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A Cross-Modal Working Memory Binding Span Deficit in Reading Disability

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Abstract

Successful reading demands the ability to combine visual-phonological information into a single representation and is associated with an efficient short-term memory. Reading disability may consequently involve an impaired working memory binding of visual and phonological information. The present study proposes two span tasks for assessing visual-phonological working memory binding. The tasks involved memorizing cross-modal associations between nonsense figures and nonwords, and they were administered, with other working memory measures, to children with and without a reading disability. The tasks required recognizing which figure was associated with a given nonword and recalling which nonword was associated with a given figure. Children with a reading disability had a similar significant deficit in both cross-modal binding tasks when compared with the control children, and the difference remained significant even after controlling for other verbal and nonverbal working memory measures. The cross-modal binding tasks described here seem to capture a core aspect of working memory associated with reading and may be a useful procedure for assessing reading disabilities.

Keywords

cross-modal binding, working memory, dyslexia, reading disability

Learning to read demands the ability to memorize arbitrary correspondences between abstract visual shapes (i.e., letters, words) and verbal codes. The type of visual-phonological association acquired in the process is an instance of cross-modal binding—that is, integrating items of information deriving from different sensory sources into a single mental representation. In fact, in controlled laboratory trials, researchers examined the ability to learn how to make such arbitrary associations within the framework of "paired associative learning" and found that it related to reading proficiency (e.g., Hulme, Goetz, Gooch, Adams, & Snowling, 2007).

There have been reports of impaired cross-modal binding among individuals with reading difficulties, such as developmental dyslexia (Aravena, Snellings, Tijms, & van der Molen, 2013; Hahn, Foxe, & Molholm, 2014; Li, Shu, McBride-Chang, Liu, & Xue, 2009; Litt & Nation, 2014). Litt, de Jong, Bergen, and Nation (2013), however, reported that it was only in tasks requiring verbal output, not in those that involved associating cross-modal associations per se, that a significant correlation with reading ability emerged.

In studies on paired associative learning, the associations were repeatedly presented to children, and only long-term retention was assessed. Both reading and the process of learning new material are supported by working memory (Baddeley, 1986), however, and this is probably true of learning new cross-modal associations too, as suggested by recent research (Allen, Hitch, & Baddeley, 2009; Cowan, Saults, & Morey, 2006).

Working memory is the cognitive system that enables the temporary storage of a limited amount of information gleaned from various sensory inputs and its processing by a central executive system. It has been claimed that working memory plays a crucial part in several areas of academic learning (Baddeley, 2000), and a weak working memory has emerged as a defining feature of learning disorders, including dyslexia (e.g., De Weerdt, Desoete, & Roeyers, 2013; Giofrè & Cornoldi, 2015; Giofrè, Toffalini, Altoè, & Cornoldi, 2017). According to Baddeley's (2000) working memory model, a particular component called the "episodic buffer" is responsible for storing multimodal information of the type involved in cross-modal binding (Allen et al., 2009). Despite its theoretical importance, surprisingly few studies have examined cross-modal binding in dyslexia using a working memory framework (Garcia, Mammarella, Tripodi, & Cornoldi, 2014; Jones, Branigan, Parra, & Logie, 2013).

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One of the few studies to examine the short-term ability to recall visual-phonological associations was conducted by Swanson (1978). The author found that typically developing children were better able to remember the locations of nonsense shapes in a probe-type serial memory task if the shapes were associated with words that meaningfully referred to a characteristic of the shape concerned, while the same effect was not seen among children with a learning disability. Swanson concluded that learning disability is associated with a deficit in the verbal rather than visual encoding of stimuli. Around the same time, other authors were considering the relationship between learning disability and the short-term recall of visual-phonological associations (e.g., Vellutino, Steger, Harding, & Phillips, 1975), but then the topic was neglected until recently, when a few studies were published with a focus within the working memory framework. In one of these studies, Jones and colleagues (2013) found that adults with developmental dyslexia had more difficulty with visual-phonological working memory binding than normal readers but only when shape-nonword pairs were presented in fixed locations across successive trials. The authors surmised that the adults with dyslexia were unable to use the constant spatial location as a cue to facilitate binding. In a study on children, however, Garcia and colleagues (2014) found no significant difference between the cross-modal working memory binding of children with dyslexia and their typically developing peers. This latter result may be due to the materials used, however, because binding was assessed with color-location associations instead of the phonological-visual associations typically involved in reading.

