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Deficits in Working Memory Visual-Phonological Binding in Children With Dyslexia

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Learning to read involves cross-modal binding processes, that is, the association between visual and phonological information in the mapping of written forms (graphemes) to phonological codes. The present study examined visual-phonological binding in a memory binding task, comparing a group of children with dyslexia with a control group of typical readers, matched for age, grade, and sex. Children were required to memorize the association between 8 shapes and nonwords presented in association for 4 times, placed either in fixed or variable spatial locations across trials. The results showed that children with dyslexia have deficits in cross-modal memory binding and are not able to use spatial location as an effective cue to bind information, as it was observed for control children. In addition, children with dyslexia made more phonological errors and binding errors than the control group. A purely phonological deficit in dyslexia does not explain the overall pattern of results, and dyslexia may involve deficits in 1 or more types of processes, including the capacity to bind visual to phonological information. Thus, assessment of binding processes may have implications both for diagnosis and treatment.

Keywords: dyslexia, memory binding, paired associate learning, reading disabilities, working memory

Learning to read and reading decoding basically involve the mapping of particular written forms or symbols to phonological codes and meaning (Perfetti, Van Dyke, & Hart, 2001). The association between visual and phonological information is a special case of a cross-modal binding process (Jones, Branigan, Parra, & Logie, 2013), that is, when information from different modalities should be associated or bound together to create unified, complex representations that can be maintained in memory (Baddeley, 2000). Some evidence indicates that cross-modal binding is crucially involved in reading (Blomert, 2011; Hahn, Foxe, & Molholm, 2014). For example, paired associate learning (PAL) of arbitrary visual-phonological associations, such as between shapes and nonwords, is both a strong correlate and a robust predictor of reading skills in children (Hulme, Goetz, Gooch, Adams, & Snowling, 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001), and smaller correlations are observed when learning involves uni-modal paired associates such as visual-visual or phonological-phonological (Hulme et al., 2007). In addition, it has been shown that children with dyslexia have deficits in general visual-

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phonological PAL and specific grapheme-phoneme PAL (Aravena, Snellings, Tijms, & van der Molen, 2013; Li, Shu, McBride-Chang, Liu, & Xue, 2009; Litt & Nation, 2014; Messbauer & de Jong, 2003; but see Litt, de Jong, van Bergen, & Nation, 2013), as well as problems in visual-auditory perceptual integration (Blau et al., 2010; Kronschnabel, Brem, Maurer, & Brandeis, 2014; Widmann, Schröger, Tervaniemi, Pakarinen, & Kujala, 2012).

However, the literature did not examine the case of memory binding in association with the use of working memory, despite the fact that working memory is the cognitive system supporting the temporary storage and processing of information from different modalities (e.g., phonological, visual, and spatial), and it is assumed to support many aspects of online cognition, including reading and learning (Baddeley, 2000).

In fact, it is only recently that attention has been devoted to investigate working memory cross-modal binding processes in individuals with dyslexia (Garcia, Mammarella, Tripodi, & Cornoldi, 2014; Jones et al., 2013), with only one study specifically examining the case of children. The recent study by Garcia et al. (2014) assessed sequential recall of colors, locations, and color-location bindings, comparing two groups of children with learning disabilities (dyslexia and nonverbal learning disability) with typically developing children. This study, however, presented some limitations as it did not assess the binding type that is specifically involved in reading and the results were inconclusive, as group differences in binding did not reach significance.

The other study examining working memory binding processes in dyslexia (Jones et al., 2013) showed that adults with dyslexia presented a visual-phonological binding deficit only when the associations between shapes and nonwords were maintained in fixed locations, whereas no deficit was observed when items were presented in variable locations. That is, individuals with dyslexia were unable to use spatial location of shapes as an effective memory cue in support of binding processes. This latter study, however, only considered adults and used meaningful nameable shapes (e.g., a heart, a triangle, etc.) as visual stimuli, in such a way that the binding could also be influenced by phonological association between shapes' labels and nonwords.

