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DOI 10.1007/s11145-010-9238-y

Effects of working memory training on reading in children with special needs

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Abstract This study examines the relationship between working memory and reading achievement in 57 Swedish primary-school children with special needs. First, it was examined whether children's working memory could be enhanced by a cognitive training program, and how the training outcomes would relate to their reading development. Next, it was explored how differential aspects of working memory are related to children's reading outcomes. The working memory training yielded effects, and these effects appeared beneficial to children's reading comprehension development. Working memory measures were found to be related with children's word reading and reading comprehension. The results show that working memory can be seen as a crucial factor in the reading development of literacy among children with special needs, and that interventions to improve working memory may help children becoming more proficient in reading comprehension.

Keywords Working memory · Working memory training · Word decoding · Reading comprehension · Small groups · Special education · Special needs

Reading difficulties are one of the greatest obstacles in education. Children lagging behind in their reading development do not seem to catch up with their peers (Torgesen, Alexander, Wagner, Rashotte, Voeller, & Conway, 2001) and this may have a long-term negative effect on their future school career (Savolainen, Ahonen, Aro, Tolvanen, & Holopainen, 2008). Phoneme awareness and letter knowledge are important predictors of early literacy problems (Lyytinen, Erskine, Tolvanen, Torppa, et al., 2006; Vellutino, Fletcher, Snowling, & Scanlon, 2004). Many studies have shown that children at risk for reading problems benefit from early intervention

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Published online: 11 May 2010

programs focusing on phonological awareness and letter identification training (Lundberg, 1994; Poskiparta, Niemi, & Vauras, 1999). However, some children do not respond to such programs (Otaiba & Fuchs, 2006). One possible explanation of the "treatment-resister" problem is that some children have working memory deficits (Howes, Bigler, Burlingame, & Lawson, 2003; Vellutino & Fletcher, 2007). Working memory (WM) can be conceptualized as a central executive with two subsystems: a phonological loop that stores verbal information, and a visuo-spatial 'sketchpad' that stores visual and spatial information (Baddeley, 2007). There is evidence that reasoning ability and working memory are highly related (Kane, Hamrick, & Conway, 2005). It can be hypothesized that working memory is needed for retaining verbal information during reading. Several studies have indeed demonstrated a relationship between working memory and reading comprehension (e.g., Cain, Oakhill, & Bryant, 2004; Perfetti, Landi, & Oakhill, 2005; Swanson, Howard, & Sáez, 2006). Research findings also suggest that dyslexia involves deficits in both phonological loop and central executive (de Jong, 2006). Furthermore, children with general learning problems perform poorly in all areas of working memory tasks with a negative impact on their reading development (Pickering & Gathercole, 2004).

If poor reading comprehension is at least partly caused by working memory problems, then training in working memory should improve reading comprehension. Working memory was traditionally thought to have a limited capacity unamenable to improvement (e.g., Niaz & Logie, 1993). However, recent studies have yielded positive outcomes from working memory training for both children (van't Hooft, Andersson, Sejersen, Bartfai, & von Wendt, 2003) and adults (Gunther, Schafer, Holzner, & Kemmler, 2003). Moreover, it was found that working memory training may have a beneficial effect on students' growth in mathematics and problem-solving (D'Amico, 2006; Holmes, Gathercole, & Dunning, 2009). Recent studies also show that children with ADHD (attention-deficit/hyperactivity disorder) may benefit in their behavior and school results from working memory training (Klingberg, Fernell, Olesen, Johnson, Gustafsson, Dahlström, et al., 2005; Klingberg, Forssberg, & Westerberg, 2002). Neurobiological markers have also been identified. Following WM training, increased brain activity is observed in the prefrontal cortex, the area associated with working memory functions (Olesen, Westerberg, & Klingberg, 2004); similarly, dopamine (the signal substance that has a central role in working memory functioning) is more abundant after 14 h of working memory training (McNab, Varrone, Farde, Jucaite, Bystritsky, Forssberg, et al., 2009).