To our knowledge, the first study to focus directly on visual-phonological binding among children within a working memory framework was conducted by Albano, Garcia, and Cornoldi (2016). The authors reported a significant binding deficit among fourth- to sixth-grade children with dyslexia as compared with typically developing children in the same age group. As with Jones et al. (2013), participants with dyslexia were unable to exploit a constant location of the stimuli to improve their performance, as typical readers normally do. Unlike adults with dyslexia, however, the children with dyslexia had more difficulty than their typically developing peers when the location of the stimuli was not fixed. This confirmed the core role of cross-modal working memory binding impairment in reading difficulty, which is especially evident in midchildhood. These results were replicated and extended in a new study (Toffalini, Tomasi, Albano, & Cornoldi, 2017) showing that the cross-modal binding performance of children with dyslexia improved when the visual-phonological pairs were presented in a fixed temporal order, rather than in fixed spatial locations, across subsequent trials.

These studies had some limitations, however. They used a complex procedure and tasks that were clearly on a supraspan level. In other words, the number of items presented explicitly exceeded the working memory capacity of the children involved, who were able to remember just a few items. The only way to assess working memory in such a situation is indirectly, because performing the task is likely to demand the involvement of long-term memory as well (Baddeley, 1986). In a study on adults with dyslexia, Jones and colleagues (2013) likewise presented a task that involved remembering a fixed (and supraspan) number of associations. The procedures used to date therefore did not test working memory alone, and their complexity would make them difficult to apply in clinical and practical settings. Another limitation of the extant studies is that they did not control for phonological and visuospatial working memory capacity or for participants' ability to remember the stimuli presented. That is, they did not strictly examine how a measure of binding could reveal a specific impairment among children with reading difficulty, over and above the known weaknesses in their verbal working memory (Toffalini, Giofrè, & Cornoldi, 2017).

Given the theoretical and applied importance of studying how cross-modal working memory binding relates to reading difficulty, further evidence is needed on this issue—hence, the need for an instrument for measuring this ability that can be administered quickly and easily among children. In clinical practice, working memory is often measured with span tasks, namely by presenting increasingly long series of items to be recalled and stopping when a child repeatedly fails on a given level of difficulty (e.g., the digit span task in the *Wechsler Intelligence Scale for Children–Fourth Edition*; Wechsler, 2003). Using the same approach to measure cross-modal working memory binding span could offer a useful and simple tool for clarifying the nature and extent of any impairment in this ability in children with a reading disability.

In the present study, we therefore developed a visual-phonological binding span task that follows the same logic as the classical digit span task—easy for clinicians to use and for children to understand. The task was administered to children with a reading disability, with paired stimuli comprising visual shapes and monosyllabic nonwords. Like Albano and colleagues (2016) but unlike Jones and colleagues (2013), we chose simple nonsense drawings rather than nameable shapes for our visual stimuli. We did this to prevent respondents from associating nonwords with the verbal labels of the shapes, which would turn the task into a purely verbal one. Furthermore, to study the generality and extent of a binding deficit among children with a reading disability, we opted to test the binding of not only pairs comprising nonwords to recall in association with shapes (as in Albano et al., 2016) but also pairs in which shapes had to be recognized in association with nonwords (as in Toffalini, Giofrè, & Cornoldi, 2017), whereas the two other possible combinations of nonwords and shapes were not used, to keep the procedure simple. The new binding tasks

Table 1. Reading Measures and Working Memory Spans With Between-Group Comparisons and Effect Sizes for the Two Groups.

	Group, *M* (*SD*)				
Measure	Reading disability (n = 30)	Control (n = 30)	t(58)	p	Cohen's d
Lexical decision accuracy	26.13 (8.69)	51.37 (6.54)	−12.71	<.001	3.28
Nonword reading					
Time	89.03 (20.60)	58.28 (12.06)	7.06	<.001	1.82
Errors	10.07 (4.86)	1.53 (1.70)	9.07	<.001	2.34
Digit span	4.80 (0.66)	5.27 (0.98)	−2.16	.035	0.56
Corsi blocks span	5.27 (0.69)	5.43 (0.82)	−0.85	.397	0.22
Nonword span	2.13 (0.35)	2.77 (0.57)	−5.21	<.001	1.35
Shape span	4.10 (1.40)	4.13 (1.31)	−0.10	.924	0.02
Binding span					
Nonword to shape	2.67 (0.55)	3.43 (0.86)	−4.13	<.001	1.07
Shape to nonword	1.87 (0.82)	2.63 (0.61)	−4.10	<.001	1.06

were designed to be of gradually increasing difficulty, based on the procedure of the classic digit span task.

One of our aims was to establish whether a binding deficit in working memory is a core feature of reading disability not better explained by other aspects of working memory known to be weak among children with this learning disorder (De Weerdt et al, 2013; Giofrè et al., 2017; Toffalini, Giofrè, & Cornoldi, 2017). To do so, we compared children with a reading disability and matched control children on our binding span task, controlling for measures of phonological and visuospatial working memory capacity, as well as for the children's ability to remember monosyllabic nonwords and nonsense shapes. The group of children with a reading disability had been identified by means of assessments conducted by clinical centers or schools, but we also included a reading assessment and compared our children on reading performance to confirm their appropriate grouping.

