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Visuospatial working memory training facilitates visually-aided explicit sequence learning

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ABSTRACT

Finger sequence learning requires visuospatial working memory (WM). However, the dynamics between age, WM training, and motor skill acquisition are unclear. Therefore, we examined how visuospatial WM training improves finger movement sequential accuracy in younger ($n = 26$, 21.1 ± 1.37 years) and older adults ($n = 22$, 70.6 ± 4.01 years). After performing a finger sequence learning exercise and numerical and spatial WM tasks, participants in each age group were randomly assigned to either the experimental (EX) or control (CO) groups. For one hour daily over a 10-day period, the EX group practiced an adaptive *n*-back spatial task while those in the CO group practiced a non-adaptive version. As a result of WM practice, the EX participants increased their accuracy in the spatial *n*-back tasks, while accuracy remained unimproved in the numerical *n*-back tasks. In all groups, reaction times (RT) became shorter in most numerical and spatial *n*-back tasks. The learners in the EX group — but not in the CO group — showed improvements in their retention of finger sequences. The findings support our hypothesis that computerized visuospatial WM training improves finger sequence learning both in younger and in older adults. We discuss the theoretical implications and clinical relevance of this research for motor learning and functional rehabilitation.

Working memory (WM) refers to the temporary storage of information for managing daily functioning and the learning of skills (Baddeley & Hitch, 1974; Bo, Borza, & Seidler, 2009). According to Baddeley (1992), WM is composed of the central executive, the visuospatial sketchpad, and the phonological loop (but see other conceptions of Engle, 2002). The central executive performs executive functions, updating, manipulating, and coordinating information from the visuospatial sketchpad and the phonological loop (Baddeley, 1996). The visuospatial sketchpad is for storage and manipulation of visuospatial information, while the phonological loop processes speech-related information. Executive functions are domain-general, whereas the functions of the visuospatial sketchpad and the phonological loop are domain-specific (Baddeley, 1992, 1996). The importance of WM has been demonstrated in high-level cognitive processes, from reading comprehension to reasoning skills (Daneman & Carpenter, 1980; Kane et al., 2004) and to the acquisition of motor skills (McNay & Willingham, 1998). The present study explores the possibility of utilizing WM training to improve motor sequence learning.

Motor learning requires WM and is critical for daily functioning (McNay & Willingham, 1998). Sufficient learning capability enables learners to meet occupational demands (*e.g.*, operating computers or machines). Compared with younger adults, older adults have reduced WM, which is probably due to reduced inhibitory control (Blair, Vadaga, Shuchat, & Li, 2011). As a result, older adults' WM can accommodate only the shorter chunks of information and it has less ability to encode or retain motor sequence information (Bo et al., 2009; Maryott & Sekuler, 2009). Cognitive and motor aging often result in deficits in motor learning (Cai, Chan, Yan, & Peng, 2014; Ren, Wu, Chan, & Yan, 2013); for example, older adults experience more difficulties than young adults in motion extrapolation, learning inter-manual coordination, and postural control (Piotrowski & Jakobson, 2011; Smolders, Doumas, & Krampe, 2010; Swinnen, Verschueren, & Bogaerts, 1998; Yan, Abernethy, & Li, 2009; Yan & Dick, 2006). For promoting health, an adequate motor learning capacity helps older adults to cope with daily mobility problems. Older adults are prone to diseases that reduce their movement capabilities; to compensate for these deficiencies, older adults have to learn to use aids (*e.g.*, wheelchairs). Taken together, this shows that motor learning capability is especially important in the everyday lives of older adults.

Sequence learning is an important part of motor learning (Clegg, DiGirolamo, & Keele, 1998; Brown, Robertson, & Press, 2009). In sequence learning, we learn the elements of a motor skill, such as key pressing, in a specific order. Thus, successful sequence learning requires an accurate memory both of the motor elements and their temporal

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relationships. In a similar manner to other cognitive tasks, in sequence learning, learners encode and rehearse the information in their WM. After repeated practice attempts, the rehearsed information is consolidated into long-term memory (Ranganath, Cohen, & Brozinsky, 2005). With an improved WM, more motor information (motor chunks or elements) can be rehearsed simultaneously, thereby resulting in the faster and more accurate learning of the entire motor sequence (Bo et al., 2009). Traditionally, motor learning is accomplished by motor practice. The present study examines the possibility of using cognitive training for improving the motor sequence learning that is associated with visuospatial WM (Bo et al., 2009).

WM can be improved through deliberate training. Lövdén, Bäckman, Lindenberger, Schaefer, and Schmiedek (2010) proposed that neural plasticity is reflected by improved task knowledge (more efficient strategies, expertise) and/or increased processing efficiency (better WM, executive control). Plasticity can be achieved through a prolonged deviation of the external demands from the supply of cognitive resources (functional supply). When external demands are greater than the functional supply, adaptation occurs in the cognitive system to narrow the gap. Computerized WM training has recently shown promising benefits, both in increasing memory capacity and improving updating, which can sometimes transfer to non-trained but related tasks (Holmes, Gathercole, & Dunning, 2009; Klingberg, 2010; Klingberg et al., 2005). Klingberg (2010), and Morrison and Chein (2011) have proposed that an effective training program has to be adaptive. This is consistent with the prediction of Lövdén et al.'s (2010), and it was supported by a study that showed that there are greater training-related gains after adaptive WM training (Brehmer, Westerberg, & Bäckman, 2012).