The present study investigated the relationship between working memory and literacy in Swedish children with special needs. These children were diagnosed as having attention deficits and general learning problems and were being educated in small groups in ordinary school settings. First of all, it was explored to what extent children's working memory could be trained and whether training of working memory would enhance children's literacy development. Therefore, a computerized working memory training program was used for 5 weeks on a daily base (cf. Klingberg et al., 2005). The data were analysed following a pretest-program-posttest-retention test design. We hypothesized that working memory ability would increase through the training with a positive effect on children's reading comprehension skills (cf. Cain et al., 2004). In addition, it was examined how working memory and reading skills at the word and text level are related in this group of children. Again, we expected high correlations between working memory and reading comprehension skills.

Method

Participants

Fifty-seven children, 11 girls and 46 boys with special education needs, in grades 3–5, ages ranging from 9 to 12 years, were recruited. They were placed in small groups of four to 11 pupils, in ordinary school settings in central Stockholm and the surrounding areas. They had not only special educational needs but also attention problems (either diagnosed ADHD or rated by a teacher or a school psychologist. Of these children, 42 formed the treatment group and 15 children the control group. Those in the control group received their ordinary special education in small groups but no additional training. Those in the treatment group received training in working memory, detailed below. The treatment group came from nine schools and the control group from seven different schools.

Instruments

Neuropsychological measures

Nonverbal reasoning ability Raven's Coloured Progressive Matrices (Raven) was used to measure nonverbal reasoning ability. The test consists of incomplete figural patterns and for each pattern, the children have a choice of six response options from which to select the correct missing piece. Each correct answer generated one point and the maximum score (untimed) was 36.

Verbal working memory Digit Span was used as a test of verbal working memory; it is part of the Wechsler Intelligence Scale for children (WISC III). The child is told to repeat verbally-presented digits forward and backward. Series of numbers begin at the level of two digits and increase every second trial. In the first part, the digits are to be repeated in the same order as presented. In the second part, the child is asked to repeat the digits in the reverse order.

Visual-spatial working memory Span Board was used as a test of visual-spatial working memory and is part of the Wechsler Adult Intelligence Scale (WAIS-NI). The test leader points at some of the ten blocks on a bar, beginning with sequences of two blocks. The child is asked to repeat the sequences in the same order, pointing to different blocks. Then the same procedure is repeated, but the child is asked to state the sequences in the reverse order.

Response inhibition Stroop was used as a test of response inhibition. Color-words, printed in a different tint from the one in which the word appears, are listed ten per row for a total of sixty. Thus, for example, the color "red" is written in green letters. The child is asked to identify the color of the letters of each word. The time for reading all 60 items is noted.

Reading measures

Reading comprehension To measure reading comprehension, narrative texts of 430–533 words from the Progress in International Reading Literacy Study and IEA Reading Literacy Study were used. Three parallel versions of the studies were slightly revised to be comparable. In the original version of the test, the questions were located at the end of the story. To ensure that all the children could complete at least some parts, regardless of whether they had severe reading problems, each narrative was divided into five parts followed by one or more questions, leaving six at the end of the story. Seven of the questions were multiple-choice and six were constructed-response. The administrator wrote the pupil's oral answers to the constructed-response questions, to ensure that handwriting problems did not interfere with reading comprehension processes. Each child took about 30 min to complete the test. The maximum total score was 19.

Word decoding To measure word decoding skills the Phonological non-word reading test was used. It taps phonological and decoding abilities and was developed for this particular study. Three parallel versions were tried out with some grade-3 and grade-4 children. The children were given 2 min in which to read as many word-pairs as possible (one word with phonological spelling and one non-word) and to mark the word which sounded like a real word in each pair. The maximum total score was 63.

Orthographic knowledge The Orthographic verification test was developed for this particular study to tap the ability to quickly recognize the orthographic pattern of common words. Three parallel versions were used. The children were given 2 min in which to indicate whether words were correctly spelled by placing a cross (x) if correct, in a box to the right of a word, or a minus sign (–) if spelled incorrectly. The children were instructed to leave a box empty if they were uncertain. All the words were selected from stories written by children. The first ten words were monosyllabic. Maximum score was 75.