Method

Participants

The study involved two groups of 30 children matched for school grade, gender, and sociocultural level. Each group included 9 fourth graders, 8 fifth graders, 4 sixth graders, and 9 seventh graders (age range, 9–13 years). In the group of children with a reading disability ($n = 30$, 15 males; age: $M = 134.67$ months, $SD = 16.20$), 18 children had a diagnosis previously established at clinical centers according to the Italian national guidelines on specific learning disorders (Istituto Superiore di Sanità, 2011). They had been tested on nonwords, words, and passage reading and obtained speed and/or accuracy scores below preset cutoffs (2 *SD* or the 5th percentile) in at least one task; the other 12 children were identified on the basis of their school reports. The control group consisted of typically developing children ($n = 30$, 15 males; age: $M = 135.53$ months, $SD = 16.13$) with a normal reading proficiency. To obtain further information on all the participants' reading abilities, we administered a reading lexical decision task (Caldarola, Perini, & Cornoldi, 2012) and a nonword reading task (Sartori, Job, & Tressoldi, 2007). The reading lexical decision task (Caldarola et al., 2012) consists of 120 items, including 60 words (all familiar to children as of the second year of primary school) and 60 nonwords. The words and nonwords are matched for length, and may have two, three, or four syllables. The child is asked to detect and tick as many nonwords as possible within a limited time (2 min). The final measure of performance is the number of correct answers (i.e., nonwords ticked) less the number of mistakes (i.e., words ticked). A brief list of 14 items is administered as an example before the test. The nonword reading task consists of a list of 48 nonwords (for a total of 127 syllables) arranged in three columns of 16 items each, that the child is asked to read as quickly and accurately as possible. The total reading time (in seconds) and accuracy (number of errors) are measured. Both tasks are printed in black on sheets of white A4-size paper.

Table 1 gives the descriptive statistics for the reading measures in the two groups and the between-group comparisons. The two groups largely differed on all reading measures (lexical decision accuracy, nonword reading speed, and nonword reading accuracy) in the expected direction, with the control group outperforming the group with reading disability (Cohen's $d \geq 1.82$ for all reading measures). All aspects of the control group's reading proficiency were in line with or above the relevant norms (Caldarola et al., 2012; Sartori et al., 2007). The participants' working memory capacity was also assessed, including visuospatial and phonological aspects (Baddeley, 2000) with adaptations of a Corsi blocks task and a digit task, respectively, which were administered in individual sessions. These tasks were selected from the BVN 5-11, a battery for the neuropsychological assessment of children that is widely used in Italy (Bisiacchi, Cendron, Gugliotta, Tressoldi, & Vio, 2005). Regarding their administration, these tasks are ended when the child repeatedly fails at a given level of difficulty; the reached span levels are considered the final scores. The Corsi blocks task (e.g., Berch, Krikorian, & Huha, 1998) consists of nine blocks placed on a rectangular board in random positions; the blocks are tapped by the experimenter in different orders and in increasingly long sequences, and the child is asked to memorize and reproduce the sequences immediately after. Similarly, the administration of the digit span task (e.g., Wechsler, 2003) consists of the experimenter verbally presenting increasingly long sequences of digits that the child has to recall immediately after.

The screening procedure and subsequent individual tests were all conducted during school hours. Formal IQ tests had been conducted at a clinical center on the subgroup of 18 children already diagnosed with dyslexia. The schools participating in the study did not allow the children to be assessed on intelligence, but we ascertained that all the children were of average intelligence on the basis of their school reports and a questionnaire completed by their teachers. On the same grounds, we excluded children with any other diagnosed psychological problems. Prior to the study, written parental consent was obtained for all the children involved.

Stimuli and Tasks

Materials. A pool of 270 visual stimuli and 207 phonological stimuli was prepared following the method described by Albano and coauthors (2016). The visual stimuli consisted of black outlines depicting nonsense shapes printed on paper cards (5 × 5 cm). The phonological stimuli consisted of monosyllabic nonwords (cf. Albano et al., 2016; Jones et al., 2013; e.g., "grol," "nant," "fost"). The stimuli were selected from a large pool by four independent adult judges based on the criteria that the nonwords should have no association with any known words and the shapes should not be easy to verbalize (see the Appendix for examples of the stimuli). The selected stimuli were randomly divided for use in four span tasks, in which different material was presented but the procedure remained the same. Sets comprising increasing numbers of items (from one or two to six or seven) were presented until the child failed twice in a set of a given length. The final score was the span—specifically, the number of items in the longest sets that a child could recall correctly in at least two of three trials. The task was terminated when a child failed to reach the next span level. The tasks were newly created for the purposes of the present research, so no previous evidence on its psychometric properties was available. The use of the associative request for similar stimuli had already been validated, however, in a recent study by Toffalini, Giofrè, and Cornoldi (2017) and in a study comparing children of different ages (Marsura & Toffalini, 2017). For the present study, we also calculated the internal consistency using Cronbach's α for ordinal data (computed on the polychoric correlation matrix, given the dichotomous nature of the data). Stimuli of all the tasks described here are provided in the supplemental online material.

