Visuospatial working memory for locations, colours, and binding in typically developing children and in children with dyslexia and non-verbal learning disability

Ricardo Basso Garcia1,2*, Irene C. Mammarella3, Doriana Tripodi2 and Cesare Cornoldi2

1Department of Psychology, Faculdade de Filosofia, Ciências e Letras de Ribeirão Preto, University of São Paulo, Ribeirão Preto, Brazil
2Department of General Psychology, University of Padova, Italy
3Department of Developmental and Social Psychology, University of Padova, Italy

This study examined forward and backward recall of locations and colours and the binding of locations and colours, comparing typically developing children – aged between 8 and 10 years – with two different groups of children of the same age with learning disabilities (dyslexia in one group, non-verbal learning disability [NLD] in the other). Results showed that groups with learning disabilities had different visuospatial working memory problems and that children with NLD had particular difficulties in the backward recall of locations. The differences between the groups disappeared, however, when locations and colours were bound together. It was concluded that specific processes may be involved in children in the binding and backward recall of different types of information, as they are not simply the resultant of combining the single processes needed to recall single features.

Since the pioneering work by Binet (1903) and Jacobs (1887), the immediate serial recall of digits or word lists has been considered a crucial clinical marker of an individual’s cognitive functioning, both in general and in developmental age. In particular, when it comes to memory development, although researchers have focused mainly on verbal memory, recent research has also considered the case of immediate visuospatial memory, revealing the need to distinguish between different children’s visuospatial processes (Mammarella, Pazzaglia, & Cornoldi, 2008). However, developmental research in this field is still scarce and has not deeply considered to what extent observations collected with adults can also be extended to children. The present study examines children’s visuospatial immediate memory for forward and backward recall of locations, colours, and colour–location bindings.

Tasks in which lists are recalled in reverse order have been useful in psychometric batteries (Wechsler, 1974, 1991). It is only recently, however, that attention has been devoted to the forward and backward recall of types of information other than digits or words, and this has raised a number of issues. One crucial issue has theoretical implications and concerns the cognitive processes underlying the immediate recall of

*Correspondence should be addressed to Ricardo Basso Garcia, Department of Psychology, FFCLRP-University of São Paulo, Av Bandeirantes 3900, Ribeirão Preto, SP CEP 14040-901, Brazil (email: rbgarcia@gmail.com).

DOI:10.1111/bjdp.12019
verbal and other types of material. Another crucial issue concerns the potential implications for the neuropsychological assessment of children.

According to theories on cognitive functioning (Baddeley, 1986), the immediate recall of ordered information relies on a system essential to the temporary retention of information, that is, working memory (WM), which is involved in a variety of activities in everyday life. In the multicomponent model of WM (Baddeley, 1986, 2000; Logie, 1995), the recall of verbal information is supported by a verbal WM component, called the phonological loop, while the recall of spatial and visual information is supported mainly by a specific component known as the visuospatial sketchpad or visuospatial working memory (VSWM; Baddeley, 1986; Logie, 1995). The WM system also comprises an attentional control system, the central executive, and an episodic buffer, which is a component responsible for binding information from the temporary storage systems, and from long-term memory too, into a multimodal code (Baddeley, 2000).

Different WM components are involved in the recall of verbal information in forward as opposed to backward order. In particular, backward verbal recall relies on additional central executive resources implicated in reversing a retained order, a process that reduces the number of items that can be recalled by comparison with forward recall (Guerard & Saint-Aubin, 2012; Hale, Hoeppner, & Fiorello, 2002; Kessels, van den Berg, Ruis, & Brands, 2008). This pattern is especially seen in children, who rely on executive resources to reverse a verbal sequence, whereas adults may use other strategies, such as online reversal during encoding (St Clair-Thompson, 2010).

Regarding VSWM, procedures for assessing the ordered recall of spatial information have been increasingly used in both experimental and clinical contexts. In particular, the Corsi blocks task (Berch, Krikorian, & Huha, 1998; Corsi, 1972; Milner, 1971) has become popular for the neuropsychological assessment of children and adults. The Corsi task apparatus consists of nine blocks randomly placed on a rectangular board; the examiner taps a sequence of blocks, and the participant is asked to reproduce the sequence from memory. The test begins with short sequences and the level of difficulty increases, adding one block to the sequence until the participant is no longer able to reproduce it correctly.

The little research comparing forward versus backward recall using the Corsi task has generated conflicting results. Some studies with adults have shown that recalling information backwards does not imply a decline in performance by comparison with forward recall (Isaacs & Vargha-Khadem, 1989; Kessels et al., 2008; Vandierendonck & Szmalec, 2004; Wilde & Strauss, 2002). Moreover, in an extensive study by Wilde and Strauss (2002), about one-third of the sample performed better on the backward than on forward spatial span, leading the authors to cast doubts on the theoretical and clinical implications of the spatial span. In contrast, other studies have found that particular populations may have an impaired backward spatial span, such as children and adults with low visuospatial abilities (Cornoldi & Mammarella, 2008; Mammarella & Cornoldi, 2005b). The backward Corsi test seems to tap specific WM resources that are impaired in individuals with visuospatial deficits – a situation not seen in other WM tasks, such as the forward Corsi or the digit span tasks. These findings show the potential of the backward Corsi test to discriminate between clinical groups, for example, children with poor visuospatial skills and children with general WM deficit.

