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FAST-TRACK REPORT

Adaptive training leads to sustained enhancement of poor working memory in children

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Abstract

Working memory plays a crucial role in supporting learning, with poor progress in reading and mathematics characterizing children with low memory skills. This study investigated whether these problems can be overcome by a training program designed to boost working memory. Children with low working memory skills were assessed on measures of working memory, IQ and academic attainment before and after training on either adaptive or non-adaptive versions of the program. Adaptive training that taxed working memory to its limits was associated with substantial and sustained gains in working memory, with age-appropriate levels achieved by the majority of children. Mathematical ability also improved significantly 6 months following adaptive training. These findings indicate that common impairments in working memory and associated learning difficulties may be overcome with this behavioral treatment.

Introduction

Working memory (WM), the cognitive system that provides temporary storage of information in the course of complex cognitive activities, appears to play a crucial role both in supporting learning and in maintaining focused behavior in practical situations. Individuals with poor WM are compromised in both these key aspects of everyday life (Gathercole, Alloway, Willis & Adams, 2006; Kane, Brown, McVay, Silvia, Myin-Germeys & Kwapil, 2007) and typically make very poor academic progress during the school years (Alloway, Gathercole, Kirkwood & Elliott, in press). These problems are by no means rare: of those children whose WM abilities fall in the bottom 10th centile, over 80% have substantial problems in either reading or mathematics or, most commonly, in both (Gathercole & Alloway, 2008). These children represent a substantial proportion of children who fail to thrive academically in school. In this article, we present evidence indicating that these WM problems can be boosted to age-appropriate levels for a sustained period by intensive practice on activities that tax WM.

WM is one of the major executive functions associated with the frontal lobes (Stuss & Alexander, 2000; Pennington & Ozonoff, 1996), and there exist a variety of models of its structure and function. Baddeley and Hitch (1974) advanced an influential multi-component model consisting of the central executive, a limited capacity component responsible for the control of attention, supplemented by domain-specific verbal and visuo-spatial stores and a multi-modal episodic buffer (Baddeley, 2000). Other theorists conceive of WM as a limited capacity process of controlled attention that activates representations in long-term memory to become the current contents of WM (Cowan, 2005; Engle, Kane & Tuholski, 1999).

The evidence linking WM capacity to the ability to learn is now extensive. Individual differences in complex span tasks that rely on the attentional component of WM are closely related to children's abilities in reading (Gathercole & Pickering, 2000; Swanson & Sachse-Lee, 2001) and mathematics (Geary, Hoard, Byrd-Craven & De Soto, 2004), and are effective longitudinal predictors of later academic attainment (Gathercole, Brown & Pickering, 2003). These associations typically cannot be accounted for simply by differences in more general intellectual abilities (Cain, Oakhill & Bryant, 2004; Gathercole *et al.*, 2006). It has been proposed that learning in children with low WM capacity is hindered by frequent WM overload in learning activities (Gathercole & Alloway, 2008).

Until recently, it has not seemed likely that the adverse consequences of low WM ability for learning could be overcome. WM ability is highly heritable (Kremen, Jacobsen, Xian, Eisen, Eaves, Tsuang & Lyons, 2007) and unlike many other cognitive assessments, appears to be relatively impervious to substantial differences in environmental experience and opportunity (Campbell, Dollaghan, Needleman & Janosky, 1997; Engel, Heloisa Dos Santos & Gathercole, in press). There has been some success in boosting performance on WM tests

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through strategy training (Turley-Ames & Whitfield, 2003), although because gains often do not extend beyond trained tasks they are unlikely to yield substantial benefits for the many and varied learning situations in which children depend on WM.

Recent reports of generalized and sustained enhancement of WM following an intensive WM training program have therefore attracted considerable attention. Developed by Cogmed, the program involves computer-based training on a variety of WM tasks for a period of 20 to 25 days. Remarkable gains have been reported both on the trained tasks and on other tests of short-term memory (STM) in children with ADHD (Klingberg, Fernell, Olesen, Johnson, Gustafsson, Dahlstrom, Gillberg, Forssberg & Westerberg, 2005) and in adult neuropsychological patients following strokes (Westerberg, Jacobaeus, Hirvikoski, Clevberger, Ostensson, Bartfai & Klingberg, 2007). Neuroimaging studies indicate that training results in increased activation in frontal and parietal areas of the brain that are known to serve WM (Olesen, Westerberg & Klingberg, 2004; Westerberg & Klingberg, 2007).