Nonword span task. Eighteen sets of nonwords were prepared, each consisting of one to six nonwords (three sets for each span level). As in the traditional forward digit span task, the child was read the set of stimuli by the experimenter (at a rate of approximately one item every 2 s) and asked to repeat the set in the same order immediately afterward. The internal consistency was acceptable (ordinal Cronbach's α = 72).

Shape span task. This task was similar to the nonword span task except that nonsense shapes were used as stimuli and recall was assessed with recognition tests. The shapes were shown one after the other for 2 s each. After the encoding phase, the previously shown shapes and the same number of new shapes were randomly placed on the table, and participants were asked to indicate the shapes seen previously in their order of presentation. The internal consistency was very good (ordinal Cronbach's α = 94).

Shape-to-nonword binding task. This was a cross-modal binding task taxing working memory, which involved remembering a number of arbitrary associations between the nonwords and shapes. It was developed on the same basis as the previously described span tasks, presenting the nonword-shape pairs to remember in increasingly long sequences (from one to six pairs). During the encoding phase, the experimenter presented one shape at a time while pronouncing the corresponding nonword in a loud clear voice (the pairs were presented at a rate of one every 3 s). For an example of the paired stimuli used in this task, see Appendix A. A cued recall test was administered after the encoding phase. All the shapes seen during the trial were presented simultaneously on the table; then, the experimenter indicated one shape at a time and asked the child to pronounce aloud the corresponding nonword. The shapes were tested in a random order to avoid any systematic serial effect. The internal consistency was very acceptable (ordinal Cronbach's α = 78).

Nonword-to-shape binding task. This cross-modal binding task was similar in all respects to the previous one, except that memory for shapes was tested and a recognition task (instead of a cued recall task) was administered after the

Table 2. Pearson's Correlations Between the Binding Span Scores and Each Working Memory Measure.

Binding span	Digit span	Corsi blocks span	Nonword span	Shape span
Nonword to shape	.24	.32*	.27*	.22
Shape to nonword	.32*	.31*	.35**	.23

Note. Variables were mean centered by group to remove the effect of the groups on the correlations.
*$p < .05$. **$p < .01$.

encoding phase. In the recognition test, all the shapes seen during the encoding phase were presented simultaneously on the table in a random configuration, and the experimenter pronounced the previously presented nonwords one at a time in a predefined random order, asking the child to indicate the corresponding shape. In this task, there was no Level 1; the task started from Level 2. The reason is that, to succeed on Level 1, the child would need to recognize only the previously presented single visual stimulus, without the need of any actual binding involved. Internal consistency was good (ordinal Cronbach's α = 87). For an example of the paired stimuli used in this task, see Appendix B.

Procedure

Apart from an initial session in the classroom lasting about 10 min, when the children were collectively administered the lexical decision task (Caldarola et al., 2012), participants were tested individually during a single session in a quiet room at school. The nonword reading task (Sartori et al., 2007), the digit span task, and the Corsi blocks task (Bisiacchi et al., 2005) were administered first, then the nonword span, the shape span, and the two binding tasks. All the tasks were always presented in the same order to make the children's performance readily comparable. The individual sessions lasted approximately 40 min, and the two binding tasks took no more than 10 min (5 min each). All participants were tested by a single female experimenter (M.M.) belonging to the same linguistic and cultural context as the children.

Results

Table 1 shows the means, standard deviations, and between-group comparisons based on *t* tests, with Cohen's *d* as the effect size indicator, for all measures collected. The two groups did not differ significantly on visuospatial working memory (Corsi blocks task and shape span), but they did differ on verbal working memory (digit span and nonword span) and on both the cross-modal working memory binding span measures. The control group always outperformed the group with reading disability. For the cross-modal working memory binding measures in particular, the between-group differences were large, with Cohen's $d > 1$.

Significant correlations emerged among different aspects of working memory (digit span, Corsi span, and nonword span) and in terms of performance in the two binding tasks. These correlations were calculated after mean centering the variables separately by group, so they did not depend merely on between-group differences. The correlations are given in Table 2.

To examine whether cross-modal working memory binding would capture a core difference between children with and without a reading disability (rather than a difference mediated by phonological aspects of working memory or the specific ability to remember nonwords), we examined the effect of group on both binding measures after controlling for all other working memory measures. To do so, we computed mixed-effects linear models with the two binding span measures as the dependent variables, with group as the predictor, and with digit span, Corsi span, nonword span, and shape span entered into the models as covariates. The type of binding task (nonword to shape vs. shape to nonword) was also entered as a predictor to test its interaction with group. Although the measures obtained from nonword-to-shape binding and from shape-to-nonword binding differed substantially, we opted to treat them as repeated measures of the same variable because our primary interest lay in whether the between-group difference in binding span was similar for the two types of binding task. Participants were considered a random effect. The significance of the effects was tested with likelihood ratios for nested models based on the chi-square distribution (Pinheiro & Bates, 2000), removing one predictor at a time from the full model.