**Working memory impairments in children with learning disabilities**

The term learning disability (LD) has been used to describe children of average or above average intelligence whose school performance is poor. A large subgroup of such cases
comprises children with dyslexia, who have impaired language abilities in reading and spelling. In another subgroup of children with LD, the neuropsychological profile is characterized by impairments in non-verbal abilities, a disorder known as non-verbal learning disability (NLD; Rourke, 1995). One of the features of NLD most often considered is a significantly lower score in tasks measuring visuospatial intelligence than in those measuring verbal intelligence, that is, a discrepancy between children’s verbal, language-based, cognitive abilities, and their non-verbal, visuospatial cognitive skills (Cornoldi, Venneri, Marconato, Molin, & Montinari, 2003; Johnson, 1987; Mammarella et al., 2009; Weintraub & Mesulam, 1983). According to Rourke (1995), the NLD syndrome is characterized by deficits grouped into three main areas: Neuropsychological, academic, and social–emotional. Neuropsychological deficits include difficulties with tactile and visual perception, psychomotor coordination, visuospatial reasoning and memory, as well as in verbal aspects, such as verbosity and lack of prosody. Academic weaknesses include difficulties with graphomotor aspects of writing, arithmetical calculation, mathematics, and science. Finally, social shortcomings include problems with social perception and social interaction.

A crucial factor underlying the difficulties encountered by children with NLD seems to relate to VSWM deficits, which would explain why these children have difficulty in a broad range of school and everyday life activities involving the handling of visuospatial information, for example, mathematics, drawing, spatial orientation, and so on (Cornoldi, Dalla Vecchia, & Tressoldi, 1995; Cornoldi, Rigoni, Tressoldi, & Vio, 1999; Cornoldi & Vecchi, 2003; Mammarella & Cornoldi, 2005a). For example, Cornoldi et al. (2003) found that a group of children with NLD fared particularly poorly in the Corsi blocks task, especially when information had to be recalled in reverse order. When Mammarella and Cornoldi (2005b) compared the forward and backward versions of the digit span test and the Corsi task between NLD cases and controls, they found that both groups performed less well in the backward version of the digit span, while a discrepancy was only seen for the children with NLD in the Corsi task. These findings further support the hypothesis that the backward Corsi involves using spatial-simultaneous processes (Cornoldi & Mammarella, 2008; Mammarella & Cornoldi, 2005b), by means of which the sequence of blocks is encoded and retained as an overall pattern of locations, that is, a simultaneous mental representation of the pathway as a whole, thus facilitating its recall starting from the last item. Given their low visuospatial abilities and poor VSWM, children with NLD may have problems with constructing and retaining a simultaneous representation of a pathway.

As for children with dyslexia, deficits involving the phonological loop’s storage capacity have been extensively described in the literature (Ackerman & Dykman, 1993; Gould & Glencross, 1990; Helland & Ashjornsen, 2004; Palmer, 2000) while there are conflicting reports on such children’s performance in VSWM tasks. Some recent studies (Jeffries & Everatt, 2004; Kibby, Marks, Morgan, & Long, 2004) found no significant difference between dyslexic and non-dyslexic children in a number of spatial WM tasks, while others provided some evidence to support an impairment in this domain in adult dyslexics (Smith-Spark, Fisk, Fawcett, & Nicolson, 2003). The WM weaknesses in dyslexics may also differ to some degree from those seen in children with other types of LD. Jeffries and Everatt (2004) drew a comparison between children with dyslexia, children with other LD, and controls, finding that children with dyslexia were comparable with controls in VSWM measures (e.g., the Corsi test), whereas the other LD group did worse than controls. On the other hand, both clinical groups fared equally worse than controls in verbal WM measures, thus showing that visuospatial tasks may be particularly useful in discriminating between different LD subtypes.
The articulation of VSTM and the case of binding

Research on WM functional structure and organization has provided converging evidence that VSTM is not a unitary system, but can be further fractionated into different spatial and visual subsystems (Baddeley, 2007; Cornoldi & Vecchi, 2003; Klauer & Zhao, 2004; Logie, 1995, 2011). In addition to a visual subsystem, some authors have suggested a further distinction between spatial-simultaneous and spatial-sequential processes (Frick, 1985; Lecerf & de Ribaupierre, 2005; Mammarella, Borella, Pastore, & Pazzaglia, 2013; Pazzaglia & Cornoldi, 1999; Pickering, Gathercole, Hall, & Lloyd, 2001), depending on whether the spatial locations are presented simultaneously (e.g., black cells in a matrix such as in the visual pattern test, see Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999) or sequentially, as in the Corsi task.

Notwithstanding the visual/spatial dissociation and the importance of examining cognitive performance for single, separate features, everyday life situations continuously demand the processing and retention of combined information involving different WM components. Information binding is a crucial aspect of cognitive functioning, and binding processes in WM have only recently come under systematic investigation (for a review, Baddeley, Allen, & Hitch, 2011). For example, it is currently being debated whether a specific WM component such as the episodic buffer is involved – as in cross-modal binding (Baddeley, 2000) – in association with specific neural processes (Mitchell, Johnson, Raye, & D’Esposito, 2000) or whether binding is the outcome of spatial and visual components joining forces (Baddeley et al., 2011; Logie, 2011).

