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Effects of skill training on working memory capacity

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Abstract

In this study we examined the effects of skill training, in particular mental abacus and music training, on working memory. Two groups of participants—children who had received mental abacus training and their controls—participated in Experiment 1. All participants performed the following span tasks: forward digit span, backward digit span, non-word span, operation span, simple spatial span, and complex spatial span tasks. Children (mean age: 12 years) who had received training exhibited greater simple spatial spans, but not other spans. In Experiment 2, the same span tests were given to groups of children (mean age: 12 years) and adults (mean age: 22 years) who had received music training and to their controls. For adults, the experimental group performed better than the control group with respect to both the digit span and non-word span tests. For children, the experimental group performed better than did the control group in all of the span tests. We discuss our results in terms of the domain-specific effects of skill training on working memory.

Keywords: Phonological store; Visual-spatial memory; Mental abacus; Music training

Recently, the issue of individual differences in working memory has drawn a great deal of attention in the research community (e.g., Miyake, 2001). Many studies have found that working memory plays a significant role in the performance of many cognitive tasks and in determining individual characteristics, such as general IQ and school achievements (for a review, see Gathercole, 1999). Specifically, studies using the individual difference approach have found that working memory capacity contributes to proficiencies in language comprehension (Daneman & Merikle, 1996), solving mathematical problems (Adams & Hitch, 1997), and following directions (Engle, Carullo, & Collins, 1991). Moreover, Kyllonen, and Christal (1990) observed near-perfect correlations between working memory capacity and fluid intelligence. Very few studies, however, have investigated the source of this individual difference, which led to the main concern of the current study, i.e., finding the sources of individual differences in working memory capacity, with particular attention on the effect of skill training on the working memory capacity.

Working memory is a theoretical construct that refers to the mechanism or system underlying the maintenance and processing of task-relevant information during the performance of a cognitive task (Baddeley & Hitch, 1974; Daneman & Carpenter, 1980). Working memory allows several pieces of information to be held in mind simultaneously and interrelatedly. It is essential for complex cognitive processes, such as spoken and written language comprehension, mental arithmetic, reasoning, and problem solving (see Baddeley, 1986). Working memory is also a subcomponent of the overall memory system, allowing the temporary storage and manipulation of information necessary for complex

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tasks. In contrast to the overall system, working memory is, however, limited in both its storage and processing capacity. This key characteristic makes working memory an important topic of research from both theoretical and practical viewpoints.

Even though researchers all agree on the importance of working memory in carrying out complex cognitive tasks, there is no consensus of a clear definition for working memory. Various theoretical perspectives have been proposed. These models of working memory differ in their views of the nature, structure, and function of working memory. According to Baddeley's multicomponent model (Baddeley, 1986; Baddeley & Hitch, 1974), working memory contains a core system—the central executive—that is responsible for controlling, regulating, and coordinating the overall system. The function of the central executive is close to the function of attention. This core system is assisted by two slave systems, which have both storage and processing functions.

The first slave system, the phonological loop, deals with phonological information, including a phonological store and an articulatory process. The function of the phonological loop is to aid phonological long-term learning, as in the case of acquiring new words (e.g., Baddeley, Gathercole, & Papagno, 1998). The second slave system, the visuospatial sketchpad, is a system for maintaining and manipulating visual–spatial information that is responsible for visual coding and handling of spatial imagery information in analog forms. It can be further subdivided into a visual component, dealing primarily with objects and their visible features, and a spatial component, dealing with locations and movements in space. The visual–spatial sketchpad is involved in visual or spatial tasks, such as remembering shapes and colors or the location and speed of objects in space. A fourth component, the episodic buffer, was included in a recent version of the model (Baddeley, 2000, 2003). The episodic buffer is also a limited-capacity storage system that is controlled by the central executive. It provides temporary storage of information held in a multimodal code. The main function of the episodic buffer is to integrate information from various subsystems and long-term memory to form a unitary episodic representation.

Cowan's (1995) embedded-processes model of working memory focuses on the close relation between memory and attention. He has proposed a hierarchical system of memory, suggesting that short-term memory is the activated portion of long-term memory. The activation is limited in duration. Items in the focus of attention are activated continuously and are directly available in working memory. Thus, the part of pre-activated memory that is in the focus of attention is the working memory, which has limited capacity. Based on this model, working memory is a global workspace used for integrating information needed for the tasks at hand (Cowan, 1988, 1993).