The present study sought to overcome some limitations from these studies and to specifically examine visual-phonological binding in children with dyslexia. In a series of four trials, children were presented eight nonsense shapes paired to nonwords and then were required to recall the nonword associated to each shape. The shape-nonword associations were always the same across trials and half of the shapes remained on fixed locations and the other half had their locations changed. Thus, this task was designed to tap processes similar to the processes that are involved in learning to read and reading decoding, but with a strong involvement of working memory, both directly implied in the first trial and in supporting learning in the successive trials (Baddeley, Papagno, & Vallar, 1988), as a consequence of the repetition of shape-nonword associations.

A pilot study was carried out with children without reading difficulties to test different set sizes (i.e., six and eight shape-nonword associations), and the results showed that performance tended to be very high with six stimuli regardless of shapes being presented in fixed or variable locations across trials. Therefore, our decision was to use eight stimuli per trial. We expected children with dyslexia to have a worse performance in binding than children proficient in reading. In addition, we also examined whether, in agreement with the observations of Jones et al. (2013), group differences were affected by fixed versus variable location of the shapes.

Method

Participants

The study comprised a group of 23 children with a diagnosis of dyslexia (mean age = 124 months, *SD* = 9.9) and a control group with 23 children within normal range of reading skills (mean age = 126 months, *SD* = 11.9). The groups were matched in terms of sex and grade distribution: each group consisted of 12 females and 11 males, with 11 children from fourth grade, 8 from fifth grade, and 4 from sixth grade. All children spoke Italian as their first language, none were visual or hearing impaired, and none had any other clinical diagnosis or neurological impairments. We obtained a signed consent form from the children's parents.

Children with dyslexia were recruited among the individuals who were followed by the Learning Disabilities Center of our university, as well as from schools. In schools, children's reading ability (very-low or proficient) was first identified on the basis of interviews with their language teachers, and schools' psychologists were consulted for providing further information about eligible children for the dyslexia and the control groups. The diagnosis of dyslexia in Italy follows both international (ICD-10; World Health Organization, 1992) and national guidelines (Lorusso et al., 2014), and requires reading performance below 2 *SD*s (speed) and/or the 5th percentile (accuracy) in standardized reading tests, in the presence of adequate instruction and level of intelligence.

Materials

Nonword reading task. Reading decoding (speed and accuracy) was assessed with a nonword reading task comprising 48 items taken from a standardized Italian battery (Sartori, Job, & Tressoldi, 2007) to compare groups' performance in reading.

Visual-phonological memory binding task. The stimuli consisted of eight shape-nonword pairs. Visual stimuli were printed black-and-white nonsense shapes similar in size that were elaborated for the present study, and verbal stimuli were presented orally by the experimenter and consisted of eight monosyllabic nonwords mainly derived from Jones et al. (2013; see Figure 1). Judgments given by a group of experts and children confirmed that shapes were not easily verbalizable and the shape-nonword associations resulted completely arbitrary.

The test consisted of four trials, each one comprising the same eight shape-nonword pairs, that is, the combination between a shape and a nonword remained constant throughout the trials and between participants. Across trials, half of the shapes remained on fixed locations and the other half had their locations changed, that is, their locations were swapped from trial to trial. Shapes with fixed and variable locations were counterbalanced between participants by using two sets of four arrays each: On set A, the shapes corresponding to *tran*, *bris*, *frem*, and *gif* (cf. Figure 1) had fixed spatial locations and the other shapes varied locations; on set B, the shapes that had fixed locations on set A were presented on variable locations, and the other four shapes were presented on fixed locations (i.e., the shapes corresponding to *prin*, *drup*, *grol*, and *cral*; cf. Figure 1).