While these early findings look promising, the educational significance of this program is as yet untested. In particular, it is not known (i) whether the training benefits extend to children with low WM who do not have ADHD, (ii) what components of WM are trained, or (iii) whether the enhancement of WM function is of a sufficient degree to ameliorate or overcome the learning difficulties associated with low WM. The purpose of the present study was to answer these three questions by evaluating the extent to which the training program boosts performance of children with low WM on a standardized battery of untrained and well-validated WM tasks (Alloway, 2007; Alloway, Gathercole & Pickering, 2006) and on measures of academic ability, both immediately following completion of training and 6 months later. A comparison group of low memory children completed a non-adaptive version of the program that did not place heavy demands on WM skills. WM has a multi-component structure, which comprises a set of interconnected but functionally distinct subcomponents (Baddeley, 2000). It was therefore anticipated that training might have a differential impact on these subcomponents. The battery used to assess WM included tests of verbal and visuo-spatial storage (STM), and verbal and visuo-spatial WM tests that tap both the central executive and the appropriate domain-specific store. Using this tool provided a comprehensive theoretical analysis of the impact of training on the subcomponents of WM.

Method

Participants

Data are reported for 22 children (12 boys, 10 girls, mean age 10y 1m) who completed the adaptive program and 20 children (15 boys, 5 girls, mean age 9 y 9 m) who completed the non-adaptive version. Participants scored at or below the 15th centile on two tests of verbal WM, listening recall and backward digit recall, from the AWMA (Alloway, 2007) and were selected via routine screening of 345 children aged 8 to 11 years attending six schools in the North-East of England. The adaptive and non-adaptive training programs were implemented in separate schools. Schools were not informed that two different versions of the program were being offered in the study. The adaptive version has subsequently been offered to schools whose pupils received the non-adaptive version.

Procedure

Prior to training, each child completed a set of pre-training assessments. Training commenced within one week of these assessments. Children completed a set of post-training assessments within one week of finishing their training. The adaptive training group was re-tested on one test of each aspect of WM and all other measures 6 months after training ceased.

Pre- and post-training assessments

Working memory

Children completed seven subtests from the AWMA (Alloway, 2007) at pre-training: two tests each of verbal STM (word recall, digit recall), visuo-spatial STM (dot matrix, block recall) and visuo-spatial WM (Mr X, spatial recall), and one test of verbal WM (counting recall). The verbal STM tests required the immediate serial recall of verbal information, such as a list of digits or words. For the visuo-spatial STM tests a series of locations were either tapped out on blocks or presented as dots in a matrix. The children were required to reproduce each sequence in the correct order. The verbal WM tasks required children to simultaneously process and store verbal information. For example, they were required to count the red circles on consecutive displays of red circles and blue triangles shown on a computer screen, whilst also remembering the count total in each display for serial recall at the end of the trial. The visuo-spatial WM tasks also required the simultaneous processing and storage of information. The test information presented was visuo-spatial in nature, and involved, in the case of spatial recall, the child judging whether two shapes were the same way around or the opposite way around to each other, whilst remembering the location of a red dot on one of the shapes for later recall. Composite scores were obtained by averaging standard scores on the relevant pairs of tests for verbal STM, visuo-spatial STM and visuo-spatial WM. For verbal WM, composite scores were obtained by averaging standard scores on the test administered pre-training (counting recall) and the two screening measures (backward digit recall, listening recall). Eight subtests from the AWMA (Alloway, 2007) were completed immediately following training: five tests that had been administered pre-training and three that had not (nonword recall, mazes memory and odd-one-out). Composite scores were calculated by averaging standard scores on the relevant pairs of tests. Note that these tests were administered following the collection of data from a comparison group of 25 children (17 girls and 8 boys) aged 8–11 years, who completed the tests on two occasions 6 weeks apart. No significant differences were found in test and re-test scores, showing that practice alone is not sufficient to boost task scores: verbal STM, test $M = 102.92$, $SD = 15.33$, re-test $M = 100.52$, $SD = 16.29$, $t(24) = .92$, $p > .05$; visuo-spatial STM, test $M = 98.56$, $SD = 7.26$, re-test $M = 101.12$, $SD = 16.7$, $t(24) = 1.2$, $p > .05$; verbal WM, test $M = 106.92$, $SD = 14.21$, re-test $M = 110.64$, $SD = 8.74$, $t(24) = .84$, $p > 05$; visuo-spatial WM, test $M = 101.48$, $SD = 17.68$, re-test $M = 105.48$, $SD = 17.12$, $t(24) = .96$, $p > 05$.