In Baddeley’s (2000) model, the episodic buffer was assumed to depend on central executive resources, leading to the hypothesis that memory binding would demand more attention than memory for single features (Baddeley, 2000; Baddeley et al., 2011). On the other hand, there is a converging body of evidence that concurrent attention-demanding tasks disrupt the recognition of individual features and bound objects to the same extent (Allen, Baddeley, & Hitch, 2006; Allen, Hitch, Mate, & Baddeley, 2012; Johnson, Hollingworth, & Luck, 2008; Moray & Bieler, 2013), even when the objects’ features are spatially or temporally separated, making binding more difficult (Karlsen, Allen, Baddeley, & Hitch, 2010). These results suggest that attention is generally involved in VSTM, supporting the view (Baddeley et al., 2011; Karlsen et al., 2010) that binding occurs not in the episodic buffer, but in the VSTM, which seems to work on integrated object representations consisting of visual and spatial features bound together (Allen et al., 2012; Baddeley et al., 2011; Luck & Vogel, 1997). In fact, some findings indicate that the locations of stimuli are encoded in WM even when the spatial dimension is irrelevant to the task (Jiang, Olson, & Chun, 2000; Olson & Marshuetz, 2005; Treisman & Zhang, 2006).

These points have important implications for our understanding of memory binding from a lifespan perspective, because findings have shown that children and older adults have a worse memory for bound objects (Brockmole, Parra, Della Sala, & Logie, 2008; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006), and certain clinical groups seem to encounter specific problems in binding information. In particular, an impaired memory for bound visual objects has been found in patients with Alzheimer’s disease (Della Sala, Parra, Fabi, Luzzi, & Abrahams, 2012; Parra, Abrahams, Logie, & Della Sala, 2010). In the case of children, developmental research has provided only limited evidence on the articulation of VSTM and the possibility of extending observations mainly collected with adults. In particular, the study of developmental clinical populations seems crucial to compare developmental trajectories in typically and atypically developing children (D’Souza & Karmiloff-Smith, 2011). In fact, there is also modest evidence of some clinical groups having memory binding problems. Jarrold, Phillips, and Baddeley (2007) showed
that individuals with Williams syndrome (be they children or adults) and children with
moderate learning disabilities bind visual to location information less well than typically
developing (TD) children. According to the authors, this deficit may stem from a poor
attentional and cognitive functioning in individuals, in particular children, with delayed
development. Therefore, it is possible that memory binding is more reliant on attentional
resources in children and older adults, and it remains an open question whether the deficit
observed in children with atypical development exists in children who have impaired
VSWM but not executive problems.

This study
This study examined the specific implications for children of the backward recall of spatial
and visual information, isolated and bound together. We focused on children aged
between 8 and 10 years given that this range seems particularly appropriate to investigate
the dissociation between different components of VSWM (Mammarella et al., 2008) and
the developmental aspects of WM, including specific characteristics of children with
weaknesses in WM (Demetriou et al., 2013).

Our study also examined to what extent two different populations with LD, both
assumed to have WM problems, might have specific deficits in VSWM tasks. In particular,
the study aimed to identify the implications of backward recall and memory binding (two
aspects that have never been systematically studied in individuals with LD) and of the two
requests being combined, that is, a task simultaneously involving the binding of
information and its recall in backward order. To study these aspects, we administered
three different VSWM tasks involving forward and backward recall to two groups of
learning-disabled children – one with NLD whose deficits in VSWM have already been
demonstrated, the other with dyslexia whose impaired VSWM is less evident – and to a
third control group of TD children. We opted to use the classical Corsi blocks task to
measure the spatial WM component. To assess visual processes, we used a task that
involved the forward and backward recall of colours in the same format as the Corsi task,
that is, participants were asked to distinguish between different colours and then
reconstruct their order of presentation (a serial recall method already used to assess the
immediate recall of visual stimuli in children, as in Hitch, Halliday, Schaafstal, & Schraagen,
1988). Memory for colours seems to be a good way to assess WM components separately
from spatial components. Administering a colour recall task is also one of the best methods
for assessing memory binding by asking participants to memorize locations and colours
concurrently. In general, memory for colours seems to involve visual WM, but it has been
reported that TD children of the same age as those considered in this study may also use
verbal codes to support visual memory in performing WM tasks requiring the recall of
visual information such as colours and familiar objects (Henry, Messer, Luger-Klein, &

Based on previous literature, we expected children with NLD to have a worse VSWM
performance than TD children. Children with dyslexia were not expected to have a
severely impaired VSWM. Concerning memory for locations, we predicted that the NLD
group would perform less well in the Corsi task than the other two groups, especially in
backward recall. As for memory for colours, we also predicted a poor performance of the
NLD group, due mainly to a VSWM-related impairment, as suggested in the literature.
Detailed predictions regarding group differences and direction of recall were not feasible
because systematic research on the direction of recall is unavailable for the visual domain.
Both groups of children with LD were expected to have difficulties in the binding task
(Jarrold et al., 2007). If the processes involved in concurrently remembering colours and locations demand both the skills needed to remember the two types of information separately, then children with NLD should find backward recall particularly difficult. On the other hand, if memory binding involves different processes, then the weaknesses seen in children with LD when it comes to the separate recall of locations and colours would not necessarily extend to the case of binding.

Method

Participants

The study involved 15 children with a diagnosis of NLD (10 M, 5 F, mean age = 100.5 months, SD = 7.3), 15 with dyslexia (6 M, 9 F; mean age = 101.7 months, SD = 8.1), and 15 TD children (8 M, 7 F; mean age = 105.9 months, SD = 11.6), mostly in their 3rd and 4th grades of primary school in small Italian towns (their ages ranged from 8 to 10 years). The groups did not differ significantly in terms of age, F(2, 42) = 1.43, p = .25, or gender distribution, χ²(df = 2) = 2.14, p = .34. All the children spoke Italian as their first language, and none were visual or hearing impaired. None of the participants had any other clinical diagnoses (including developmental coordination disorder) or neurological impairments. A signed informed consent form was obtained from the participants' parents.