The third type of working memory model is Engle's controlled attention framework. His idea is similar to Cowan's view that the working memory is an active portion of the long-term memory and is close to the controlled attention. Moreover, working memory is a unitary, domain-general system with limited capacity (Engle, Cantor, & Carullo, 1992). The main approach of this framework focuses on the individual differences. For example, Engle, Tuholski, Laughlin, and Conway (1999) demonstrated that participants' working memory capacity was related to the general factor of intelligence and domain-general ability of controlled attention. In addition, Carpenter and colleagues suggest that individual differences reflect variations in the total amount of mental resources available (e.g., Just & Carpenter, 1992) that are dynamically divided between processing and storage capacity (Daneman & Carpenter, 1980). According to these researchers, working memory is a domain-general capacity used to maintain information in the STM and is assumed to be inherently different across individuals.

Alternatively, Ericsson & Kintsch (1995) have proposed that long-term knowledge and skills provide a better account of individual differences in working memory capacity. According to this view, working memory capacity is determined by the ability to efficiently assess task-relevant information in the LTM. Moreover, extensive knowledge acquired from experience in a particular domain can be used to overcome the capacity limits of working memory. Thus, this model predicts that acquired domain-specific skills can enhance the efficiency of memory storage and retrieval. Similarly, within the connectionist framework, MacDonald and Christiansen (2002) have suggested that individual differences in performance emerge from the interaction of experience and biological factors. Any architectural changes caused by these factors would have effects on both the processing capacity of the network and the nature of the representations embodied in the network. In other words, the connectionist approach does not postulate a working memory for temporary storage and processing that is separated from the representation of long-term knowledge. Moreover, the connectionist approach provides an account of how increased processing capacity in skilled performance may be acquired through learning. Based on these two frameworks, we hypothesized that acquired domain-specific skills may enhance not only the recall of domain-specific information, such as chess positions by expert chess player (e.g., Gobet & Simon, 1996; Sarriluoma, 1989) and patient information on medical diagnosis (Groen & Patel, 1988), but also the measures of domain-related working memory capacity. We designed the present study to test our prediction.

In the current study we investigated the effect of music and mental abacus training on the working memory capacity. Based on the domain-general fixed capacity view, training would have little impact on the working memory capacity, whereas the domain-specific skill-based view would predict that different kinds of skill training, such as music training and mental abacus training, would affect the different domains or components of the working memory and, as a result, the working capacities.

1. Experiment 1

In Experiment 1 we examined how mental abacus training affects the working memory. A ''mental abacus'' refers to an abacus-based mental arithmetic technique. While calculations with an abacus utilize the device to perform addition, subtraction, multiplication, division, and extraction of roots, a mental abacus process involves conducting these abacus computations mentally. Mental abacus calculation is a typical example of overlearned cognitive skills. The ability to perform mental abacus calculations is usually acquired after intensive and long sessions of training with an abacus. Most people acquire this ability after their abacus skills have become fully automatic and extremely skillful. They can not only form a mental image of the abacus but also mentally manipulate the abacus in the same manner as they do when using a real abacus. In addition, some studies have found that visuo-spatial processing underlies mental abacus calculations (Hatta & Ikeda, 1988; Stigler, 1984). Therefore, based on the domain-specific skill view (e.g., Ericsson & Kintsch, 1995), training in mental abacus calculation should have a beneficiary effect on the visual–spatial working memory. Specifically, mental abacus training should improve performance on tasks that tap the participants' ability to store visual–spatial information and not on tasks that involve the central executive, the more active component of working memory. This hypothesis was based on the consideration that mental abacus training is simply focused on ''doing abacus calculation in the head'' and not on coordination or integration between different skills. According to the domain-general capacity view, however, the working memory capacity is a stable individual characteristic that should not be affected by training.