The training program

The treatment group trained daily at school for 30–40 min, over a period of 5 weeks. The format of the training was individual and the work took place in a quiet room next to the classroom, one child at a time with an adult providing support.

The children used a computerized training program (RoboMemo) originally developed to improve working memory in children with ADHD (Klingberg, Forssberg, & Westerberg, 2002; Klingberg, et al., 2005). The program contains visuo-spatial and verbal working memory tasks, with a fixed number of trials (100 for most children) to be completed each day. The level of difficulty is adapted to the ability of the child on a trial-by-trial basis, thus training takes place at the limit of the child's working memory capacity. The software guides the child through eight exercises each day. Scores and verbal feedback on performance are given immediately. Scores from the training program were analyzed in terms of an index. Scores at day one (start index) and the maximum scores received during the training (max index) were considered.

With one exception, all the training-group children completed 20–25 days of training, following the stipulated training criteria.

WM-memory training scores

The working memory training scores are measured in terms of index scores, i.e., start index (the results of the training at the very first day of the training period) and maximum index (the highest scores received during the training period).

Procedure

During the week prior to the onset of training, the treatment group completed a set of assessments in nonverbal reasoning, working memory, and reading. The treatment group then completed working memory training for 5 weeks. Reading-related skills in the control group were measured within the same time interval as the treatment group. All the children completed three sessions of assessments within the same time intervals: (1) pre-test, (2) post-test, 5–6 weeks later, and (3) 6–7 months later. Thus, assessments were conducted within the same periods for the treatment group as for the control group.

To find out how far WM training enhanced cognitive and literacy development, a pre-test-intervention-post-test-retention test design was followed. Multivariate analysis of variance with repeated measures was conducted to evaluate training effects from the cognitive and the three literacy measures being administered. Also, Cohen's d was used for calculating effect sizes. Furthermore, we conducted correlation analyses (Pearson correlation coefficient) to find out how nonverbal reasoning and working memory factors relate to children's literacy profiles.

Results

Table 1 shows the performance for the WM-training program, the cognitive and academic tests. There were differences in baseline literacy scores (T1) between the treatment group and the control group. However, none were significant.

Table 1 Descriptive statistics and ES (effect sizes) for cognitive and literacy measures in the treatment group and the control groups

Time	Treatment group						Control group						Effect sizes	
	T1		T2		T3		T1		T2		T3		T2–T1	T3–T1
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD		
Psychological measures														
Span board forward	4.54	0.9	5.68	1.0	5.55	1.0	4.20	0.8	4.36	1.0	4.46	1.0	0.98	0.74
Span board back	3.96	1.1	5.13	1.4	4.99	1.1	3.90	1.1	4.26	0.8	4.22	0.9	0.71	0.62
Digit span forward	4.24	0.7	4.72	0.9	4.63	0.9	4.34	1.0	4.26	0.9	4.46	0.8	0.66	0.33
Digit span back	3.02	0.7	3.71	1.0	3.34	1.1	2.92	0.9	3.04	0.7	2.84	0.8	0.67	0.46
Stroop: time (s)	121.86	34.6	112.39	32.4	103.61	43.0	121.68	27.6	115.08	34.0	107.68	30.8	−0.06	−0.16
Raven; RCPM	27.23	5.0	29.68	4.7	29.90	4.5	24.80	3.7	26.44	4.2	27.84	4.4	0.26	−0.11
Literacy measures														
Word decoding	11.74	3.8	12.88	5.4	13.45	5.2	13.67	6.4	12.73	9.4	14.60	7.5	0.37	0.17
Orthographical verification	17.14	14.5	19.93	15.1	25.03	15.1	21.80	15.4	28.20	19.7	31.07	24.1	−0.39	−0.13
Reading comprehension	8.45	3.7	11.10	3.0	11.10	3.1	10.13	5.0	10.27	4.7	10.13	4.7	0.88	0.91
WM-training measures														
Start scores (T1) and maximum scores (T2)	72.21	12.4	93.11	15.0	–		–		–		–		–	–