During the group selection process, we ensured that children met specific criteria. General verbal and visuospatial abilities were assessed using the Verbal Meaning and Spatial Relations subtests of the Primary Mental Ability (PMA) test (Thurstone & Thurstone, 1963). Visuospatial constructional abilities were tested using Rey’s (1941, 1968) Complex Figure test, asking the child to copy a complex drawing. Reading decoding (speed and accuracy) was assessed with a lexical decision task (Caldarola, Perini, & Cornoldi, 2012) and a pseudoword reading task (derived from Sartori, Job, & Tressoldi, 2007). Finally, the children were also identified on the basis of difficulties detected by their teachers using the Shortened Visuospatial (SVS) Questionnaire (Cornoldi et al., 2003). The SVS questionnaire is a tool developed in Italy and Scotland to identify children with NLD – teachers have to judge whether a child has a given characteristic on a four-point scale. The SVS questionnaire generates a visuospatial score (range 10–40) based on 10 items with a demonstrated sensitivity in detecting some of the deficits that represent crucial features of NLD (Cornoldi et al., 2003). The questionnaire also includes an item that enables teachers to estimate a child’s sociocultural level, and children judged to have a very low sociocultural level were not included in the study groups.

All the children with NLD scored around 1.5 SD below the mean in the Spatial Relations subtest of the PMA (M = 8.05, SD = 4.1),¹ and they had visuospatial scores in the SVS questionnaire lower than the 15th percentile and a very poor performance in Rey’s Complex Figure test, while they had average scores in the Verbal Meaning subtest of the PMA (M = 10.09, SD = 3.9), in the lexical decision task (M = 0.11, SD = 1.3) and in pseudoword reading. All the children with dyslexia had scores around 1.5 SD below the mean in the lexical decision task and impaired pseudoword reading skills, while their scores were average in the Spatial Relations and Verbal Meaning subtests of the PMA, in

¹ Because no recent normative values were available for some of the screening procedures adopted in this study, means (M) and standard deviations (SD) of the lexical decision task (Caldarola et al., 2012) and the Verbal Meaning and Spatial Relations subtests of the PMA test (Thurstone & Thurstone, 1963) were obtained from a sample of 351 children of the same age range as those considered in this study.
Rey’s Complex Figure test, and in the visuospatial index of the SVS questionnaire. The control group of TD children had average scores in all the above-mentioned tasks. Table 1 summarizes the descriptive statistics for the children’s performance by group (NLD, dyslexia, and TD) and the results of group comparisons based on one-way ANOVA and pairwise comparisons with Bonferroni’s correction.

**Experimental materials and procedure**

We used a laptop computer with a 15-inch LCD screen, and all the experimental procedures were programmed with the E-Prime software (Schneider, Eschman, & Zuccolotto, 2002). Participants were tested individually in a quiet room. The child sat in front of the computer screen, and the experimenter sat to the right of the child to present the trial and manage the mouse. In these computerized tests, the children were asked to indicate their response on the screen, and the experimenter inputs their answers with the mouse.

The presentation of the stimuli was similar for all the tests conducted in the present study. The basic screen (i.e., the Corsi board) consisted of nine 3 × 3 cm grey squares against a white background, placed so as to retain the same proportions and distances as in the original version of the Corsi blocks task (Corsi, 1972; Milner, 1971). The experimenter pressed the space bar to start the trial, the Corsi board remained unchanged for 1,200 ms, and then, a sequence of squares appeared. Each square was highlighted by a change of colour for 1,000 ms, with an interstimulus interval of 500 ms. Within a given sequence, each square became a different colour, and there were six possible colours, that is, black, green, purple, red, turquoise, and yellow (with the following RGB coordinates, respectively: 0/0/0, 0/255/0, 255/0/255, 255/0/0, 0/255/255, 255/255/0). The end of a sequence was marked by a rectangular frame appearing around the Corsi board for 500 ms, followed immediately by the task display (i.e., the screen for inputting the answers), which varied according to the task.

<table>
<thead>
<tr>
<th>Test</th>
<th>TD M (SD)</th>
<th>Dyslexia M (SD)</th>
<th>NLD M (SD)</th>
<th>One-way ANOVA</th>
<th>Bonferroni’s post-hoc&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMA spatial</td>
<td>9.7 (2.8)</td>
<td>9.0 (2.6)</td>
<td>3.0 (0.7)</td>
<td>39.99***</td>
<td>NLD &lt; DYS; NLD &lt; TD</td>
</tr>
<tr>
<td>PMA verbal</td>
<td>10.7 (2.6)</td>
<td>9.0 (2.7)</td>
<td>9.3 (3.0)</td>
<td>1.54 ns</td>
<td></td>
</tr>
<tr>
<td>Lexical decision</td>
<td>-0.14 (0.56)</td>
<td>-1.56 (0.45)</td>
<td>0.16 (0.74)</td>
<td>36.11***</td>
<td>DYS &lt; TD; DYS &lt; NLD</td>
</tr>
<tr>
<td>Pseudoword reading</td>
<td>63.4 (13.1)</td>
<td>86.9 (20.0)</td>
<td>65.3 (16.3)</td>
<td>9.07***</td>
<td>DYS &gt; TD; DYS &gt; NLD</td>
</tr>
<tr>
<td>SVS spatial</td>
<td>32.0 (9.8)</td>
<td>30.9 (8.1)</td>
<td>22.2 (7.4)</td>
<td>6.04**</td>
<td>NLD &lt; TD; NLD &lt; DYS</td>
</tr>
<tr>
<td>Rey</td>
<td>31.2 (3.0)</td>
<td>27.9 (6.4)</td>
<td>19.7 (7.5)</td>
<td>14.68***</td>
<td>NLD &lt; TD; NLD &lt; DYS</td>
</tr>
</tbody>
</table>

*Note. PMA, SVS, and Rey are raw scores. Lexical decisions are z-scores. Pseudoword reading is time in seconds.