1.1. Method

1.1.1. Participants

Thirty-two students participated in this experiment. Sixteen of them (mean age: 12.6 years) had received mental abacus training and the other 16 (mean age: 12.5 years) were in a matched control group. The trained group of students, who were selected randomly from several training schools in a local community, attended regular schools during the daytime and received one-and-a-half hours of training twice a week after regular classes. During their training, the students practiced arithmetic calculations intensively, with and without an abacus. They first learned abacus calculations, including addition, subtraction, multiplication, and division, through repetitive practice. For the following mental abacus training, the students had to mentally manipulate the abacus in the same manner as they did when using the abacus. Each of the trained students had received such training for at least a year and had reached the advanced level on a national qualification examination held by the Chinese Abacus and Mental Calculation Development Association.

The children of the matched control group were classmates of the members of the trained group and were selected by their teachers to ensure that the two groups were equivalent in terms of both their academic performance in the school and the educational levels of their parents (for the trained group: two of the parents were educated at college level, one at primary school level, and the rest at high school level; for the untrained group: three of the parents were educated at college level, one at primary school level, and the rest at high school level). The participants' exam grades in mathematics for the two semesters prior to abacus training were also comparable (average grades of both groups: B+). None of the students had received any special music training. They were paid for their participation in this experiment.

1.1.2. Procedure

All of the working memory tests were administered to each student. These tests measured the digit span, non-word span, operation span, simple spatial span, and complex spatial span. The order of administration of these tests was held constant for each student. The students were tested individually in a quiet room at the school and they completed all of the tests during a single session.

1.1.3. Forward/backward digit span and non-word span

Several sequences of digits were presented aurally for immediate serial recall. Two digits were first read aloud by the experimenter at a rate of approximately one digit per second. After presentation of the last digit, participants were required to recall the digits in a correct forward or backward sequence. If the recall was correct for two trials, the number of digits was increased by one. This procedure was repeated until the participants recalled a set of two digit sequences inaccurately. The digit score was the total number of digit sequences correctly recalled by participants. Procedures for the non-word span were the same, with nine nonsense syllables replacing the nine digits.

1.1.4. Operation span

The task used to measure the operation span was developed based on the approach used by Turner and Engle (1989). During the task, participants were presented with sets of operation word strings [e.g., “$(9/3) + 5 = 8$? D”]. Each participant was required to multiply or divide two integers and then add or subtract a third integer. The integers ranged from 1 to 10. The participant was told to read the operation aloud, to say ‘‘yes’’ or ‘‘no’’ at the question mark to indicate whether the number to the right of the equal sign was the correct answer, and then to state the letter aloud. Participants were instructed to remember the letter for later recall. Operation-letter sequences were presented in increasing set size. Participants completed trials with a set size of two, followed by trials of a set size of three, and so on. After each set size of operation-letters, participants had to recall the letter in correct order. Each set size contained three trials. The testing procedure was repeated until the participant failed to recall the letters on three consecutive trials. The operation score was the total number of trials in which the participants correctly recalled the letter and solved the mathematical operation.

1.1.5. Simple spatial span

Five drawings of unfamiliar objects were used. These objects appeared in different cells of a grid. The sizes of grids were 2×2, 2×3, 3×3, 3×4, and 4×4. For each grid size, half of the cells (four in the case of the 3×3 grid) were filled with objects selected randomly from five of the unfamiliar objects. There were two trials for each grid size. Participants were asked to remember the object and the location of the object in each grid. Grids were presented in increasing size. Testing was terminated when participants failed to recall both the object and the location of the object correctly in both trials of a given grid size. The object-only score was the number of grids in which the participants had recalled the object correctly but failed to remember the position of the object correctly. The position-only score was the number of grids in which the participants indicated the location of the object correctly but recalled the wrong object. The combined score was the number of grids for which participants had recalled both the objects and their positions correctly.

1.1.6. Complex spatial span

The design of this task was based on the approach reported by Hegarty, Shap, and Miyake (2000). The participants were required to verify a matrix equation while simultaneously remembering a dot location in a 5×5 grid. Each trial included a set of matrix equations to be verified, followed inspection of a 5×5 grid containing one dot. For each matrix equation, a simple addition or subtraction equation was presented. The participants were told to indicate orally whether the matrix to the right of the equal sign was the correct answer and then immediately thereafter the dot grid was presented. The participants had to remember the dot grid. After a sequence of between two and five equation/grid pairs, the participants were asked to recall which grid spaces had contained dots. The testing procedure was repeated until the participant failed to recall the dot grid on two consecutive trials. The complex spatial score was the total number of trials in which participants recalled the dot grid and solved the matrix equation correctly.