Control group, psychological measure = the Klingberg, et al. control group (2005) ($n = 25$); control group, literacy measures = children in small groups in the present study ($n = 15$); Treatment group ($n = 41$); Dashes = no results completed

Working memory training effects

First, the outcome of the working memory training in the experimental group was investigated. Multivariate analysis of variance with repeated measures was conducted to evaluate training effects from the cognitive measures being administered. The effect of training was tested by comparing the outcome score at post-test (Time 2; T2) in the treatment group scores at pre-test (Time 1; T1), controlling for age and gender. The performance on three out of four working memory measures (Span board forward, $p < .001$, Span board back, $p < .05$, and Digit back, $p < .01$), and of nonverbal problem solving (Raven, $p < .05$) was improved at T2 relative to T1.

It was not possible to compare the results between groups as the control group did not take the cognitive measures at Time 2. However, data from a randomized experimental study were available (Klingberg et al., 2005), allowing us to compare the effect of working memory training in the treatment group with a control group, controlling for baseline scores, age, and gender. As the two studies used the same training program, tests and the same timeframe for test- and re-test, we could weigh the results from the treatment group in the present study against an active control treatment; that is, the control group worked with a "low-dose" computerized working memory training program for 5 weeks. This program was identical to the program used for the treatment group except that the level of difficulty was not adapted to the ability of each child but remained at a low level during the whole training session. The control group comprised 25 children with ADHD (21 boys and 4 girls; mean age 10.3 years). To control for possible differences between the treatment group and the control group at pre-test, the covariates were used. The scores of the adjusted post-tests were analyzed to compare the groups.

Table 1 shows that the results of working memory in the treatment group ($n = 41$) were improved compared to this control group ($n = 25$) (Span board forward and back, $p < .001$, Digit forward, $p < .001$, and Digit back, $p < .05$). The results of Raven did not enhance. At Time 3 (T3) the performance on Span board forward ($p < .001$), and Span board back tasks ($p < .05$) was improved. The results at T2 were consistent with the analysis of the outcome for the treatment group, with two exceptions, the results of Raven and Digit forward task.

Having shown that training in working memory enhanced cognitive skills, the effects of training on the three literacy measures administered were evaluated. The effect of training was tested by comparing the outcome scores at post-tests (T2 and T3) in the treatment group and the control group, controlling for baseline scores, age, and gender. Only the results of reading comprehension improved at T2, (estimated treatment effect = 2.51, SE = 0.8, $t = 3.27$, $p < .01$, $d = 0.88$), and at T3 (estimated treatment effect = 2.43, SE = 0.9, $t = 2.72$, $p < .05$, $d = 0.91$).

Correlations

Next, the relationship between literacy measures and cognitive measures was analyzed (Table 2). Also, training scores (start index and max index scores) were

Table 2 Correlations between cognitive measures at Time 1, 2, and 3 and literacy as well as WM-training measures (index scores), at Time 1, 2, and 3 in the treatment group

Time 1	Word decoding	Orthographic verification	Reading comprehension	WM-training scores: start index
Span board forward	.20	.12	.31*	.67**
Span board back	.29	.08	.38*	.68**
Digit forward	.14	.30	.27	.47**
Digit back	.33*	.16	.30	.57**
Stroop; Time	−.05	−.26	.03	−.14
Raven	39*	.37*	.52**	.41**
Time 2	**Word decoding**	**Orthographic verification**	**Reading comprehension**	**WM-training scores: max index**
Span board forward	.18	−.05	.38	.62**
Span board back	.02	.10	.25	.75**
Digit forward	.18	.21	.23	.50**
Digit back	.31.	.25	.22	.40**
Stroop; Time	−.33*	−.21	−.37*	−.32*
Raven	.37*	.33	.41**	.44**
Time 3	**Word decoding**	**Orthographic verification**	**Reading comprehension**	
Span board forward	.05	.10	.11	–
Span board back	.11	−.10	.30	–
Digit forward	.32*	.26	.19	–
Digit back	.20	.31	.28	–
Stroop; time	−.01	−.28	−.11	–
Raven	.15	.25	.50**	–

* $p = < .05$, ** $p = < .01$

considered. At T1, the performance on WM training start index scores was significantly correlated with performance on all cognitive measures except the Stroop task (time, seconds). At T2, the training max index scores were related to all cognitive measures, including the Stroop measure. The working memory measure Span board was related to reading comprehension performance at T1 (Table 2). The performance on the Raven task was correlated with WM training and literacy results at time 1 and 2 and with reading comprehension results at Time 3 (Table 2).