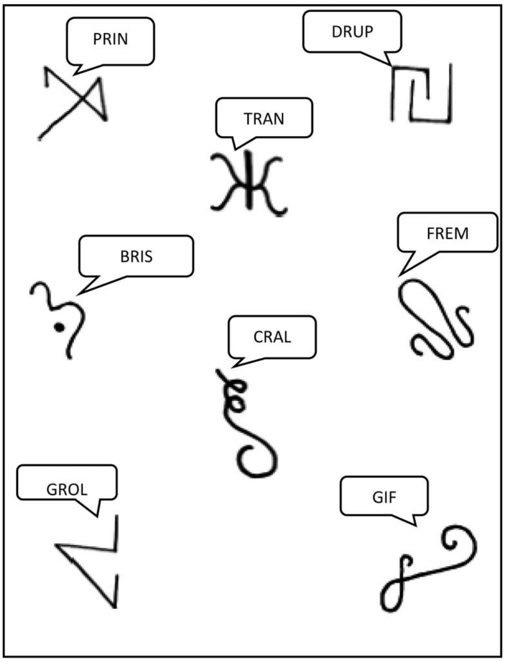

Figure 1. Non-sense shapes with their respective nonwords used as stimuli in the visual-phonological binding task.

Procedure

Participants were tested individually in a single session carried out in a quiet room. Two experimenters belonging to the same linguistic and cultural context of the children were responsible for testing children with dyslexia and their corresponding matched controls. The two experimenters were instructed and trained to rigidly follow the same administration protocols. The session took around 20 min to complete and started with the nonword reading task. Participants were informed that the task comprised meaningless word forms, and were required to read the nonwords as quickly and accurately as possible. Reading time in seconds and reading errors were registered on the basis of the Manual instructions.

The visual-phonological binding task consisted of four trials, and the two sets A and B of stimuli arrays were counterbalanced between participants. In contrast with the traditional PAL paradigm in which children are specifically instructed to learn associations between stimuli and have their answers corrected constantly during the test phase, we only required children to memorize shape-nonword pairs, without making any reference about the characteristics of the task or providing feedback about their answers. In particular, participants received the following instructions:

> This task comprises shapes and words without sense. I am going to point each shape and say a word, which you should repeat aloud after me. When I finish the presentation of the shapes and words, I am going to point one shape and then you have to recall the word that was presented together with that shape. I will point each one of the shapes, therefore pay attention to every shape and word that were presented to you.

On each trial, the child was given a paper sheet with the visual stimuli array, and the experimenter's protocol consisted of the equivalent stimuli array displaying both shapes and their corresponding nonwords. The experimenter indicated with the finger shapes on the participant's sheet, and pronounced its corresponding nonword with a loud and clear voice. The participant was required to repeat it back aloud immediately to ensure the correct encoding of the nonword and its respective shape. In rare occasions in which participants made mistakes in repeating nonwords, they were corrected promptly. Stimuli were presented from the top to the bottom and from the left to the right of the array at a rate of approximately 2 s. The presentation of the last pair of shape and nonword was immediately followed by a cued-recall phase, and the trial's visual stimuli array was always in the view of the participant. The experimenter indicated a shape and the participant's task was to say aloud its respective nonword. Shapes were indicated at random by the experimenter to avoid systematic influence of serial order effects, except for the first and the last shapes of the sequence that were never presented as the first shape in the recall phase. The participants' answers were registered by the experimenter on a specific protocol. At the end of the session children were invited to comment the task, but no specific questions or information about the task were given to avoid that they could influence other children they knew and who were also participating to the study.

Dependent Variables

For each participant we computed the number of correct answers with regard to the match between shapes and nonwords for fixed locations and variable locations separately and pooled, and we adopted a strict accuracy criterion by considering only nonwords pronounced accurately together with their corresponding shapes. We also analyzed incorrect answers to better understand memory difficulties faced by children. In particular, we noticed that approximately half of nonwords pronounced inaccurately were very similar in sound to an original one, maintaining the same order of phones and presenting a difference only in one phone (e.g., 'gis' rather than 'gif'). For this reason, we divided errors into two types: Phonological errors consisted of nonwords pronounced inaccurately by children, even when only one phone was different from the original one, and binding errors consisted of mismatches between shapes and nonwords, that is, all cases in which nonwords were pronounced accurately or almost-accurately in association with incorrect shapes. We computed the number of each type of error observed, as well as the number of omissions (i.e., cases in which no answers were provided).