After completing these span tasks and took a 5-min break, the participants had to solve 20 mental arithmetic questions. They had to solve the questions as accurately and quickly as possible and to write down their answers next to each question. The participants’ response times were recorded; they had a maximum of four minutes to solve the problems.

1.2. Results and discussion

Table 1 presents the mean scores of the working memory tests for both the trained and control groups. In the mental calculation test, the trained group took an average of 1.13 min and the control group took an average of 3.80 min to complete the 20 questions. The mean correct percentages were 95% for the trained group and 75% for the control group. The two groups differed significantly in both their mean response times [$t(30) = 10.08$, $p < 0.01$] and mean correct percentages [$t(30) = 3.40$, $p < 0.01$].

As for the span tests, planned comparisons were undertaken to compare the results from the trained and control groups. The trained group scored significantly higher than the control group on the three simple spatial span measures: object-only [$F(1, 30) = 4.17$, MSe = 6.91, $p < 0.05$], location-only [$F(1, 30) = 6.70$, MSe = 11.66, $p < 0.05$], and combined [$F(1, 30) = 7.81$, MSe = 5.18, $p < 0.01$] scores. The two groups of participants did not differ significantly in the results of the other span tests [for forward digit span: $F(1, 30) = 2.17$, MSe = 6.96, $p = 0.15$; for backward digit span: $F(1, 30) = 3.03$, MSe = 8.68, $p = 0.10$; for non-word span: $F(1, 30) = 1.20$, MSe = 3.14, $p = 0.28$; for operation span: $F(1, 30) = 1.98$, MSe = 4.05, $p = 0.17$; for complex spatial span: $F(1, 30) = 0.30$, MSe = 0.94, $p = 0.59$).]

To further test the hypothesis that the trained and control groups differed only in the results of the simple spatial span measures, we tested whether there was an interaction between the degree of training (trained vs. untrained) and task type (simple spatial spans vs. other spans). The interaction was significant, $F(1, 30) = 4.45$, MSe = 6.64, $p < 0.05$. The main effects of training [$F(1, 30) = 7.50$, MSe = 20.22, $p < 0.05$] and task type [$F(1, 30) = 39.76$, MSe = 6.64, $p < 0.001$] were also significant.

Overall, the trained group performed better than the control group in the mental calculation test in terms of both their accuracy and speed, confirming the effect of expertise. The trained group also performed better than the control group in the simple spatial span tests. These results suggest that training to perform mental abacus calculations enhances a participants' ability to store visual–spatial information. The two groups did not differ in the tests of the phonological loop and the tests that measure both the processing and storage of working memory, such as the backward digit span, operation span, and complex spatial span tests. These results also suggest that even though these two groups of participants were not randomly assigned, they were matched in the cognitive abilities that are not related to visual–spatial storage. Moreover, the participants were classmates in a regular school and had matching grades in mathematics (prior to training), academic performance, and socioeconomic status. Therefore, it is highly likely that the difference between the trained and untrained groups in the short-term storage of visual–spatial information arose from their different degrees of mental abacus training.

2. Experiment 2

In this experiment we examined whether music training had an effect on working memory capacity, and whether the effect was the same for both children and adults. The effect of training might not be evident for adults because they have reached a mature state of cognitive development. According to the domain-specific skill view, music training

Table 1
Mean scores for different kinds of working memory tests as a function of training in Experiment 1

	Mental abacus trained group	No mental abacus trained group
Digit span		
Forward	13.63 (2.75)	12.25 (2.52)
Backward	8.81 (3.31)	7.00 (2.53)
Non-word span	5.88 (1.50)	5.19 (2.01)
Operation span	6.13 (2.28)	5.13 (1.71)
Complex spatial span	2.81 (0.98)	2.63 (0.96)
Simple spatial span		
Object	8.81 (3.80)*	5.69 (2.98)
Location	13.31 (2.65)*	11.44 (2.61)
Combined	8.63 (2.55)*	6.38 (1.96)

*A significant difference was found between the trained and untrained groups.
SDs are provided in parentheses.

should be related to phonological storage, because both involve auditory information processing. Moreover, some studies have found that music training enhanced spatial, mathematical, and reading abilities (Gardiner, Fox, Knowles, & Jeffrey, 1996; Rauscher et al., 1997) as well as various subtests of the IQ test (Schellenberg, 2004). Thus, it is possible that music training would also increase scores of other span tests. Based on the domain-general capacity view, however, training should have limited impact on the working memory capacity.

