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THE IMPACT OF ABACUS TRAINING ON WORKING MEMORY AND UNDERLYING NEURAL CORRELATES IN YOUNG ADULTS

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Abstract—Abacus-based mental calculation (AMC) activates the frontoparietal areas largely overlapping with the working memory (WM) network. Given the critical role of WM in cognition, how to improve WM capability has attracted intensive attention in past years. However, it is still unclear whether WM could be enhanced by AMC training. The current research thus explored the impact of AMC training on verbal and visuospatial WM, as well as the underlying neural basis. Participants were randomly assigned to an abacus group and a control group. Their verbal WM was evaluated by digit/letter memory span (DMS/LMS) tests, and visuospatial WM was assessed by a visuospatial *n*-back task. Neural activity during the *n*-back task was examined using functional MRI. Our results showed reliable improvements of both verbal and visuospatial WM in the abacus group after 20-day AMC training but not in the control. In addition, the *n*-back task-induced activations in the right frontoparietal circuitry and left occipitotemporal junction (OTJ) declined as a result of training. Notably, the decreases in activity were positively correlated with performance gains across trained participants. These results suggest AMC training not only improves calculating skills but also have the potential to promote individuals' WM capabilities, which is associated with the functional plasticity of the common neural substrates.

Key words: working memory, training, abacus-based mental calculation, functional MRI, frontoparietal circuitry, occipitotemporal junction.

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Abbreviations: AMC, abacus-based mental calculation; ANOVA, analysis of variance; BA, Brodmann area; BOLD, blood-oxygenation level dependent; DMS, digit memory span; FG, fusiform gyrus; fMRI, functional magnetic resonance imaging; IPL, inferior parietal lobule; LMS, letter memory span; MFG, middle frontal gyrus; MNI, Montreal Neurological Institute; OTJ, occipitotemporal junction; PFC, prefrontal cortex; RT, reaction time; SPL, superior parietal lobule; VSWM, visuospatial working memory; WM, working memory.

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INTRODUCTION

Working memory (WM) refers to a system that is responsible for the active maintenance and manipulation of information for higher order cognition (Baddeley, 1992, 2003; Buschkuehl et al., 2012). It plays a central role in a wide range of cognitive tasks, such as comprehension, planning, problem solving and mathematics (Rasmussen and Bisanz, 2005; Alloway, 2009; Giofrè et al., 2013). Within the educational settings, WM has been shown to predict academic achievement better than measures of intelligence (Alloway and Alloway, 2010). Children with poor WM are often observed to have difficulties in acquiring knowledge and new skills (Martinussen et al., 2005; Alloway, 2009).

Given the importance of WM to general cognitive processing and academic attainment, studies showing that WM can be improved by training started to emerge a few years ago (Klingberg et al., 2005; Chein and Morrison, 2010; Jaeggi et al., 2010; Jaušovec and Jaušovec, 2012), which challenged the established view that WM is fixed. However, the reported effects of training on WM were not consistent, due to variances in the training program, intensity and trained populations. For example, effects induced by explicit training (teaching specific strategies such as rehearsal techniques, chunking and meta-cognitive strategies) were highly material-specific (Ericcson et al., 1980). Klingberg (2010) proposed that implicit, adaptive and extensive training (at least 3 weeks or 8 h) could be critical factors for successful WM training. In addition, the extent of training effects might also be limited by age-related cognitive or neural deficiencies (Shipstead et al., 2012). In two studies conducted by Dahlin et al. (2008a,b), they did find training-induced improvements in the *n*-back performance for young adults but not for older adults. Finally, most WM training programs focus either on increasing WM capacity or specifically on the updating process (see Klingberg, 2010 for a review). Improvements induced by such kind of training are often restricted to task-specific components of WM (Dahlin et al., 2008b; Li et al., 2008). It is suggested that interventions involving both aspects would be more helpful to enhance WM in general (Jaeggi et al., 2008; Klingberg, 2010).

WM interventions that have been developed so far adopt variants of traditional WM paradigms such as the object span task, *n*-back task and delayed recognition task, which may have difficulties in generalizing to the practical use. Therefore, it would be of great importance to explore whether WM could be trained by tasks measuring other cognitive abilities correlated with WM (i.e. via far transfer) and more applicable to our daily life. In a study by Takeuchi et al. (2011), they found that adaptive training of WM using mental calculations improved complex arithmetic ability as well as verbal letter span, accompanied by reduced gray matter volume in the bilateral frontoparietal regions. This indicates that interventions other than WM tasks are promising to promote WM capabilities and affect the underlying neural substrates.