Statistical Analyses

Statistical analyses based on *t* tests for independent samples were carried out to compare the two groups in all the above-mentioned dependent variables, with significance level set at 0.05 and the Cohen's *d* as the effect size indicator (Cohen, 1988). In addition, the participants' performance in terms of the mean number of correct shape-nonword bindings was further analyzed taking into consideration that shapes were presented either on fixed or variable locations, and that a learning effect was expected given that shape-nonword bindings were the same for all the trials. We first analyzed groups' performance in the first trial, that is, prior to learning, which better reflected the working memory component of the task. To investigate whether memory binding performance was significantly higher for stimuli presented on fixed locations than on variable locations (i.e., a one-sided comparison), *t* tests for independent variables were carried out separately for each group of children. Finally, to investigate the learning effect, performance in Trials 1 and 2 and in Trials 3 and 4 were pooled and analyzed separately for each group of children, that is, we performed t tests for independent variables to investigate whether performance in Trials 3 and 4 was significantly better than in Trials 1 and 2, and whether performance was significantly higher for stimuli presented in fixed locations than in variable locations in Trials 1–2 and 3–4.

Results

Table 1 summarizes the descriptive statistics for groups' performance in all the measures collected for the nonword reading task and the visual-phonological memory binding task, and the results of group comparisons based on t tests. As can be seen in Table 1, significant differences with large effect sizes (greater than two standard deviations or Cohen's d) between the groups were observed in nonword reading both with respect to time and number of errors, thus confirming that the two groups were substantially different in reading abilities. With regard to the binding task, large and significant differences (greater than one standard deviation) between the groups were observed for the number of correct matches between shapes and their respective nonwords, both for the pairs in fixed and in variable locations considered separately, and for the total number of correct matches. In fact, the dyslexia group remembered correctly a mean of 11.1 associations (approximately 35% of the cases), whereas the controls had a performance 66% higher than dyslexics, with a mean number of 18.5 correct answers (approximately 58% of the cases). Concerning different types of memory errors, children with dyslexia produced more binding errors than the control group, indicating a failure in associating a correct or almost-correct phonological information with the corresponding shape. In addition, they also produced more phonological errors than children from the control group, indicating a failure in retrieving accurate phonological information. Finally, with regard to the number of omissions, the groups did not differ significantly using a two-sided t test ($p = .084$), although it is worth noting that the groups differed significantly using a one-sided t test ($p = .042$), that is, by testing the specific hypothesis that the dyslexia group omitted more responses than the control group. In fact, the mean difference of 2.2 items was 0.52 standard deviations (or Cohen's d), which represents a moderate effect size. Such effect was consistent using scoring procedures other than the raw number of omissions, such as the proportion of omissions by number of answers, $t(44) = 1.84$, $p = .037$ (one-sided), Cohen's $d = 0.54$, or the proportion of omissions by number of items, $t(44) = 1.77$, $p = .042$ (one-sided), Cohen's $d = 0.52$. Thus, we have evi-

Table 1

Mean (M) Performance, With Standard Deviations (SD) and Confidence Intervals (95% CIs) in All the Measures Collected in the Nonword Reading Task and the Visual-Phonological Memory Binding Task for Each Group of Children

	Control ($n = 23$)		Dyslexia ($n = 23$)			
Measure	*M* (*SD*)	95% CI	*M* (*SD*)	95% CI	$t(44)$	Cohen's d
Nonword reading						
Time (s)	60.0 (14.1)	[53.9, 66.0]	133.2 (49.1)	[112.0, 154.5]	6.87^{**}	2.03
Errors	1.3 (1.3)	[.7, 1.9]	10.6 (6.1)	[8.0, 13.3]	7.12^{**}	2.10
Memory binding						
Variable location	8.3 (2.5)	[7.2, 9.4]	5.7 (2.0)	[4.8, 6.6]	3.87^{**}	1.14
Fixed location	10.3 (3.7)	[8.6, 11.9]	5.4 (3.6)	[3.8, 7.0]	4.47^{**}	1.32
Total correct	18.6 (3.8)	[16.9, 20.2]	11.1 (4.4)	[9.2, 13.0]	6.19^{**}	1.83
Binding errors (mismatches)	3.0 (2.9)	[1.7, 4.2]	4.8 (2.7)	[3.6, 6.0]	2.21^{*}	.65
Phonological errors	1.8 (2.3)	[.8, 2.8]	5.0 (5.8)	[2.5, 7.4]	2.45^{*}	.72
Omissions	7.4 (4.0)	[5.7, 9.1]	9.6 (4.5)	[7.6, 11.6]	1.77^{a}	.52

[a] $p = .084$ (two-sided) or $p = .042$ (one-sided).