2.1. Method

2.1.1. Participants

Forty children (mean age: 12 years) and 40 adults (mean age: 22 years) participated in this experiment. A questionnaire regarding music training and language background were first given to a large sample of participants from two different universities and a primary school. The adult participants were college students selected randomly from those with music training and those without music training. The children were selected randomly from the primary school. Half of the children had received an average of 6.1 years of music training; half of the adults had received an average 14.3 years of training. Each of these participants had learned to play at least one kind of musical instrument. The other children and adults did not receive any special training in music. There were no differences in the number of languages or dialects that the participants spoke. The trained and untrained groups of children were matched in both the Raven Standard Progressive Matrices Test, taken before training (trained group: mean, 81.35; SD, 10.63; untrained group: mean, 83.65; SD, 13.43), and the educational levels of their parents (for both groups, 75% were educated at the college level and 25% at high school level).

2.1.2. Procedure

All participants performed forward and backward digit span, non-word span, operation span, and simple spatial span tasks. The trained groups performed these tasks after music training. The order of administration of the tests was held constant for each participant. Each participant was tested individually in a quiet room; all tests were completed during a single session.

All the span tasks were conducted in the same manner as those described for Experiment 1. Before the span tasks, as a manipulation check, the participants' music ability was tested using a tone identification test. A total of 10 music tones were played one at a time on a piano. After each tone, the participants had to report its pitch name. Each tone was played for 1 s and the participants had three chances to report the pitch name. The next tone was played after the participants had failed three times.

2.2. Results and discussion

The mean number of tones that the participants correctly identified was 9.3 for the child trained group, 9.5 for the adult trained group, 1.0 for the untrained-child group, and 0.8 for the untrained adult group. These results suggest that the trained groups performed almost perfectly in the tone identification task and much better than did the untrained groups.

Table 2 presents the mean scores of the working memory tests for both the trained and control groups. A series of 2 (children vs. adults) by 2 (trained vs. untrained) ANOVAs were undertaken. Both the forward digit span and non-word span tests measured the phonological component. For the forward digit span, there were significant effects of both training [$F(1, 76) = 10.13$, MSe $= 5.70$, $p < 0.05$] and age [$F(1, 76) = 33.69$, MSe $= 5.70$, $p < 0.05$]. The interaction was not significant, $F(1, 76) = 0.01$, MSe $= 5.70$, $p = 0.93$. The non-word span test produced significant main effects of training [$F(1, 76) = 9.45$, MSe $= 2.92$, $p < 0.05$] and age [$F(1, 76) = 12.01$, MSe $= 2.92$, $p < 0.05$]. The interaction effect was not significant, $F(1, 76) = 0.72$, MSe $= 2.92$, $p = 0.40$.

Both the backward digit span and operation span tests involved the central executive component. The backward digit span had a main effect of age, $F(1, 76) = 15.39$, MSe $= 5.72$, $p < 0.05$; the training and age interaction was also significant, $F(1, 76) = 13.27$, MSe $= 5.72$, $p < 0.05$. Tukey HSD tests revealed that the untrained group of children scored lower than the other three groups (all ps < 0.01). Next, the operation span resulted in an effect of training [$F(1, 76) = 8.30$, MSe $= 4.07$, $p < 0.05$] and an interaction between training and age [$F(1, 76) = 11.06$, MSe $= 4.07$, $p < 0.05$]. Tukey HSD tests revealed that the untrained group of children scored lower than the other three groups (all ps < 0.01).