The following instructions task developed by Gathercole and colleagues (Gathercole, Durling, Evans, Jeffcock & Stone, in press) was also administered, in order to provide a more practically based assessment of WM use in the classroom. For this task, the child was seated in front of an array of props (rulers, folders, rubbers, boxes, pencils) in a range of colors (blue, yellow, red) and attempted to perform a spoken instruction, such as *Touch the yellow pencil and then put the blue ruler in the red folder*. A span method was used in which the number of actions in the instructions was increased to the point at which the child could not perform the task accurately. The total number of trials correct to this point was scored.

Ability measures

Participants completed the Wechsler Abbreviated Scales of Intelligence (WASI; Wechsler, 1999), yielding measures of verbal and performance IQ, the basic reading subtest of the Wechsler Objective Reading Dimensions (WORD; Wechsler, 1993) and the mathematical reasoning subtest of the Wechsler Objective Number Dimensions (WOND; Wechsler, 1996).

WM training

Children engaged in training on a variety of WM tasks in a computerized game environment for approximately 35 minutes a day in school for at least 20 days in a period of between 5 and 7 weeks. Children completed 115 trials every day. The trials were divided between eight different tasks each day, selected from a bank of 10 tasks. Children trained on the same eight tasks for the first 5 days of the training period. On the sixth day, and on every fifth day thereafter, one of the tasks was replaced by a different task from the bank of 10.

Each training task involved the temporary storage and manipulation of sequential visuo-spatial or verbal information, or both. Three of the tasks involved the temporary storage of sequences of spoken verbal items, such as letters. These tasks tapped verbal STM, although simultaneous presentation of verbal information on the computer screen as it was spoken aloud in two of the tasks likely also tapped visuo-spatial STM and WM. Two tasks involved the immediate serial recall of visuo-spatial information, such as a series of lamps that illuminated successively and which the child attempted to recall in the correct order by clicking the appropriate location with the computer mouse. Verbal WM was tapped by two tasks, which involved the immediate recall of a sequence of digits in backward order. In one task the digits were spoken aloud at the same time as the corresponding numbers lit up on a keypad. The child attempted to recall the sequence of digits in backward sequence by clicking on the keypad. In a second task the numbers were not displayed as they were spoken aloud. Three tasks required the processing and immediate serial recall of visuo-spatial information that was either moving around the screen during presentation and recall (e.g. asteroids that were continuously moving around the screen lit up one at a time and had to be remembered and recalled in the correct order) or moved spatial location between presentation and recall (e.g. lamps light up one at a time in a grid, the entire grid then rotates 90 and the child recalls the order in which the lamps lit up, even though they are now in new positions).

Motivational features in the program included positive verbal feedback, a display of the user's best scores and the accumulation of 'energy' based on performance levels that was spent on a racing game completed after training each day. The racing game was included as a reward and did not tax WM.

Two versions of the program were used in the current study. In the standard adaptive version, task difficulty was matched to the child's current memory span on a trial-by-trial basis for each task. In the non-adaptive version, which was developed by Cogmed for the purpose of trial evaluations of the product (Klingberg *et al.*, 2005), tasks were set to the initial low level in the adaptive program, meaning difficulty levels were fixed at sequence lengths of two items on each trial throughout the training period. A repeated list length of two items was used to ensure that training did not tax WM, but instead provided a control for the experience of sitting in front of a computer and engaging with tasks with a training aide and behavioral rewards. The pre-training span levels for children in this condition were above two for all aspects of WM: verbal STM, $M = 3.96$; visuo-spatial STM, $M = 3.96$; verbal WM, $M = 3.46$; visuo-spatial WM, $M = 2.02$. Aside from the difficulty level of the training tasks, the two versions of the program, including the motivational features, were identical. All training was completed in school in small groups of between four and eight children, supervised by a training aide who was a paid research associate.