* $p < .05$ (two-sided). ** $p < .001$ (two-sided).

dence that children with dyslexia were likely to omit more responses than the control group.

Figure 2 shows the mean number of correct responses in binding for variable and fixed stimuli locations pooled by Trials 1 and 2 and Trials 3 and 4 for each group of children. The difference between groups was evident at the first trial, because the mean score of the dyslexia group was of 1.6 items ($SD = 1.6$), which was significantly worse than the control group with a mean score of 3.4 items ($SD = 1.3$), $t(44) = 4.16$, $p < .001$, Cohen's $d = 1.23$. The learning effect was consistent for both group of children, given that performance in Trials 3 and 4 was significantly better than in Trials 1 and 2 for the control group (mean difference = 2.6), $t(44) = 3.89$, $p < .001$, Cohen's $d = 1.15$, as well as for the dyslexia group (mean difference = 2.2), $t(44) = 2.92$, $p = .005$, Cohen's $d = 0.88$. Furthermore, as can be seen in Figure 2, the presentation of stimuli in fixed locations across trials affected learning only for the control group, that is, the number of correct bindings for the last two trials was significantly higher for fixed locations than for variable locations (mean difference = 1.4), $t(44) = 1.96$, $p = .028$ (one-tailed), Cohen's $d = 0.58$, whereas for Trials 1 and 2 no significant effect of stimuli location was observed (mean difference = 0.6), $t(44) = 1.12$, $p = .12$ (one-tailed), Cohen's $d = 0.37$.

Discussion

Despite its involvement in learning to read (Hulme et al., 2007; Warmington & Hulme, 2012; Windfuhr & Snowling, 2001), and its potentially crucial involvement in dyslexia (Aravena et al., 2013; Jones et al., 2013), the ability to temporarily store new associations between shapes and speech sounds has never been, to the best of our knowledge, systematically studied in children with dyslexia. The few studies that have investigated cross-modal working memory binding offered uncertain evidence. Thus, to our knowledge, this is the first study that offers clear evidence of working memory binding deficits in children with dyslexia, which specifically concern the case of cross-modal association of not-verbalizable visual material with nonsense phonological material. The study offered evidence in support of visual-phonological working memory binding deficits, given that children with dyslexia fared worse than controls for bindings presented both on fixed and on variable locations and the effect was clearly evident also at the first trial. In addition, a learning effect from Trials 1–2 to Trials 3–4 was observed for both groups of children, suggesting that cross-modal learning is spared in children with dyslexia, which is in agreement with other studies (Li et al., 2009; Messbauer & de Jong, 2003), but that impairments rely on cross-modal binding processes (Blau et al., 2010; Blomert, 2011). In contrast with traditional PAL studies, which mainly focused on long-term memory without considering the possible role of immediate recall, the present study assumed a strong involvement of working memory in learning, as also suggested by Baddeley et al. (1988), and used a method devoted to emphasize this involvement due to the number of presented items and the absence of feedback, corrections, and instructions focused on learning.

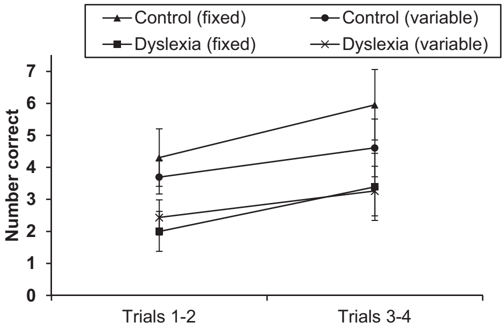

Figure 2. Mean number of correct matches between shapes and nonwords in fixed and variable locations for Trials 1–2 and Trials 3–4, for each group of participants. Error bars represent 95% confidence intervals of the mean.