Table 2
Mean scores for different kinds of working memory tests as a function of age and training[a] in experiment 2

	Children		Adults	
	MTG	NMTG	MTG	NMTG
Digit span				
Forward	13.85 (2.25)*	12.20 (2.17)	17.00 (2.13)*	15.25 (2.91)
Backward	8.00 (2.58)*	5.30 (2.83)	8.15 (1.14)	9.35 (2.64)
Non-word span	6.05 (1.82)*	4.55 (1.54)	7.05 (1.70)*	6.20 (1.77)
Operation span	7.30 (2.32)*	4.50 (1.82)	6.60 (1.76)	6.68 (2.12)
Simple spatial span				
Object	7.35 (4.45)*	4.50 (2.84)	8.90 (4.40)	10.00 (3.93)
Location	12.75 (2.17)*	10.65 (2.64)	13.85 (1.87)	13.90 (2.22)
Combined	8.65 (2.76)*	5.25 (2.86)	9.35 (2.80)	9.90 (3.34)

*A significant difference was found between the trained and untrained groups.
SDs are provided in parentheses.
[a] MTG: music trained group; NMTG: no music trained group.

Finally, analyses were performed on the results of the spatial span tests. The object-only scores resulted in a significant main effect of age [$F(1, 76) = 15.85$, MSe $= 15.67$, $p < 0.05$] and an interaction between training and age [$F(1, 76) = 4.97$, MSe $= 15.67$, $p < 0.05$]. Tukey HSD tests revealed that the untrained group of children scored lower than the rest of three groups (all *p*s < 0.01). Analyses of the location-only scores revealed significant effects of training [$F(1, 76) = 4.17$, MSe $= 5.03$, $p < 0.05$] and age [$F(1, 76) = 18.79$, MSe $= 5.03$, $p < 0.05$] as well as an interaction between training and age [$F(1, 76) = 4.59$, MSe $= 5.03$, $p < 0.05$]. Tukey HSD tests revealed that the untrained group of children scored lower than the other three groups (all *p*s < 0.01). The combined scores resulted in significant main effects of training [$F(1, 76) = 4.67$, MSe $= 8.69$, $p < 0.05$] and age [$F(1, 76) = 16.46$, MSe $= 8.69$, $p < 0.05$] and an interaction between training and age [$F(1, 76) = 8.97$, MSe $= 8.69$, $p < 0.05$]. Tukey HSD tests revealed that the untrained group of children scored lower than the other three groups (all *p*s < 0.01).

Two main conclusions can be drawn from those analyses. First, for the span tasks that measure phonological storage (forward digit span and non-word span tests), adults performed better than children and the trained groups performed better than the untrained groups. Second, for the span tasks involving the central executive (backward digit span and operation span tests) and the visual–spatial store (object-only, location-only, and combined scores tests), the trained-child group performed better than the untrained-child group, but there was no difference between the two adult groups. These results suggest that both age and the degree of music training had effects on measures of phonological storage. Moreover, the effects of music training on measures of central executive and visual–spatial storage were more obvious for children than for adults.

Various attempts were made to match the children's fluid intelligence and their social economic status, even though in this study we did not assign participants randomly to the trained and untrained groups. For the adults, it was very likely that the members of the trained and untrained groups were matched in their other cognitive abilities because these two groups differed only in their measures of phonological storage. Nonetheless, to provide a causal link between the degree of music training and the working memory capacity, further research will be necessary using a true experimental design.

3. General discussion

There were several important findings in the current study. First, training at mental abacus calculations is associated with a child's ability to store visual–spatial information, whereas music training is related to both adults' and children's performances associated with phonological storage. Both lines of evidence are consistent with the proposal that domain-specific training enhances the efficiency of storing and assessing task-relevant information (Ericsson & Kintsch, 1995). Performing mental abacus calculations involves mainly visuo-spatial processing (Hatano & Osawa, 1983; Stigler, 1984). Specifically, the participants not only store digits in the form of visuo-spatial imagery but also rely on visuo-spatial imagery processing to perform mental arithmetic. After training, the participants became more efficient at the storage and retrieval of visuo-spatial information.

The music training resulted in evidence that speech and music share some cortical areas and mechanisms (e.g., Patel & Peretz, 1997). Moreover, the finding that music perception skills were related to phonological awareness in children (Anvari, Trainor, Woodside, & Levy, 2002) suggested that both skills involve the same auditory resource. These findings are consistent with our current results indicating that music training is related to both music perception and the efficiency of phonological storage, as measured by forward digit span and non-word repetition tests, which we consider herein to be pure measures of phonological storage.

