative human cognition* approach (Myerson et al. 2003) that global factors may effectively characterize the cognitive slowing of different groups of individuals. Both dyslexic children (as compared to controls) and older adults (as compared to younger adults) showed delayed RTs to a number of experimental conditions. Consistent with the DEM prediction, the present study shows that these group differences can be described most effectively and parsimoniously in terms of deficits in domains encompassing a variety of experimental conditions. At the same time, results are in keeping with DEM's prediction that the function relating means and SDs represents an invariant element across tasks and groups.

Dyslexic children showed an across-the-board deficit in all orthographic conditions, and their difficulty could be well accounted for by a single multiplicative factor (i.e., a value representing the extent of their slowing with respect to proficient peer readers) along with a constant value (i.e., the intercept on the *x*-axis of the plot contrasting means and SDs). This was true in both experiments although the impairment was considerably more severe for the children of Experiment 2 (slope of the Brinley plot = 3.59) than those of Experiment 1 (slope = 1.57).

By contrast, the use of a powerful analysis allowing partialling out the influence of over-additivity effects indicated a limited role of specific factors in modulating the reading deficit. In particular, only the length by group interaction was present in both experiments indicating that unlike controls, dyslexic children were sensitive to length even for the shortest stimuli. In previous research, we often obtained a specific effect of length over and above the effect of over-additivity (Paizi et al. 2013; Zoccolotti et al. 2008) although not in all studies (Marinelli et al. 2014). A small residual effect of length presumably contributes to the dyslexic children's deficit, at least in transparent orthographies. The number of letters in the word may be an important feature for targeting a pre-lexical grapheme description deficit in dyslexia (Marsh and Hillis 2005). By contrast, examination of specific effects indicated that dyslexic children showed lexicality effects similar to their peers once the over-additivity was controlled for. Results for frequency were similar although the frequency effect was somewhat elusive across the two experiments possibly indicating large item variability. This pattern is generally in keeping with the idea that lexical activation is largely spared in these children (Paizi et al. 2013) and the key deficit is at the pre-lexical level (Zoccolotti et al. 2008). However, it must be added that some authors have proposed that even though dyslexic children show the expected organization of the lexicon in terms of frequency they may show a deficit in lexical expansion, i.e., the actual number of lexical entries may be reduced in comparison to typically developing children (Angelelli et al. 2010).

We think that a molar approach may be instrumental for the interpretation of the reading deficit. In particular, present results indicate that the reading deficit cuts across lexicality effects. These results and interpretation are at variance with the frequently reported idea that dyslexic children are selectively impaired in reading non-words (Rack et al. 1992; van Ijzendoorn and Bus 1994). However, it has been shown that if care is taken in controlling for general levels of performance, this deficit no longer holds (van den Broeck and Geudens 2012). Present data are fully consistent with this latter view.

The comparison of older and younger adults is consistent with a large literature showing reduced processing speed in the elderly (e.g., Verhaeghen and Cerella 2002), likely due to multiple factors such as structural and functional changes at brain level (Park and Reuter-Lorenz 2009). Older individuals were significantly slower than younger adults across all tasks (whether based on orthographic or pictorial stimuli). As expected for lexical/verbal tasks (Hale and Myerson 1996; Lawrence et al. 1998), the slowing of elderly responses was moderate and accurately described in terms of a single multiplicative factor with no additional influences of factors such as lexicality, frequency and length. Possibly due to the presence of greater deficits in the visual–spatial domain, reading has not been one key area of research in the aging literature but interest in this topic has increased recently (Froehlich et al. 2016; Davies et al. 2017).

Overall, the RT slowing of dyslexic children can be expressed in terms of an orthographic domain while that of older individuals in terms of a verbal domain. This distinction may be instrumental toward the understanding of the mechanisms underlying the slowing shown by these two groups. Notably, these two domains partly overlap so that some processes are shared by the two domains (such as lexical access and retrieval of the phonological output) while others are not (such as orthographic analysis). This underscores the need for a large-scale analysis to find the clusters of tasks that distinguish between targeted groups.

Consistent with the DEM predictions individual variability in the four groups and in the two domains grew following the same rule (Fig. 3). This occurred despite the fact that slowing of information processing was limited to orthographic stimuli in the children with dyslexia, while it cut across verbal tasks in older adults. Thus, independent from deficits in different domains, we expect the slowness of different groups to be expressed as a shift away from the origin of the *x*-axis along a single line fitting the experimental points, a prediction fit in the present study. However, different intercept values were not expected by the DEM. We note that Myerson et al. (2003) were not particularly interested on the sensory-motor compartment and made simplifications about the effect at this stage. Here, words and pictures were matched in both experiments, allowing for a close comparison between the two sets of tasks. Also, for both words and pictures, we measured the vocal RTs excluding any differential contribution of the "motor" component (that may play a role when hand responses vs. vocal responses are considered). Thus, it seems that the longer intercept for naming pictures than reading the corresponding words is due to differences in early visual processing of pictures, namely to the "sensory" component of the sensory-motor compartment, according to Myerson et al.'s (2003) definition. In line with the DEM, this visual processing would precede and be independent of the central, decisional stages concerning picture identification. As the present findings are novel, future investigations are needed to further delineate the nature of this effect. At present, we note that findings on intercepts parallel the well-known effect that the retrieval of word names is less effortful and error prone than the retrieval of object names at least in the case of multiple, distinct semantic categories (e.g., Damian et al. 2001).