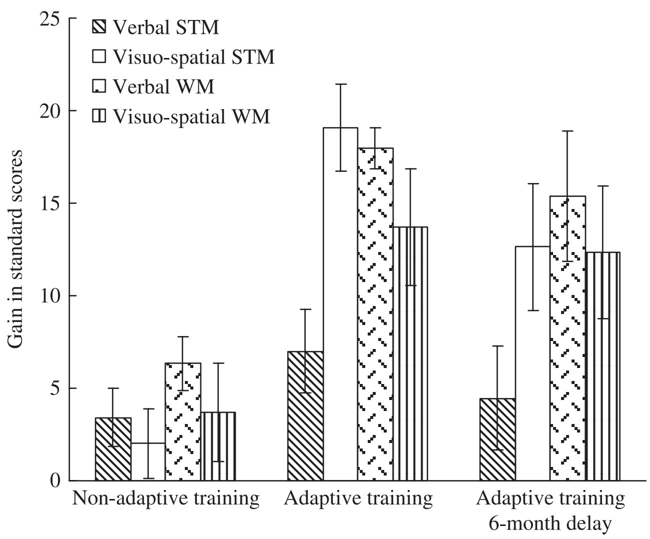

Figure 1 *Impact of training on working memory.*

Results

Figure 1 shows the training gains (in standard scores) for the four aspects of WM, averaged in each case over all relevant test scores taken before, immediately after and 6 months after training. Mean scores, *p*-values and Cohen's *d* effect size values showing the pre- to post-training gains and pre- to follow-up gains for WM are shown for the adaptive and non-adaptive groups in Table 1.

A series of MANOVAs established that there were no significant differences between the adaptive and non-adaptive groups at pre-training on three of the four memory measures: verbal STM, $F(1, 40) = .88$, $MSE = 75.54$, $p = .34$, verbal WM, $F(1, 40) = 2.76$, $MSE = 68.99$, $p = .10$, and visuo-spatial WM, $F(1, 40) = 1.65$, $MSE = 129.51$, $p = .21$. There was, however, a significant difference between the groups on the visuo-spatial STM measure, $F(1, 40) = 5.99$, $MSE = 154.68$, $p = .02$, with the non-adaptive group outperforming the adaptive group. These scores were subsequently covaried in analyses that compared the impact of training between the groups. Further MANOVAs established that there were no significant differences at baseline between the two groups across the following instructions test, $F(1, 40) = 3.27$, $MSE = 18.4$, $p = .08$, or the ability measures: verbal IQ, $F(1, 40) = 2.20$, $MSE = 170.26$, $p = .15$, performance IQ, $F(1, 40) = .02$, $MSE = 159.89$, $p = .88$, basic word reading, $F(1, 40) = 4.43$, $MSE = 197.23$, $p = .04$, mathematical reasoning, $F(1, 40) = .01$, $MSE = 176.07$, $p = .93$.

Children completing the adaptive training showed significant improvements in all aspects of WM: verbal STM ($p = .01$, $d = .62$), visuo-spatial STM ($p < .01$, $d = 1.20$), verbal WM ($p < .01$, $d = 1.55$), and visuo-spatial WM ($p < .01$, $d = 1.03$). Gains for the group receiving non-adaptive training were significant only for verbal STM ($p = .04$, $d = .49$) and verbal WM ($p = .02$, $d = .48$).

Corresponding ANOVAs established significant group by time interactions for visuo-spatial STM, $F(1, 40) = 31.31$, $MSE = 47.99$, $p < .01$, verbal WM, $F(1, 40) = 16.60$, $MSE = 42.79$, $p < .01$, and visuo-spatial WM, $F(1, 40) = 5.80$, $MSE = 90.38$, $p = .02$. In all cases, the training gains were significantly greater for the adaptive than the non-adaptive group. Importantly, training gains in each of these three aspects of WM remained significant after 6 months for the adaptive group: visuo-spatial STM, $F(1, 18) = 13.42$, $MSE = 112.93$, $p < .01$, verbal WM, $F(1, 18) = 13.88$, $MSE = 110.16$, $p < .01$, visuo-spatial WM, $F(1, 18) = 11.89$, $MSE = 121.74$, $p < .01$. The interaction term for verbal STM was not significant, $F(1, 40) = 1.64$, $MSE = 40.85$, $p = .21$.

The same pattern of selective enhancement with adaptive training extended to the classroom analogue test of WM, the following instructions task, $F(1, 40) = 10.07$, $MSE = 10.15$, $p < .01$. These gains also persisted 6 months after training for the adaptive group, $F(1, 17) = 4.95$, $MSE = 8.97$, $p = .04$.