In the present study we also found that the group trained in mental abacus calculations did not differ from the control group in the tasks that measured the phonological and central executive aspects of the working memory. Because phonological storage is not obviously related to mental abacus training, this result is not surprising. The backward digit span, complex spatial span, and operation span were considered measuring the more active working memory component, i.e., the central executive. In particular, both the complex spatial span and operation span tests tap processing and storage of the working memory simultaneously and they also involve a resource-sharing and task-switching mechanism (see Saito & Miyake, 2004). Our current findings suggest that the active aspect of the working memory is not affected by training.

The musically trained children performed better than the control group on tasks that not only measured phonological storage but also were related to central executive and visual–spatial storage. Considering the recent findings on the effect of music training on various cognitive tasks, the relationship between music training and working memory capacity may be more complex than it first appeared. Studies have found that music training enhances both spatial and mathematical abilities (Gardiner et al., 1996; Rauscher et al., 1997). There was also a correlation between the degree of musical training and the differences in the neural architecture used for mathematical processing (Schmithorst & Holland, 2004). Thus, it seems that music training enhances both complex cognitive skills and spatial abilities. The reason might be that music training improves the ability to simultaneously store and process information and that this ability is also related to visuo-spatial processing. Further research is required to clarify the relationships between music training and the various kinds of cognitive processing and, more importantly, the underlying mechanisms for these relationships.

Finally, the current findings showed that mental abacus and music training have very different effects on working memory. Relatively speaking, mental abacus training is simpler, involving only the intensive practice of manipulating the abacus mentally. It focuses mainly on visuo-spatial processing, whereas music training involves more kinds of cognitive skills, such as motor, task switching, and memory skills. The music training effect was more obvious for children than for adults; adults with prior music training may have reached an optimal level of performance, and adults with no prior music training may have acquired these skills through other kinds of experiences or training.

Many studies of individual differences in working memory have examined the relationship between working memory capacity and cognitive deficiency of some sort, such as learning and mathematics disabilities (e.g., Palladino & Cornoldi, 2004; Wilson & Swanson, 2001). The present study demonstrates that training in cognitive skills is also related to working memory capacity, further illustrating the close links between working memory and complex cognitive skills. An acquired domain-specific skill did play an important role in accessing information from working memory. More importantly, the increases in the working memory capacity occur as a result of changes not only in the brain that are determined by biological or epigenetic factors, but also in the degrees of experience and training. Moreover, there seem to be reciprocal interactions between the brain and the working memory. A recent report (Olesen, Westerberg, & Klingberg, 2004) found changes in brain activity that were induced by working memory training. That study provided evidence for training-induced plasticity in the neural system that underlies the working memory. These findings highlight the essential role of enriched experiences in improving basic cognitive capacities and have substantial implications for the learning and remedy in education. Students should be given opportunities to develop various cognitive skills through training.

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References

Adams, J. W., & Hitch, G. J. (1997). Working memory and children's mental addition. *Journal of Experimental Child Psychology, 67*, 21–38.

Anvari, S. H., Trainor, L. J., Woodside, J., & Levy, B. A. (2002). Relations among musical skills, phonological processing, and early reading ability in preschool children. *Journal of Experimental Child Psychology, 83*, 111–130.

Baddeley, A. D. (1986). *Working memory*. New York: Oxford University Press.

Baddeley, A. D. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences, 4*, 417–423.

Baddeley, A. D. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience, 4*, 829–839.

Baddeley, A. D., Gathercole, S. E., & Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review, 105*, 158–173.

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory, Vol. 8* (pp. 47–89). New York: Academic Press.

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. *Psychological Bulletin, 104*, 163–191.

Cowan, N. (1993). Activation, attention, and short-term memory. *Memory & Cognition, 21*, 162–167.

Cowan, N. (1995). *Attention and memory: An integrated framework*. New York: Oxford University Press.

Daneman, M., & Carpenter, P. A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning & Verbal Behavior, 19*, 450–466.

Daneman, M., & Merikle, P. M. (1996). Working memory and language comprehension: a meta-analysis. *Psychonomic Bulletin & Review, 3*, 422–433.

Engle, R. W., Cantor, J., & Carullo, J. J. (1992). Individual different in working memory and comprehension: a test of four hypotheses. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 18*, 972–992.