In our study, as noted by the experimenters during the session, children in general (with only few exceptions) did not notice crucial aspects of the task, namely, that shape-nonword associations were always the same throughout the trials and that some shapes were always presented on fixed locations. Thus, there is evidence that learning occurred quite implicitly in our sample, but future studies should better examine this and other issues. For example, on the basis of the present study we cannot know to what extent the binding failure of children with dyslexia was due to weaknesses in other related aspects, such as memory load and interference control. Future research could help to understand such issues, for example, by using an incremental memory span procedure and a serial memory task (e.g., Garcia et al., 2014).

It is worth noting that our binding task tapped basic working memory processes that are assumed to be involved both in the PAL paradigm and, in particular, in learning to read. On this respect, our results may seem highly predictable given that reading also involves the association of shapes (letter shapes) with speech sounds. However, surprisingly, in the consideration of developmental dyslexia the focus has been typically directed toward the processing of single features, and in particular of phonological representations (e.g., Ramus, 2003) rather than on the integration between distinct features. In fact, our results could be interpreted on the basis of phonological difficulties of children with dyslexia in the memorization of nonwords (Litt et al., 2013) as phonological errors were more frequent in the group with dyslexia, representing a difficulty to retrieve accurately the nonwords. However, it is worth noting that a phonological difficulty explanation should also include the consideration of a binding deficit to explain the overall pattern of data, including the facts that we found a greater number of mismatches between shapes and nonwords and no advantage because of the fixed location in the group with dyslexia, two difficulties that cannot be associated only with a phonological deficit. For the control group, the location effect, which mirrors the pattern found with adults (Jones et al., 2013), shows that individuals who are efficient in binding may take advantage from the location cue when associating phonological and visual information. In fact, evidence shows that location plays an important role in memory binding, that is, given that location changes of stimuli disrupt recognition of bound objects (e.g., colored shapes) but not recognition of single features (Treisman & Zhang, 2006; see also Hollingworth & Rasmussen, 2010). Thus, our results suggest that location is also beneficial in support of cross-modal binding memory and learning for individuals who are efficient in binding (see also Jones et al., 2013).

Thus, our results are consistent with the view that visual-phonological cross-modal binding processes are crucially involved in reading (Blomert, 2011; Hahn et al., 2014), and provide new insights on the role of binding and working memory processes in reading disorders. Evidence indicates that phonological awareness and visual-phonological PAL tasks tap separate processes involved in learning to read (Windfuhr & Snowling, 2001), and it is reasonable to argue that reading disabilities may involve deficits in one or more types of processes, but also in the capacity to bind visual to phonological information in memory.

The present study deserves further developments both to extend the findings to a larger sample of children and to samples from different languages, especially with opaque orthographies. Testing a larger number of participants would increase the power of statistical analyses and the strength of evidence concerning differences between the groups and between fixed and variable stimuli locations. In addition, it is also important to test samples from different languages. It should be noted that the Italian language has a transparent orthography with straightforward and consistent associations between graphemes and phonemes. For this reason, it might be the case that reading disabilities in transparent languages could be more associated with deficits in cross-modal binding processes, whereas in opaque orthographies they could be more associated with phonological awareness. Thus, future research is needed to explore these issues.

In conclusion, the present study offers the first clear evidence of a visual-phonological binding difficulty in children with dyslexia, suggesting that more attention should be devoted to this aspect both in diagnosis and in treatment. For example, a working memory test measuring visual-phonological binding could be used in the assessment of children with dyslexia to better understand their difficulties in reading and spelling. For those children presenting a low ability in binding, intervention could also focus in enhancing this ability. This should be consistent with recent evidence showing that remedial methods should focus both on enhancing the quality of phonological representations and on strengthening associations between orthographic and phonological representations (Gang & Siegel, 2002; Hahn et al., 2014).

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