<sup>a</sup>Only significant pairwise comparisons are given.

**p < .01; ***p < .001.**
Corsi task
The Corsi board with the nine grey squares was shown on the screen, and participants completed the standard Corsi task, that is, they were asked to indicate the locations of sequences of squares that had been highlighted, in their order of presentation (forward version) or in reverse order (backward version). The trials included sequences from two to six squares, and two trials were administered for each sequence length.

Colour task
The Corsi board disappeared, and the six colours appeared at the bottom of the screen (from left to right: Turquoise, red, purple, yellow, black, and green). Participants were asked to recall the colours in their order of presentation (or in reverse in the backward version). The trials included sequences from two to five colours, and two trials were administered for each sequence length.

Colour-location binding task
The Corsi board remained on the screen, and the six colours appeared at the bottom. Participants were asked to indicate first the colour and then its location. For example, in the forward recall task, they had to indicate the first colour and the first block, then the second colour and the second block, and so on. The trials included sequences from two to five coloured blocks, and two trials were administered for each sequence length.

A pilot study was carried out on a random sample of children to test different sets of stimuli (six different colours vs. one colour in six shades varying from pale to dark) and how children would perform in the colour and the colour-location binding tasks. Performance proved to be very low with shades of colour, and the binding task became much more difficult. Hence, our decision was to use six different colours and to present the tasks in increasing levels of difficulty.

For each task and recall condition, all the participants performed all the trials for each sequence length. The tasks were administered in an order designed to avoid the children becoming confused by switching between forward and backward recall or presenting the memory tasks in random order. In particular, direction of recall was blocked and counterbalanced (Cornoldi & Mammarella, 2008; Mammarella & Cornoldi, 2005b). For each group, half of the participants started the session with the forward recall for all the tasks, while the other half started with the backward recall tasks. For each block, the tasks were administered in the following order: Location, colour, and colour-location binding. To ensure the children had understood what they had to do, instructions were given and practice trials were run at the beginning of each task. The whole session took around 35–40 min to complete, including the time taken to provide instructions and the practice trials, as well as the experimental trials. Each Corsi and colour task lasted around 5 min, and the binding task took about 7–10 min.

We computed the order score for each trial, that is, the percentage of items recalled in the right order, which is a more sensitive measure than the span, based on the number of sequences recalled correctly (Fischer, 2001; Vandierendonck, Kemps, Fastame, & Szmalec, 2004). For example, the sequence of blocks ‘5–2–4–3–1’ recalled as ‘5–4–2–3–1’ has two serial order errors (i.e., the swap between blocks ‘2’ and ‘4’) and is awarded a score of 60% (=3/5 × 100). In the binding task, both colour and location had to be recalled in the right order for the answer to be counted as correct, and the score resulted from the percentage of colour-location bindings correctly recalled in the right order. For
example, in a hypothetical situation where a participant correctly recalls two colour-location bindings across all sequence lengths, the average score will be 64.2%; in a worst-case scenario where only one binding is recalled correctly per sequence length, the average score will be 32.1.

Results

Preliminary analyses indicated that age, gender, and task order had no significant effect, so these variables were subsequently disregarded. In particular, because half of the participants started with forward and the other half with backward recall tasks, a preliminary ANOVA was conducted with the order of the forward/backward tasks as a covariate factor. No effect of presentation order emerged, indicating that practice in one recall condition did not affect performance in the other.

Table 2 shows the mean percentage of correct answers, with the standard deviations and confidence intervals (95% CI), for forward and backward recall in the three VSWM tasks for each group of children. In the following analyses of variance, the significance level was set at .05, an effect size indicator was computed, that is, the partial eta-squared ($\eta^2_p$), and the post-hoc test was applied, using Bonferroni’s correction, as necessary.

We performed a 3 group (TD vs. dyslexia vs. NLD) × 3 task (Corsi vs. colour vs. binding) × 2 recall (forward vs. backward) mixed ANOVA with group as the between-subjects factor and task and recall as the within-subjects factors. A main effect of group was observed, $F(2, 42) = 4.78, MSE = 740, p = .013, \eta^2_p = .19$, and the post-hoc test revealed a major discrepancy ($p = .012$) between the TD group ($M = 70\%$) and NLD group ($M = 58\%$), whereas the dyslexic group ($M = 62\%$) did not differ significantly from the others. We also observed a main effect of task, $F(2, 84) = 81.00, MSE = 156, p < .001, \eta^2_p = .66$, and post-hoc comparisons revealed significant differences ($p < .001$) in performance in the three tasks: It was worse in the colour task ($M = 66\%$) than in the Corsi task ($M = 74\%$) and better than in the binding task ($M = 50\%$). A main effect of recall was also observed, $F(1, 42) = 8.14, MSE = 139, p = .007, \eta^2_p = .16$, resulting from a better performance in forward ($M = 65\%$) than in backward recall ($M = 61\%$). We also found a significant interaction between task and recall, $F(2, 84) = 12.27, MSE = 111, p < .001, \eta^2_p = .23$, in which it was only for the colour task that we found a significant difference ($p < .001$) between forward ($M = 72\%$) and backward recall ($M = 59\%$). Direction of recall also interacted significantly with group, $F(2, 42) = 4.11, MSE = 139,$