Table 1 *Impact of training on cognitive measures*

	Non-adaptive						Adaptive									
	Pre-training		Post-training		Pre- to post-training		Pre-training		Post-training		Pre- to post-training		6-mth follow-up		Pre- to follow-up	
	Mean	*SD*	Mean	*SD*	*p*	*d*	Mean	*SD*	Mean	*SD*	*p*	*d*	Mean	*SD*	*p*	*d*
Verbal STM	87.25	8.18	90.68	5.85	0.04	0.47	89.82	9.44	96.82	12.18	0.01	0.62	95	13.67	0.13	0.44
Visuo-spatial STM	92.78	10.47	94.8	8.79	0.29	0.21	83.36	13.98	102.4	11.49	<.01	1.2	96.05	14.12	<.01	0.83
Verbal WM	82.85	1.47	89.18	9.54	<.01	0.78	78.3	6.58	96.27	9.66	<.01	1.55	93.68	14.84	<.01	1.16
Visuo-spatial WM	84.73	13.42	88.43	10.97	0.18	0.3	80.2	9.15	93.91	13.55	<.01	1.03	92.63	16.86	<.01	0.85
Following instructions (max. 30)	16.85	4.57	16.25	4.3	0.52	0.14	14.45	4.02	18.27	4.37	<.01	0.83	16.5	3.59	0.04	0.52
Verbal IQ	94.7	14.9	92.85	10.9	0.36	0.14	88.73	11.14	90.86	11.52	0.2	0.19	92.78	9.1	0.08	0.39
Performance IQ	88.65	12.1	93.65	11.1	0.01	0.43	88.05	13.09	90.68	12.96	0.11	0.2	87.11	9.07	0.72	0.08
Basic word reading	83.3	14.2	83.9	13.3	0.68	0.04	83.68	12.35	83	15.06	0.64	0.05	82.83	14.14	0.36	0.07
Mathematical reasoning	93.4	15.8	96.4	16.2	0.18	0.19	84.27	12.28	85.68	12.7	0.31	0.11	89.94	9.88	0.01	0.49

Because visuo-spatial STM baseline scores for the adaptive and non-adaptive groups differed significantly, ANCOVAs were performed with the visuo-spatial STM measure as a covariate. These established significantly greater training gains for the adaptive than the non-adaptive group for verbal WM, $F(1, 39) = 16.29$, $MSE = 43.31$, $p < .01$, and visuo-spatial WM, $F(1, 39) = 3.57$, $MSE = 180.86$, $p = .06$. The interaction term was not significant for verbal STM, $F(1, 39) = 1.94$, $MSE = 83.07$, $p = .17$, and it was not possible to compare gains between the groups in this set of analyses for visuo-spatial STM as pre-training visuo-spatial STM scores were entered as a covariate. The adaptive group made significantly greater training gains on the following instructions task than the non-adaptive group when visuo-spatial STM scores were covaried, $F(1, 39) = 7.71$, $MSE = 20.73$, $p < .01$.

In order to quantify the extent to which training boosts the children's WM from deficit to age-appropriate levels, the proportion of children with composite WM scores (averaged across the visuo-spatial STM, verbal WM and visuo-spatial WM scores) in excess of 95 (at or above the 39th centile) after training was calculated. A significantly greater proportion of the children receiving the adaptive training achieved scores in this age-appropriate range (68%) compared with the non-adaptive training group (25%), $\chi^2(1) = 37.16$, $p < .01$, $V = .43$. Further comparisons revealed that the proportion of children making gains of 5, 10 and 15 standard score points in their composite memory scores between pre-training and post-training was significantly greater for the adaptive than the non-adaptive group: 5 points (91% adaptive, 40% non-adaptive, $\chi^2(1) = 57.55.16$, $p < .01$, $V = .54$); 10 points (77% adaptive, 15% non-adaptive, $\chi^2(1) = 77.38$, $p < .01$, $V = .62$); 15 points (50% adaptive, 0% non-adaptive, $\chi^2(1) = 66.66$, $p < .01$, $V = .58$). Corresponding values for the 6-month follow-up assessments for the adaptive group were: 5 points (84%); 10 points (63%); 15 points (32%).