A significant main effect of group emerged, $\chi^2(1) = 11.29$, $p < .001$, confirming that controls outperformed children with a reading disability in the binding tasks, $\beta = -.31$. The type of binding task also had a significant main effect, $\chi^2(1) = 39.06$, $p < .001$, indicating that the children scored higher in the nonword-to-shape task than in the shape-to-nonword task, $\beta = -.12$ (see Table 1). The Group × Type of Binding Task interaction was not significant, $\chi^2(1) = .01$, $p = .99$, and the estimated parameter of interaction was extremely small, $\beta = .01$, suggesting that the between-group difference in binding span was not moderated by the type of binding task. Figure 1 shows the estimated binding spans in working memory by group and type. Among the control variables, only the nonword span had a significant main effect on

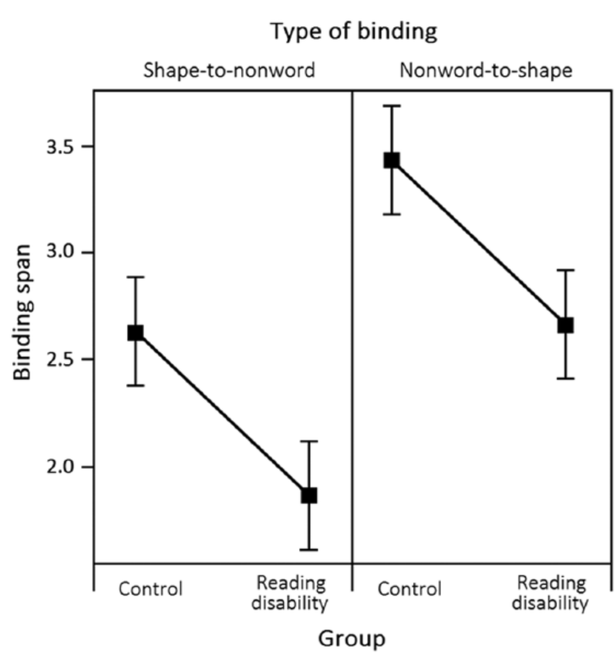


Figure 1. Estimated mean working memory binding span as a function of group and type of binding task, controlling for all other measures of working memory. Error bars represent 95% confidence intervals.

binding, $\chi^2(1) = 3.85, p = .049$, which was positive but small, $\beta = .20$. No other significant effects emerged ($p > .07$).

A significant association between the binding measures and the reading measures also emerged at the correlational level. Regarding the bivariate correlations, the nonword-to-shape binding span correlated with performance in the reading lexical decision task, $r = .49, p < .001$, and with nonword reading errors, $r = –.50, p < .001$, and with nonword reading time, $r = –.39, p < .001$. The shape-to-nonword binding span also correlated with performance in the reading lexical decision task, $r = .51, p < .001$, and with nonword reading errors, $r = –.53, p < .001$, and with nonword reading time, $r = –.47, p < .001$. Even after partializing for visuospatial (Corsi span, shape span) and verbal (digit span, nonword span) measures of working memory, the nonword-to-shape binding span significantly correlated with performance in the reading lexical decision task, $r = .33, p = .01$, and with nonword reading errors, $r = –.30, p = .02$, but not with nonword reading time, $r = –.12, p = .38$. The shape-to-nonword binding span significantly correlated with performance in the reading lexical decision task, $r = .33, p = .01$, and with nonword reading errors, $r = –.29, p = .02$, but again not with nonword reading time, $r = –.19, p = .14$.

Discussion

In the present study we assessed cross-modal binding among children with a reading disability, within a working memory framework. Our aim was to test the hypothesis that a core deficit of children with a reading disability concerns the binding of phonological and visual information within the working memory system. We developed a task for assessing cross-modal (visual-phonological) working memory binding among children in fourth to seventh grade and tested its efficacy in differentiating between children with and without a reading disability. We adopted a procedure resembling the working memory span tasks typically used in clinical practice (e.g., in the Wechsler battery; Wechsler, 2003). It consisted of a series of trials in which increasingly long sets of stimuli were presented until a child repeatedly failed to complete a trial on a given level of difficulty. As predicted, the children with a reading disability had more difficulty than the control children in both versions of the visual-phonological binding task.