Transfer effects of WM training have been noted (Karbach & Verhaeghen, 2014). A recent meta-analysis has shown a small facilitating effect of *n*-back training on the fluid intelligence (Au et al., 2014). Salminen, Strobach, and Schubert (2012) showed that 14 days of WM training (simultaneous visual and auditory *n*-back tasks) led to improvements in the trained tasks in younger adults. Most importantly, transfer effects to some other executive functions were observed (WM updating, task switching and attentional processing). However, transfer to non-trained domains was not consistently observed, even after controlling individual differences (*e.g.*, the need for cognition, belief in malleability, age; Melby-Lervåg & Hulme, 2013; Sprenger et al., 2013; Xin, Lai, Li, & Maes, 2014). It has been suggested that factors contributing to successful training may include motivation, personality, pre-existing ability, and self-theory of intelligence (Jaeggi, Buschkuehl, Shah, & Jonides, 2014).

The effectiveness of cognitive training can be extended to older adults. Both younger and older adults can benefit from cognitive and WM training to improve everyday functioning (Ren et al., 2013; Willis et al., 2006; Yan, 2000; Yan, Thomas, Stelmach, & Thomas, 2000). Four sessions of verbal WM training (retaining a list of words whilst performing a distracting task) improved performance in the trained task; this improvement persisted at eight-month follow-up in older people (≥75 years); however, no transfer to visuospatial WM and processing speed was detected (Borella, Carretti, Zanoni, Zavagnin, & De Beni, 2013). In another study young–old and old–old people took part in a three-session visuospatial WM training program, in which they had to remember the position of the last dot in each of a series of matrices. Both of the young–old and old–old groups showed improved visuospatial and verbal WMs, which were preserved for at least eight months. Transfer to short-term memory and processing speed were observed only in the young–old participants (Borella et al., 2014). Previous results have shown that training-induced WM improvement and transfer are negatively associated with age (Jaeggi et al., 2014; Zinke et al., 2014).

In our study, an explicit finger-sequence learning task was used to assess learning proficiency. A study showed that, after WM training (remembering words or locations that occurred occasionally while working on a secondary task), there were improvements in reading span (near-transfer) and verbal learning (far-transfer) (Richmond, Morrison, Chein, & Olson, 2011). Thus, it was hypothesized that, in contrast to non-adaptive training, adaptive computerized visuospatial WM training not only facilitates the performance of the trained task, but it also brings about improvement in explicit finger sequence learning, as demonstrated by more accurate finger sequence reproduction that relies on visuospatial WM (Bo et al., 2009). Numerical and spatial *n*-back tasks assess different modalities of WM. We included a numerical *n*-back task as a transfer task to see whether visuospatial WM training can also benefit non-spatial WM in addition to motor sequence learning, which depends on spatial ability. Limited improvements in numerical WM were expected. Because previous studies have shown that training-induced WM improvement and transfer are negatively associated with age (Jaeggi et al., 2014; Zinke et al., 2014), we hypothesized that there should be greater training-related gains in younger adults.

1. Method

1.1. Participants

Twenty-six young adults (YA, $M \pm SD = 21.1 \pm 1.37$ years) and 22 older adults (OA, $M \pm SD = 70.6 \pm 4.01$ years) had normal or corrected-to-normal vision and none reported any confirmed motor or neurological disorders. They had similar educational levels. According to a previous study, experience with computers can mediate the results of computerized memory tests (Laguna & Babcock, 2000); to minimize any possible confounding effects of computer experience, the recruited participants were all frequent computer users. The Mini Mental State Exam (MMSE; Folstein, Folstein, & McHugh, 1975) was used to screen for dementia. Participants answered a set of questions, with answers scoring a total of 0 to 30 marks. No older adults were excluded because they all had MMSE scores ≥24. Participants were all right-handed, as assessed by using the Edinburgh Handedness Inventory (Oldfield, 1971). Written informed consent, approved by the Institutional Review Board, was obtained prior to the experiment. Participants in each age group were randomly assigned to the experimental (EX) or the control (CO) groups. Each participant received a payment of HK$500 after completion of the study. Table 1 shows the demographics of the participants in each group.

1.2. Apparatus and procedure

A standard desktop computer with a 17″ CRT monitor running at 100 Hz was used for presenting stimuli and recording motor responses. Programs for testing and training were programmed in JAVA language. The experiment had three phases: pre-test; training; and post-test (Table 2). Participants performed the numerical *n*-back, spatial *n*-back, and finger sequence learning tasks in the pre- and post-test phases. The order of task administration was randomized across participants. In the training phase, participants in the EX group were given 10 sessions of an adaptive spatial *n*-back task, whereas those in the CO group practiced a non-adaptive task. Each training session lasted for about one hour. Participants practiced the training task each day for 10 consecutive days after the pre-test. Within a week of completing their training, participants performed the post-test, which included

Table 1
Demographics of participants.

	N	Sex (*M*/*F*)	Age	MMSE
Younger adults EX	13	5/8	20.67 (1.03)	29.50 (0.71)
Younger adults CO	13	5/8	21.75 (1.71)	29.40 (0.70)
Older adults EX	12	5/7	70.50 (3.99)	28.90 (1.00)
Older adults CO	10	5/5	70.75 (4.65)	29.10 (1.10)

Note. EX and CO represent experimental and control groups, respectively. Mean age and MMSE are presented. SD is presented in parentheses.