At Time 1, the scores of Raven were significantly correlated with Span board back scores ($r = .51$, $p < .001$), Span board forward scores ($r = .40$, $p < .01$), and Digit back scores ($r = .44$, $p < .001$). The Stroop task was negatively correlated with the Digit back task ($r = -.36$, $p < .05$), and Span board forward ($r = -.31$).

The outcome scores, T3–T1, of Raven were related to the Span board forward scores, T3–T1 ($r = 41$, $p < .01$) as well as to Digit back scores, T3–T1 ($r = -.41$,

$p < .01$). The difference between WM-training results (max index—start index) were significantly correlated with Span board back differences, T2–T1 ($r = .33$, $p = < .05$), and T3–T1 ($r = .41$, $p < .01$), Span board back results at T3 ($r = .49$, $p < .001$), start index ($r = .55$, $p < .001$), and max index results ($r = .88$, $p < .001$).

Finally, differences, i.e., T2–T1, were regressed on T1 for the treatment group and the control group, respectively, calculated from the components of variance. The results for the treatment group show that progress at Time 2 (T2–T1) in Span board forward and reading comprehension could be predicted by results at Time 1 (Table 3, 4). The children performing at the lowest level improved the most at Time 2 as compared to Time 1 . However, none of the changes in literacy skills (T2–T1) regressed on T1 within the control group showed any significant results.

In sum, the treatment group enhanced its results of working memory measures at Time 2 compared to Time 1. Reading comprehension performance enhanced in the treatment group at time 2 and 3 compared to Time 1 and the control group. This was the only significant enhancement noted in literacy measures. The working memory measures Span board forward and back were related to reading comprehension and Digit span to word decoding at Time 1. Raven was related to reading comprehension at all time points. The improvements of WM-training scores (max index minus start index) correlated significantly with Span board back improvements at T2 and T3. Regression analysis revealed that the children performing at the lowest level improved the most in Span board forward and in reading comprehension at Time 2 compared to Time 1.

Table 3 Differences of T2 (post-test)—T1 (pre-test) scores of cognitive measures regressed on T1 in the treatment group

Assessment	*n*	*r*	*b* (SE)	*p*
Span board forward	41	−.51	−0.55 (0.2)	<.01
Span board backward	41	−.35	−0.39 (0.2)	n.s.
Stroop, time	41	−.54	−0.52 (0.2)	<.01
Digit span forward	41	−.40	−0.46 (0.2)	<.05
Digit span backward	41	−.43	−0.57 (0.2)	<.05
Raven's matrices	41	−.45	−0.27 (0.2)	n.s.

n number of children; *r* correlation coefficient; *b* regression coefficient; (*SE*) standard error; *p* probability

Table 4 Differences of T2 (post-test)—T1 (pre-test) literacy scores regressed on T1 in the treatment group

Assessment	*n*	*r*	*b* (SE)	*p*
Reading comprehension	42	−.69	−0.61 (0.2)	<.001
Word decoding	42	−.29	−0.40 (0.3)	n.s.
Orthographic verification	29	−.24	−0.14 (0.3)	n.s.

n number of children; *r* correlation coefficient; *b* regression coefficient; (*SE*) standard error; *p* probability

Conclusions and discussion

The aim of this study was to investigate whether working memory training could affect WM-measures and improve children's reading comprehension. It was found that comparison of the experimental group with an additional control group showed that the training indeed enhanced children's working memory. The results from the pre- and post-tests of the treatment group were also compared to a group which did not receive any additional training. The word decoding and orthographic verification tests were used mainly for control reasons. As expected, training of working memory did not enhance the performance on these tasks. The only reading task for which training improved performance was the reading comprehension task, and the effect size turned out to be substantial ($d = .91$).