The present results extend to working memory the evidence emerging from previous studies with tasks that involved associative long-term learning of visual-verbal pairs (e.g., Aravena et al., 2013; Li et al., 2009; Warmington & Hulme, 2012). Our results are also in line with recent studies assessing supraspan cross-modal memory of adults (Jones et al., 2013) and children (Albano et al., 2016; Toffalini, Tomasi, et al. 2017). It should be noted, however, that Garcia et al. (2014) found no binding deficit in working memory for color-location associations among children with a reading disability. This would mean that only the type of binding specifically involved in reading is impaired in dyslexia. It is worth emphasizing that, in the present study, the between-group differences in binding span were not explained by verbal and nonverbal working memory variables. An effect of group on binding emerged even after controlling for phonological and visuospatial working memory measures. We surmise that our binding task captured a core deficit associated with reading disability, an impairment that may distinguish between children with a reading disability and typically developing children over and above the (predictable) phonological working memory deficit.

It is also worth noting that our binding tasks tapped the phonological and visuospatial components of working memory simultaneously. Within the latest framework of working memory proposed by Baddeley (2000), the role of this cross-modal association has been related to a specific component called the *episodic buffer* (for an explanation of the relationship between cross-modal working memory binding and the episodic buffer, see Allen et al., 2009). This buffer has been described as the storage component of working memory that, unlike the phonological loop and visuospatial sketchpad, is based on a multidimensional code. Our results are consistent with the claim that the episodic buffer is crucial to several areas of academic learning, reading included (Baddeley, 2000), but these findings could be considered in relation to other developmental accounts of working memory too. In particular, Cowan and colleagues (2006) provided an intriguing account of how working memory for verbal-spatial associations develops throughout the school years and into early adulthood.

It has also been stressed that we need to distinguish between the phonological and visuospatial components of working memory, as different patterns of performance may emerge for the phonological versus visual spans (Baddeley, 1986, 2000). In line with previous literature (De Weerdt et al., 2013; Giofrè & Cornoldi, 2015; Giofrè et al., 2017; Maehler & Schuchardt, 2016; Swanson, 1999; see also Swanson, 1978; Vellutino et al., 1975), we found that children with a reading disability had more difficulty than controls in phonological working memory tasks (digit span and nonword span) but not in visuospatial working memory tasks (Corsi blocks task and nonsense shape span), further confirming the importance of examining the two components separately.

Apart from the between-group differences, we observed relationships between binding span and other working memory aspects. The shape-to-nonword task in particular (which involved recalling nonwords to associate with shapes) correlated significantly with both measures of the phonological loop (digit span and nonword span) and with the Corsi blocks task, whereas the nonword-to-shape task correlated significantly with the nonword span and Corsi blocks task (cf. Table 2). Taken together, the present results suggest that working memory binding is related to (and presumably affected by) the ability to remember unimodal (phonological or visual) information. As already stressed, however, the binding tasks add a specific request that is not explained by the spans alone.