Engle, R. W., Carullo, J. J., & Collins, K. W. (1991). Individual differences in working memory for comprehension and following directions. *Journal of Educational Research, 84*, 253–262.

Engle, R. W., Tuholski, S. W., Laughlin, J. E., & Conway, A. R. A. (1999). Working memory, short-term memory, and general fluid intelligence: a latent-variable approach. *Journal of Experimental Psychology: General, 128*, 309–331.

Ericsson, K. A., & Kintsch, W. (1995). Long-term working memory. *Psychological Review, 102*, 221–245.

Gardiner, M. F., Fox, A., Knowles, F., & Jeffrey, D. (1996). Learning improved by arts training. *Nature, 381*, 284.

Gathercole, S. E. (1999). Cognitive approaches to the development of short-term memory. *Trends in Cognitive Sciences, 3*, 410–419.

Gobet, F., & Simon, H. A. (1996). Recall of rapidly presented random chess positions is a function of skill. *Psychonomic Bulletin & Review, 3*, 159–163.

Groen, G. J., & Patel, V. L. (1988). The relationship between comprehension and reasoning in medical expertise. In M. T. H. Chi, R. J. Glaser, & M. Farr (Eds.), *The nature of expertise* (pp. 287–310). Hillsdale, NJ: Erlbaum.

Hatano, G., & Osawa, K. (1983). Digit memory of grand experts in abacus-derived mental calculation. *Cognition, 15*, 95–110.

Hatta, T., & Ikeda, K. (1988). Hemispheric specialization of abacus experts in mental calculation: evidence from the results of time-sharing tasks. *Neuropsychologia, 26*, 877–893.

Hegarty, M., Shap, P., & Miyake, A. (2000). Constrains on using the dual-task methodology to specify the degree of central executive involvement in cognitive tasks. *Memory & Cognition, 28*, 376–685.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: individual differences in working memory. *Psychological Review, 99*, 122–149.

Kyllonen, P. C., & Christal, R. E. (1990). Reasoning ability (is little more than) working memory capacity? *Intelligence, 14*, 389–433.

MacDonald, M. C., & Christiansen, M. H. (2002). Reassessing working memory: a comment on Just & Carpenter (1992) and Waters & Caplan (1996). *Psychological Review, 109*, 35–54.

Miyake, A. (2001). Individual differences in working memory: introduction to the special section. *Journal of Experimental Psychology: General, 130*, 163–168.

Olesen, P. J., Westerberg, H., & Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nature Neuroscience, 7*, 75–79.

Palladino, P., & Cornoldi, C. (2004). Working memory performance of Italian students with foreign language learning difficulties. *Learning & Individual Differences, 14*, 137–151.

Patel, A. D., & Peretz, I. (1997). Is music autonomous from language? A neuropsychological appraisal. In I. Deliege, & J. A. Sloboda (Eds.), *Perception and cognition of music* (pp. 191–215). Hove, UK: Erlbaum.

Rauscher, F. H., Shaw, G. L., Levine, L. J., Wright, E. L., Dennis, W. R., & Newcomb, R. L. (1997). Music training causes long-term enhancement of preschool children's spatial–temporal reasoning. *Neurological Research, 19*, 2–8.

Saito, S., & Miyake, A. (2004). On the nature of forgetting and the processing–storage relationship in reading span performance. *Journal of Memory & Language, 50*, 425–443.

Sarriluoma, P. (1989). Chess players' recall of auditorily presented chess positions. *European Journal of Cognitive Psychology, 1*, 309–320.

Schellenberg, E. G. (2004). Music lessons enhance IQ. *Psychological Science, 15*, 511–514.

Schmithorst, V. J., & Holland, S. K. (2004). The effect of musical training on the neural correlates of math processing: a functional magnetic resonance imaging study in humans. *Neuroscience Letters, 354*, 193–196.

Stigler, J. W. (1984). "Mental abacus." The effects of abacus training on Chinese children's mental calculation. *Cognitive Psychology, 16*, 145–176.

Turner, M. L., & Engle, R. W. (1989). Is working memory capacity task dependent? *Journal of Memory & Language, 28*, 127–154.

Wilson, K. M., & Swanson, H. L. (2001). Are mathematics disabilities due to a domain-general or a domain-specific working memory deficit? *Journal of Learning Disabilities, 34*, 237–248.