Table 2. Mean percentages ($M$) of correct answers, with standard deviations (SD) and confidence intervals (95% CIs) in the Corsi, colour, and binding VSWM tasks, for each group

<table>
<thead>
<tr>
<th>Tasks</th>
<th>TD</th>
<th></th>
<th>Dyslexia</th>
<th></th>
<th>NLD</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M (SD)</td>
<td>95% CI</td>
<td>M (SD)</td>
<td>95% CI</td>
<td>M (SD)</td>
<td>95% CI</td>
</tr>
<tr>
<td>Corsi fwd</td>
<td>77.7 (12.1)</td>
<td>[71.0, 84.4]</td>
<td>71.7 (12.9)</td>
<td>[64.6, 78.9]</td>
<td>69.3 (14.0)</td>
<td>[61.6, 77.1]</td>
</tr>
<tr>
<td>Corsi bwd</td>
<td>83.7 (11.9)</td>
<td>[77.1, 90.3]</td>
<td>78.2 (13.5)</td>
<td>[70.7, 85.7]</td>
<td>61.3 (16.0)</td>
<td>[52.5, 70.2]</td>
</tr>
<tr>
<td>Colour fwd</td>
<td>80.2 (9.3)</td>
<td>[75.1, 85.3]</td>
<td>66.7 (22.9)</td>
<td>[54.0, 79.4]</td>
<td>70.0 (18.4)</td>
<td>[59.8, 80.2]</td>
</tr>
<tr>
<td>Colour bwd</td>
<td>66.3 (13.2)</td>
<td>[59.0, 73.6]</td>
<td>60.9 (16.7)</td>
<td>[51.6, 70.1]</td>
<td>50.7 (15.5)</td>
<td>[42.2, 59.3]</td>
</tr>
<tr>
<td>Binding fwd</td>
<td>55.6 (14.2)</td>
<td>[47.7, 63.5]</td>
<td>48.3 (21.3)</td>
<td>[36.5, 60.1]</td>
<td>48.3 (13.2)</td>
<td>[41.0, 55.7]</td>
</tr>
<tr>
<td>Binding bwd</td>
<td>56.7 (10.9)</td>
<td>[50.7, 62.8]</td>
<td>47.1 (19.0)</td>
<td>[36.5, 57.6]</td>
<td>46.2 (14.2)</td>
<td>[38.4, 54.0]</td>
</tr>
</tbody>
</table>

Note. VSWM, visuospatial working memory; fwd, forward; bwd, backward.
shown in Table 2, however, a major forward recall might suggest a specific impairment in backward recall in children with NLD. As VSWM tasks, especially in backward recall tasks. The interaction between groups and group differences emerged. Children with NLD fared worse than TD children in the interaction between the groups and task factors (p = .005) between forward and backward recall in the NLD group (M = 63% vs. M = 53%), but not in the TD group (71% vs. 69%) or dyslexic group (62% vs. 62%). The NLD group had a significantly worse backward recall than the TD (p = .008), but there were no significant differences between the groups in forward recall. No significant interactions emerged between the group and task factors (p = .32, $\eta^2_p = .05$) or between all three factors (p = .22, $\eta^2_p = .06$).

As we can see from the above results, the cognitive requirements of the tasks varied and group differences emerged. Children with NLD fared worse than TD children in the VSWM tasks, especially in backward recall tasks. The interaction between groups and recall might suggest a specific impairment in backward recall in children with NLD. As shown in Table 2, however, a major forward–backward discrepancy emerged for the TD group in the colour task too, while no recall or group discrepancies were apparent for the binding task. Further statistical analyses were conducted separately for each test to gain a better understanding of the group differences relating to direction of recall.

A $3 \times 2$ recall mixed ANOVA on the scores in the Corsi task revealed a main effect of group, $F(2, 42) = 6.55$, MSE = 276.3, $p = .003$, $\eta^2_p = .24$. The post-hoc test showed that the NLD children’s overall performance (M = 65%) was significantly worse than (p = .003) the TD group’s (M = 83%), but did not differ significantly (p = .09) from that of the children with dyslexia (M = 75%). The main effect of recall was not significant, $F(1,42) < 1$, $p = .50$, MSE = 87.1, $\eta^2_p = .01$, while there was a significant interaction, $F(2, 42) = 5.79$, MSE = 87.1, $p = .006$, $\eta^2_p = .22$. Post-hoc comparisons showed that the NLD group had a significantly worse backward recall than either the TD (p < .001) or the dyslexic children (p = .016), but the group differences in the forward version were not statistically significant.