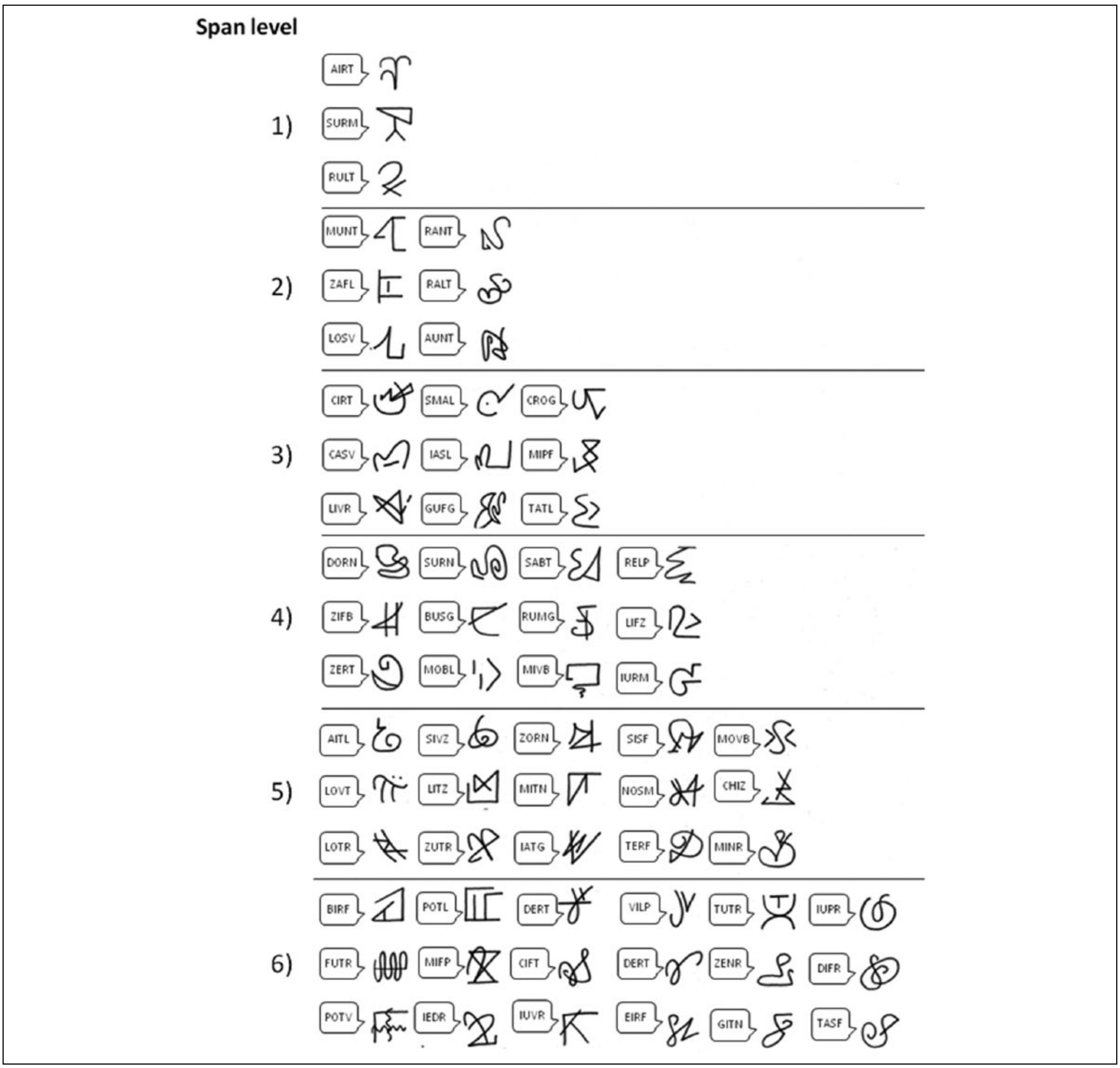
It is worth mentioning that higher spans emerged with the recognition procedure of shapes (nonword-to-shape task) than with the cued recall of nonwords (shape-to-nonword task). This was to be expected because recognition is generally easier than recall. Furthermore, the binding assessment could be refined from an experimental point of view by including all four combinations of the types of binding and test (recall vs. recognition). This would make the assessment potentially difficult, however, and we were more interested in devising a task that could be administered quickly and easily in clinical and other settings. In particular, a recall version of the nonword-to-shape binding task might prove difficult to assess because it would involve answering by drawing the shapes by hand. In our opinion, the crucial point is that the between-group differences in binding performance were almost identical in both versions of the task, as seen in Figure 1, and from the absence of a Group × Type of Binding Interaction. In other words, the two versions of the task seemed equally capable of distinguishing between children with a reading disability and controls, whether the required output was verbal or not. This seems to be inconsistent with the report from Litt and Nation (2014) that children with dyslexia revealed a weakness in paired associative learning of visual-verbal pairs only when a verbal output was required—an impairment wholly attributable to a deficit in phonological learning. Litt and Nation assessed long-term learning across repeated presentations, however, whereas no "learning" was involved in the present study because we assessed immediate recall.

To sum up, the evidence emerging from the present study supports the hypothesis of a visual-phonological working memory binding deficit in children with a reading disability. Previous research assessed binding in supraspan procedures without considering the role of general phonological or visuospatial working memory capacity (e.g., Albano et al., 2016). Our results revealed instead that differences in binding span persist even after controlling for measures of phonological and visuospatial working memory. In other words, we found evidence of children with a reading disability having a specific impairment in cross-modal working memory binding span that is not accounted for by their deficits in phonological aspects of working memory.