Table 1 summarizes performance on the IQ, reading and mathematics tests. No significant gains were found immediately following the completion of training for either group on measures of verbal IQ, $F(1, 40) = .64$, $MSE = 126.46$, $p = .84$, performance IQ, $F(1, 40) = .20$, $MSE = 113.19$, $p = .66$, basic word reading, $F(1, 40) = .67$, $MSE = 173.03$, $p = .42$, or mathematical reasoning, $F(1, 40) = 1.58$, $MSE = 161.10$, $p = .22$. The group receiving adaptive training did, however, show a significant gain in 6-month post-training scores in mathematical reasoning compared with pre-training baseline levels, $F(1, 17) = 9.50$, $MSE = 48.66$, $p < .01$.

Discussion

On average, there will be four or five pupils in a class of 30 who have WM abilities as low as the children participating in this study, and they will typically be making poor academic progress (Gathercole & Alloway, 2008). This study provides the first demonstration that these commonplace deficits and associated learning difficulties can be ameliorated, and possibly even overcome, by intensive adaptive training over a relatively short period: just 6 weeks, typically. The majority of the children who completed the adaptive program, which involved intensive training of 35 minutes a day in school for at least 20 days, improved their WM scores substantially over this period and for a further 6 months after training had been completed. The gains generalized to independent and validated WM assessments that were not trained, and were greatest for the tests involving either the storage of visuo-spatial material, or the simultaneous storage and manipulation of either visuo-spatial or verbal material. These tasks are supported by the central executive component of WM (Alloway *et al.*, 2006; Bayliss, Jarrold, Gunn & Baddeley, 2003; Kane, Hambrick, Tuholski, Wilheim, Payne & Engle, 2004), a limited capacity component that controls the allocation of attention under demanding immediate memory conditions. Importantly, it is these tasks that are most strongly predictive of children's learning abilities. In contrast, the adaptive training program did not have a significant impact on verbal STM, a distinct subcomponent of WM associated with a pre-frontal and parietal neural circuit (Smith & Jonides, 1997) that has been suggested to support language learning (Baddeley, Gathercole & Papagno, 1998). This aspect of the findings lends further support to the distinction between an attentional control component and a temporary verbal store in WM. The parallel impacts of training on visuo-spatial STM and WM measures in either domain fits well with other recent evidence indicating that storage of nonverbal material is supported by the central executive rather than a specialized visuo-spatial store analogous to verbal STM (Thompson, Hamilton, Gray, Quinn, Mackin, Young & Ferrier, 2006).

Adaptive training had little detectable impact on measures of the children's academic skills immediately following completion of training. This is unsurprising, as any improved cognitive support for learning caused by training would be expected to take some time to work its way through to significant advances in performance on standardized ability tests. And indeed, a significant boost to mathematics performance was found 6 months following adaptive training. Training gains therefore appear to extend to at least some of the learning difficulties associated with poor WM. Interestingly, IQ did not show a comparable boost with training, indicating that although WM and IQ are undoubtedly related (Kane & Engle, 2002; Jaeggi, Buschkuel, Jonides & Perrig, 2008), its contribution to learning can be distinguished in struggling learners (Cain *et al.*, 2004).

This adaptive WM training program meets the criteria we set in advance of the study for educational significance: its benefits extend to the many children whose low WM abilities are accompanied by poor academic learning but who often fall below the radar of recognition for special needs, the gains generalize to a wide range of non-trained WM assessments, including a classroom analogue test of WM, and the training leads to detectable gains in academic skills.

The nature of the cognitive and neural changes that underpin the dramatic gains in WM with this adaptive training program are yet to be fully understood and will require further investigation. The experience of taxing WM to its limits intensively over a sustained period of time may induce long-term plasticity through either improving the efficiency of neuronal responses or extending the cortical map serving WM (Westerberg & Klingberg, 2007). The training program may also promote self-awareness and the development of compensatory strategies capitalizing on personal cognitive strengths to overcome areas of weakness. After training was complete, the children were asked what they thought had helped them to improve on the training activities. Of those who answered, 37% reported concentrating harder by closing their eyes or focusing more on the presented information and a further 27% reported using a variety of other strategies, including rehearsing the information or tracing the patterns on the computer screen with their eyes. These introspective reports obtained from the children after adaptive training suggest that training may indeed enhance attentional focus and stimulate a whole set of strategies that can be flexibly deployed with generalized benefits in a wide range of activities that place heavy demands on WM.

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