Abacus-based mental calculation (AMC) is a mental arithmetic skill based on manipulating beads on an imaginary abacus (Stigler, 1984; Frank and Barner, 2012). The AMC operation requires the integration of multiple cognitive processes, namely retrieval of relevant principles, temporary storage and updating of intermediate results, and manipulation of the mental abacus (Hanakawa et al., 2003; Hu et al., 2011). These cognitive processes are closely related to the function of WM (Baddeley, 2003). In addition, functional neuroimaging studies on AMC have consistently reported activation of the frontoparietal areas (Hanakawa et al., 2003; Chen et al., 2006; Ku et al., 2012; Tanaka et al., 2012; Du et al., 2013), which largely overlap with the activation patterns induced by WM tasks (Wager and Smith, 2003; Owen et al., 2005). It has been proposed that transfer can occur if the training task engages similar cognitive operations and neural substrates with the outcome task (Dahlin et al., 2008a; Buschkuehl et al., 2012). Considering the relation between AMC and WM both at the cognitive and neural level, it is interesting to explore whether AMC could serve as an effective intervention to promote individuals' WM.

Given that the feature of AMC lies in a visuospatial strategy (Hatano and Osawa, 1983; Stigler, 1984; Hanakawa et al., 2003; Chen et al., 2006; Tanaka et al., 2012), it is possible that AMC training may affect the visuospatial component of WM especially. In terms of neural activity, studies indicate that improved performance induced by WM training is often accompanied by complex changes in the functional activation pattern (Buschkuehl et al., 2012). However, the AMC training effect on visuospatial WM (VSWM) performance and underlying neural activity has not been fully investigated. The current study thus would examine whether AMC training was helpful to promote VSWM, and how VSWM-related cortical activity would be altered by AMC training with a longitudinal design.

Superior verbal WM for digits has been consistently observed in AMC experts (e.g. Hatano and Osawa, 1983; Tanaka et al., 2002). Tanaka et al. (2002) argued that a visuospatial representation of numbers (developed through AMC training) was utilized in digit WM tasks as it might be more efficient to mentally manipulate large numbers using such a representation than a sequentially organized phonological representation. A cross-sectional study by Hu et al. (2011) also observed greater letter memory spans (LMS) in children after AMC training, indicating that the improved verbal WM capacity was not limited to numeral information. Considering these findings and the fact that VSWM and verbal WM share most parts of neural substrates (Owen et al., 2005), AMC may also have an influence on verbal WM.

Our behavioral data revealed reliable improvements of both verbal WM (assessed by a forward memory span test) and VSWM (assessed by a visuospatial *n*-back task) in the abacus group after 20-day AMC training but not in the control group. Meanwhile, the functional magnetic resonance imaging (fMRI) data showed that activations induced by the *n*-back task declined in the right frontoparietal circuitry and the left occipitotemporal junction (OTJ) for the abacus group as a result of training. Notably, the decreases in activity were positively correlated with the task performance gains across trained participants. These findings suggest that AMC training not only improves an individual's calculating skill but also helps to promote the WM capability, which is accompanied by the functional plasticity of their common neural substrates.

EXPERIMENTAL PROCEDURES

Participants

This study was approved by the Research Ethics Review Board of Zhejiang University. All procedures followed were in accordance with the Declaration of Helsinki. Thirty-six undergraduate students were recruited from Zhejiang University and then randomly assigned into two groups, an abacus group and a control group. All participants were right handed with normal or corrected-to-normal vision, and reported no history of psychiatric or neurological disorders. They signed written informed consent before testing and received compensation for their time. One participant from the control group quit the test at the very start of our study, and two other participants from this group did not complete the whole test. Their data were excluded from analyses. As a result, the abacus group consisted of 18 participants (one female, mean age = 21.38, SD = 0.77), and the control group included 15 participants (0 female, mean age = 21.57, SD = 0.96). The two groups were matched by age ($p = 0.53$) and gender ($p = 0.55$). None of the participants had prior experience of abacus or mental abacus calculation.

Training session

Participants of the abacus group were trained together in a classroom by an experienced AMC teacher 90 min per day for successive 20 days (with only one-day break). The participants first learned the principles of abacus manipulation, and manipulated the beads on a physical abacus with both hands to perform arithmetic calculations (only addition and subtraction due to the limited training period) for 2–3 days. An abacus is a simple device consisting of beads and rods, and numbers can be represented by the spatial locations of beads. Within each column of beads, a bead above the horizontal bar (heaven bead) equals to 5 when it is pushed down, and a bead below the bar (earth bead) equals to 1 when pushed up. Fig. 1A illustrates the procedure of solving an addition problem via abacus