A $3 \times 2$ mixed ANOVA on the colour task scores showed a main effect of group, $F(2, 42) = 3.42$, MSE = 391.1, $p = .042$, $\eta^2_p = .14$. The post-hoc test showed that the TD group’s performance (M = 74%) was better (p = .046) than that of the NLD group (M = 60%), while it did not differ (p = .21) from the dyslexic group’s (M = 64%). The main effect of recall was significant, $F(1, 42) = 24.45$, MSE = 155.5, $p < .001$, $\eta^2_p = .37$, indicating that backward recall proved more difficult than forward recall, and the interaction was not significant, $F(2, 42) = 2.19$, MSE = 155.5, $p = .12$, $\eta^2_p = .09$. In this task, a different pattern from the Corsi task emerged, because both the TD and the NLD groups performed less well in backward recall. As shown in Table 2, differences of around 14% and 19% between forward and backward recall (together with dissociated 95% CIs) emerged for the TD and NLD groups, but the difference in the dyslexic group was around 6% (a value overlapping with the 95% CIs). The backward recall score for the NLD group fell outside the 95% CIs of the TD group, possibly indicating an impairment in backward recall. Contrary to the Corsi task, the NLD group seems to have experienced a general difficulty in the colour task, with a 10% drop in forward recall performance by comparison with the TD group and a 16% drop in backward recall.

A $3 \times 2$ mixed ANOVA on the scores obtained in the binding task showed no main effect of group, $F(2, 42) = 1.96$, MSE = 384.9, $p = .15$, $\eta^2_p = .09$, or recall version, $F(1, 42) < 1$, MSE = 119.1, $p = .74$, nor any interaction, $F(2, 42) < 1$, MSE = 119.1, $p = .83$. Thus, given the need to recall colours and locations concurrently, the effects on memory for single features are no longer observable. Although no reliable statistical effect was found, it is worth noting in Table 2 that the lower bounds of 95% CIs indicate that some children with dyslexia and NLD had severe difficulties in the binding task, as was to be expected.
Discussion and conclusions

This study analysed the processes involved in performing three different VSWM tasks by testing forward and backward recall of locations, colours, and colour-location bindings in TD children and in children with two different types of LD (NLD and dyslexia). Our aim was to extend to children the observations on VSWM functioning until now mainly collected with adults. In particular, we intended to study the patterns of VSWM performance in children and to ascertain whether children with LD have problems with such tasks and whether their performance can shed light on the processes involved in different VSWM tasks across the three developmental groups.

Our results indicate that children's VSWM has important specific features that can be better understood taking into consideration not only typical but also atypical development. By considering different subtypes of learning disabilities, the present study further supports the idea that a deep comprehension of cognitive development requires the consideration not only of TD children, but also of groups with specific disabilities (D'Souza & Karmiloff-Smith, 2011). The observation of different patterns of performance in our samples also supports that the age range considered in the present study is particularly appropriate for investigating both the development of VSWM (Mammarella et al., 2008) and children’s individual differences in VSWM. In fact, Demetriou et al. (2013) observed a robust relationship between WM and intelligence (with the implication that this age range is particularly appropriate for studying individual differences in WM), and, more specifically, the transition from iconic to symbolic (verbal) WM, suggesting that the pattern of performance in VSWM tasks may be partly stabilized at this age.

In general, it is worth noting the different patterns of recalling information in backward order: TD children were not impaired when they had to recall spatial information or the binding of visual and spatial information, whereas backward recall was impaired in the case of colour memory. Concerning children with LD, we found VSWM impairments in both LD groups, because they had more difficulty than TD children in the immediate recall of locations and colours. These difficulties also differed to some degree between children with NLD and those with dyslexia.

It is worth emphasizing that children of this age are characterized by shifts in coding strategies. The differences we have identified cannot be associated with VSWM alone because children with typical development of this age may use verbal recoding of stimuli and verbal rehearsal strategies to support visual memory when recall of colours and familiar objects is required (Gathercole, 1998; Gathercole & Pickering, 2000; Henry et al., 2012; Hitch et al., 1988; Pickering et al., 2001), as well as employ controlled attentional processes to refresh memory traces (Camos, Mora, & Oberauer, 2011). In particular, children with NLD, who have higher verbal than visuospatial skills, could also have taken advantage of verbal strategies to compensate their impairment in visuospatial processes. Interestingly, children with dyslexia seem to present the opposite pattern, that is, a reliance on visuospatial processes to compensate their difficulties in using a phonological strategy to support VSWM.

Children with dyslexia were not significantly impaired in their VSWM task performance by comparison with TD children, although the former generally did worse than the latter in the colour and colour-location binding tasks. Given dyslexic children’s language-related problems, this group’s difficulty in the colour task may be partially attributable to finding it more difficult to use adequate verbalization strategies. In other words, their more limited use of phonological recoding and rehearsal (Camos et al., 2011; Henry et al., 2012; Palmer, 2000) may have reduced the need to reverse the sequence of
information. Only the dyslexic group had a similar performance in the forward and backward recall of colours (with a difference of only 6% between the two situations, see Table 2), and we surmise that this reflects a strategy more reliant on non-verbal, VSWM resources. The other two groups are more likely to have used verbal WM and attentional resources to support their VSWM, especially to encode information and to revert its order, respectively, because their worse performance in backward recall resembled the typical effect seen in verbal WM tasks, such as the digit span (Camos et al., 2011; St Clair-Thompson, 2010). A limitation of the current study lies in that we did not collect measures of phonological memory (e.g., non-word repetitions), which might have further supported the hypothesis of a verbal WM deficit in children with dyslexia (Snowling, 2009); such measures would also have helped to clarify to what extent the performance patterns observed with verbal material should mirror the patterns seen in the colour task. Further studies are needed to shed more light on the strengths and weaknesses of children with dyslexia and NLD by measuring phonological memory too. In addition, the use in future research of either irrelevant speech or articulatory suppression in the colour task could help to understand whether children with NLD used verbal strategies to support their VSWM.