Performance of dyslexic children in picture naming was essentially spared. This finding confirms and extends previous observations on Italian children with vocal RTs (Zoccolotti et al. 2008) as well as data obtained with a similar procedure on German-speaking dyslexics (Trauzettel-Klosinski et al. 2006). In our previous study, picture naming conditions showed a limited range of variability. Here, we manipulated both frequency and length and obtained a greater spread of performance. This is an important prerequisite to estimate the presence of global components in the data. At any rate, results remained essentially the same: in both experiments children with dyslexia showed no deficit in retrieving the phonological representation associated with the target pictures. This latter finding is important because other authors (Nation et al. 2001; Swan and Goswami 1997) proposed that a possible cause or a concurrent cause of dyslexia is a deficit in the access to the phonological lexicon. This hypothesis was mostly based on tests of confrontation naming. It has been observed that deficits in confrontation naming are subtle (McCrory et al. 2005) and tend to vanish with age (Felton et al. 1990; Hanley 1997). Accordingly, they may more selectively mark children with specific language impairment (Leonard et al. 1983) than children with dyslexia.

One can also envisage the possibility that naming deficits are at least partially language specific. Indeed, most data indicating deficits in picture naming were obtained in children speaking English (Nation et al. 2001; Swan and Goswami 1997), a language with a particularly irregular orthography, while data pointing to spared object naming skills come from dyslexic individuals speaking German (Trauzettel-Klosinski et al. 2006) or Italian (Zoccolotti et al. 2008 and present findings), two languages with regular orthographies. One could imagine that linguistic factors may be more prominent on reading acquisition and breakdown in a complex language such as English. Indeed, it has been shown that at least in the initial acquisition phases, English children rely on their lexical skills much more than German-speaking children, as indicated by a much greater proportion of word-substitution errors when reading nonwords (Frith et al. 1998; Landerl et al. 1997). The presence of partial overlap between different linguistic and reading deficits is well known, and in recent years, it is taken to indicate the presence of comorbidities between these deficits at different levels of analysis, i.e., diagnostic, cognitive, and etiological (Pennington and Bishop 2009). In this perspective, deficits are seen as due to independent (although partially overlapping) mechanisms, a view that strongly contrasts the earlier idea of a continuity between oral and written linguistic deficits (e.g., Shankweiler et al. 1992). Comorbidities between speech sound disorder, language impairment, and reading disability vary in extent and direction and language type may well contribute to this complex pattern. Nevertheless, in Italian, it has been observed that phonological deficits are limited to those children who had a previous delay in their language acquisition (Brizzolara et al. 2006; Chilosi et al. 2009; Angelelli et al. 2016). This evidence is consistent with the idea that although partially overlapping, linguistic and reading problems should be seen as separate entities (Pennington and Bishop 2009).

Data on picture naming also derive from a paradigm known as rapid automatized naming (RAN; Denckla and Rudel 1976a, b). It is well known that dyslexic children are slower in naming sequences of pictures (or colors or digits). However, other authors proposed alternative interpretations for this effect (e.g., Wolf and Bowers 1999; Wolf et al. 2000). In particular, it has been observed that the deficit is much smaller (and performance is unrelated to reading) if a discrete presentation of stimuli (one item at a time) is used rather than the typical large multiple target display characteristic of RAN (e.g., Georgiou et al. 2013). We recently showed that it is the need to process multiple stimuli that is crucial to obtain the group difference between the dyslexic and control children typical of RAN tasks, not the requirement of accessing the name of the target picture (Zoccolotti et al. 2014).

In summary, the present study shows that an approach focused on detecting global components in performance is well suited to describe the slowness in processing shown by such different groups as dyslexic children and older adults. Such a molar approach proves more effective than one trying to identify deficits in isolated experimental conditions. In fact, deficits are best accounted for in terms of different domains, i.e., wide clusters of tasks/experimental conditions. Two features characterize this perspective. First, domains of impairment are broad but do not necessarily encompass general impairments. In fact, dyslexic children showed a single, global deficit across orthographic conditions but not when processing pictures. By contrast, the slowing of older adults was pervasive across all verbal tasks tested. Second, single factors (such as frequency, lexicality and length) exert a clear influence over RTs but contribute very little (if anything) in modulating the group differences in slowness both in the case of dyslexic children and older adults.

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