This is consistent with the suggested role of working memory in comprehension (Cain et al., 2004; Swanson et al., 2006). Swanson and colleagues (2006) stressed the importance of executive processing for comprehension, finding differences in working memory ability between skilled readers and readers with deficits in comprehension, when phonological, inhibition, speed, verbal intelligence, and working memory measures were extrapolated from the analysis. It has been suggested that executive function is more strongly related to visuo-spatial memory than to verbal memory (Gathercole, Pickering, Ambridge, & Wearing, 2004) and that visuo-spatial memory may require more attention ability than verbal memory does (Baddeley, 2007). Children with ADHD performed worse than other children in visuo-spatial tasks (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005) suggesting that this kind of task requires attention ability, which these children lack.

Correlation analyses of baseline performance on academic tests confirmed the correlation of reading comprehension with WM capacity. These results are consistent with those of previous studies (e.g., Cain et al., 2004; Gathercole et al., 2004). The performance on non- verbal WM-measure Span board was also significantly related to only one reading measure in this study, reading comprehension. These results confirm the central role of working memory in reading comprehension, not only in the phonological loop but in the central executive and the visuo-spatial working memory as well. This relation appears to be specific to reading comprehension tasks. Low results in visuo-spatial memory were also found in children, who were impaired in reading and in mathematics, in a study by Pickering & Gathercole (2004).

Furthermore, inhibition control as measured with the Stroop task (low results are better) was negatively correlated with WM measures. The weak, but still significant, influence of the Stroop task may reflect the fact that the trained children's inhibition control was not a major problem, as few (33%) had a formal ADHD diagnosis. More than 60% were rated as inattentive by their teachers. Finally, nonverbal reasoning was significantly correlated with performance on three literacy measures at Time 1 and 2, but only with one at time 3, i.e., reading comprehension.

The role of working memory for reading may be associated with the improved ability to store verbal information as well as with the link between working memory and control of attention. The weakest performers improved their result in Span board forward (Table 3), which may be why they performed better in reading comprehension. As predicted, the training did not improve performance on decoding or orthographical tasks. This suggests that the training effect was not a general improvement in motivation, or a consequence of time-on-task, but a more specific effect related to working memory capacity. This confirms the central role of working memory capacity for academic achievement (e.g., Holmes et al., 2009; Pickering & Gathercole, 2004), and suggests that evaluation of working memory capacity in young children and its training may yield significant reward for children with special educational needs.

Several limitations apply to the present study. To begin with, there is a large difference in size between the treatment group and the control group, since we included more children in the treatment group. We expected higher variability in the treatment group but this assumption proved to be incorrect. Another critical issue concerns the increased reinforcement in the treatment group. The treatment group received a good deal of extra encouragement at school and at home during the 5-week pre-test period. It may be argued that the improvements in reading comprehension were due to this increased reinforcement from teachers, parents, and the research team. But if so, then significant improvements should have been noted in all the measures used. This was not the case: for the reading tasks, only the most working memory-related reading comprehension task improved, while other tests such as orthographic reading did not. This militates against a general, non-working memory-related explanation of the training effect. You may want to add though that future studies should compare against an alternative and equally intensive treatment.

The present study indicates that training of working memory may be useful for children with reading comprehension problems, special-education needs, and attention problems. The study thus has important practical implications. First, working memory capacity may be valuable in identifying children at risk poor scholastic progress. It is important to screen working memory ability in the lower grades, as Alloway, Gathercole, Kirkwood and Elliot (2009) suggest. Likewise, such screening may be an alternative to clinical diagnosis for identifying those children who might benefit from working memory training. Another practical implication is that working memory training may improve reading comprehension skills in children with problems in literacy and in attention. Notably, reading comprehension improved as a result of the intervention whereas word-level reading skills did not. This finding suggests that working memory training may facilitate reading comprehension processes directly, and not via improvements in word-level reading processes.

Acknowledgments This research was supported by The Swedish Research Council.

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