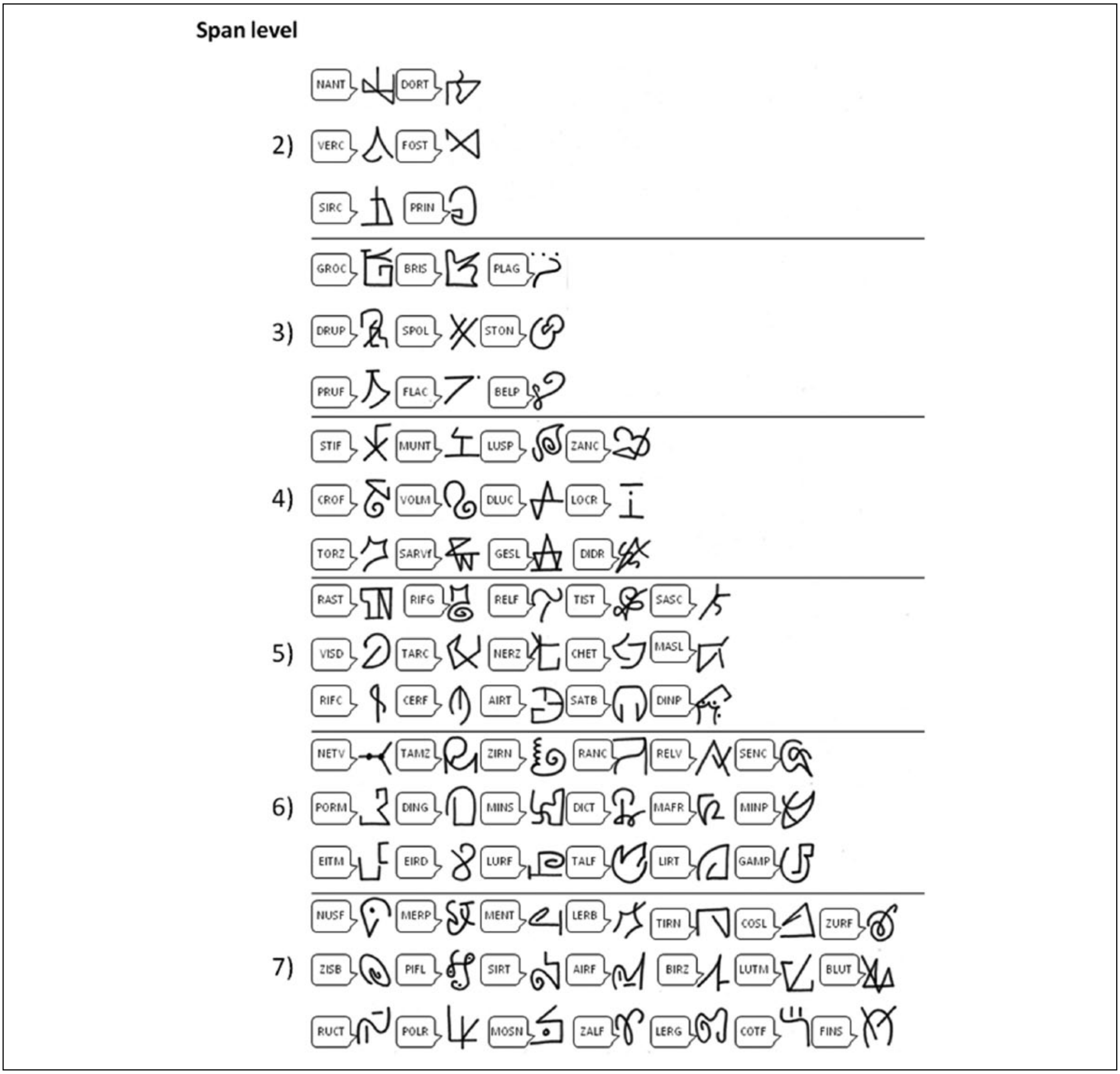
A limitation of our study that needs to be acknowledged is that the average span measured was generally small, especially for the children with a reading disability, in both versions of the task administered. This limited the range of the scores and suggested that our task was rather difficult for primary school children. It also meant that the task that we developed may not enable researchers to detect subtle differences among individuals or groups. It nonetheless captured a core difference between groups of children differing in terms of their reading ability. A second limitation lies in that IQ measures were not available for all our participants, a limitation partly overcome by considering school reports and teachers' judgments and by controlling for a series of working memory measures. Future research should match groups more closely on intelligence, however. Finally, a third limitation concerns the size of our sample, which was not large enough to conduct an analysis on the real diagnostic power of our binding task. In fact, it would be useful to establish the degree to which cross-modal binding span discriminates between children with a reading disability and typically developing children. Future research should collect data on larger samples for two purposes: to obtain normative data by age group and to establish the power of the binding task to "diagnose" reading disability (e.g., with linear discriminant analysis by group).

In conclusion, visual-phonological working memory binding deficits seem to be a core feature of children with a reading disability, and the present study shows that this issue can be assessed with binding span tasks that take <10 min to administer. Although purely phonological working memory performance was lower for the children with a reading disability than the typically developing controls, this did not explain the between-group difference in the visual-phonological binding. We believe that a task such as ours, for measuring cross-modal working memory binding, may have educational and clinical implications. First, it could serve as part of a comprehensive screening of children's learning skills not only at school but also in clinical settings. A better understanding of the specific fundamental binding difficulties of children with a reading disability could also be important for the purpose of devising educational programs. For example, if these children need more exposure to visual-phonological pairs, future studies could examine which exposure conditions would facilitate the learning of such pairs—for instance, by (a) presenting pairs across sequences of systematically repeated, increasingly long trials or (b) initially making the order of pairs constant (as suggested by Toffalini, Tomasi, et al., 2017). Another point worth investigating is the feasibility of more general training of a visual-phonological working memory binding ability and whether this could benefit children with a reading disability in a manner similar to other working memory programs that seem to support children with a learning disability (Dahlin, 2011). Given its simplicity and adaptability, our binding span task could be included in such a training, gradually adjusting the levels of difficulty to an individual's performance.

Appendix



Appendix A. Example of the stimuli of the "shape to nonword" binding task.



Appendix B. Example of the stimuli of the "nonword to shape" binding task.

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