As expected, the children with NLD had a significantly impaired memory for locations and colours, but this did not correlate with an impaired colour-location binding performance. These results further support findings concerning the articulation of VSWM in children (Mammarella et al., 2008) and VSWM difficulties in children with NLD (Cornoldi et al., 1995, 1999; Mammarella & Cornoldi, 2005b), extending them to the case of memory for colours. It is also worth noting that backward spatial recall posed particular problems for children with NLD, further demonstrating that this deficit is a characteristic of such children, so this task can be used to discriminate this particular LD population (Mammarella & Cornoldi, 2005b). This impairment may relate to a symptom often seen in children with NLD, that is, they get lost easily and are unable to find their way back (Cornoldi et al., 1995). The backward Corsi task may involve specific spatial processes – possibly of a spatial-simultaneous nature (Cornoldi & Mammarella, 2008; Mammarella & Cornoldi, 2005b). Using spatial-simultaneous processes, the sequence of blocks is encoded and retained as an overall pattern of locations – that is, a simultaneous mental image of a pathway as a whole – making it unnecessary to retain the sequence in the original order and then reverse it. In fact, children with dyslexia and TD children performed even better in backward recall than in forward recall. Children with NLD could find it difficult to construct and retain such mental images of a pathway because of their weak visuospatial skills and VSWM. On the other hand, the forward Corsi task relies on spatial-sequential processes because the retrieval process should mimic the presentation of the stimuli, that is, the pathway should be recalled in the order in which it was codified. The NLD children’s difficulties with backward recall were also apparent in the colour task, but they were not alone in this case: The TD children found it difficult too.

Taken together, these results confirm the importance of assessing both forward and backward recall of visuospatial information. Backward recall performance in VSWM tasks did not always reflect the typical pattern seen when verbal information is recalled (i.e., a worse performance than in forward recall). The dyslexic group’s performance in the colour task did not deteriorate significantly, and all three groups’ performance was much the same in the forward and backward versions of the colour-location binding task. In the Corsi task, both the TD children and the children with dyslexia did better in backward than in forward recall, a pattern already reported in the literature (Wilde & Strauss, 2002). This means that the general assumption that backward verbal recall entails people first
storing a sequence in forward order and then reversing it – at a considerable cost to their performance – may not apply to all VSWM span tasks.

Regarding the colour-location binding task, the patterns seen in the Corsi and the colour tasks disappeared when locations and colours had to be recalled together. No particular difficulties came to light in the groups with LD, neither of which differed from the TD children. This would suggest that specific processes are involved in binding spatial and colour information and that these processes are not impaired in NLD children. With reference to the Baddeley's WM model (Baddeley, 2000), this finding suggests that binding involves either the central executive or an independent episodic buffer. Binding might still involve the VSWM, but a particular component of it that remains intact in children with LD. This hypothesis may relate to our general finding that children with LD have specific, not general, problems in VSWM tasks. The LD groups’ different patterns relating to the direction of recall were not seen in the colour-location binding task, and this means that binding location and colour demand different processes from those involved in recalling either location (as tested in the Corsi task) or colour (as tested in the colour task). It is important to mention that children’s performance in the binding task was poor and the discriminatory power of the binding task may have been insufficient, given that it was a difficult task for all the children, even the TD children.

To sum up, this study contributes to our understanding of how children’s VSWM is organized and the distinctive characteristics of children with different learning disorders, with potential applications to clinical practice and everyday life. From a general viewpoint, our results show that different processes are implicated in children in tasks requiring the recall of locations or colours and combinations of the two. The distinction between children’s visual and spatial WM, already discussed in the literature (Logie & Pearson, 1997; Mammarella et al., 2008), seems to need further articulation, taking into consideration the specific cases represented by backward recall and binding. These processes are presumably related partly to the functioning of the spatial and visual components of VSWM, respectively, with an independent system or specific processes devoted to encoding and retaining bound information. The way in which VSWM is organized needs to be further defined to explain the specific patterns seen in backward spatial recall, distinguishing between a spatial-sequential process involved in the forward recall of locations and a spatial-simultaneous process needed for backward recall. In fact, our results indicate that backward recall performance is not the outcome of memorizing the forward order of a sequence and then reversing it (as in the case of verbal information).

Our findings will need to be confirmed and extended because our study necessarily had a number of limitations that would have to be carefully tested in future research. One of the main limitations of this study concerns the choice of tasks, which only represent a sample of the domains considered in the study. For the purposes of the present study, for instance, we had to devise new adaptations of tasks for assessing VSWM and the psychometric properties of these tasks are not known. Another problem concerns the colour recall task, which presumably involves other processes as well as VSWM. A third problem is related to the limited age range of our sample, and future work should also consider a wider range to better understand developmental variations in VSWM.

Finally, the present study shows the importance of examining forward and backward recall of visual and spatial information (both separately and bound together) and of considering their implications when assessing both the typical VSWM development and the difficulties encountered by learning-disabled children. In particular, our work has generated more information on a specific deficit in children with NLD, that is, a worse performance in the backward than in the forward Corsi task. Our results also show that the
processes involved in binding colours and locations may not be the same as those needed to perform tasks that separately involve the recall of colours or locations, and further research is required for a deeper comprehension of the specific processes involved in memory binding.

Acknowledgements

Ricardo B. Garcia was supported by Capes Foundation (Scholarship BEX 6824/10-2).

References


Received 23 August 2012; revised version received 11 July 2013