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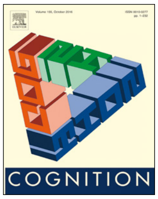

Original Articles

Working memory training and perceptual discrimination training impact overlapping and distinct neurocognitive processes: Evidence from event-related potentials and transfer of training gains

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ABSTRACT

There is emerging evidence that working memory (WM) can potentially be enhanced via targeted training protocols. However, the differential effects of targeted training of WM vs. training of general attentional processes on distinct neurocognitive mechanisms is not well understood. In the present study, we compared adaptive n-back WM training to an adaptive visual search training task that targeted perceptual discrimination, in the absence of demands on WM. The search task was closely matched to the n-back task on difficulty and participant engagement. The training duration for both protocols was 20 sessions over approximately 4 weeks. Before and after training, young adult participants were tested on a battery of cognitive tasks to examine transfer of training gains to untrained tests of WM, processing speed, cognitive control, and fluid intelligence. Event-related brain potential (ERP) measures obtained during a Letter 3-Back task and a Search task were examined to determine the neural processes that were affected by each training protocol. Both groups improved on measures of cognitive control and fluid intelligence at post- compared to pretest. However, n-back training resulted in more pronounced transfer effects to tasks involving WM compared to search training. With respect to ERPs, both groups exhibited enhancement of P3 amplitude following training, but distinct changes in neural responses were also observed for the two training protocols. The search training group exhibited earlier ERP latencies at post- compared to pretest on the Search task, indicating generalized improvement in processing speed. The n-back group exhibited a pronounced enhancement and earlier latency of the N2 ERP component on the Letter 3-back task, following training. Given the theoretical underpinnings of the N2, this finding was interpreted as an enhancement of conflict monitoring and sequential mismatch identification. The findings provide evidence that n-back training enhances distinct neural processes underlying executive aspects of WM.

1. Introduction

Working memory (WM) is generally characterized as the short term maintenance and manipulation of information for the purpose of completing task-specific goals. While its precise structure is not universally agreed upon, a popular view is that there are multiple component processes engaged during WM, including distinct buffers that serve to store different types of sensory information, as well as an overarching central executive system that selectively manipulates information within those stores (aka "supervisory attentional system"; Baddeley & Hitch, 1974; Repovs & Baddeley, 2006). More recently, WM is suggested to be a limited resource system that involves the activation and maintenance of sensory information in distributed cortical regions, with executive control over the information that is maintained in WM exerted primarily via prefrontal cortex (D'Esposito & Postle, 2015). WM is thought to be central to cognition and have a broad relationship with multiple cognitive domains. For example, individual differences in WM functioning have been associated with variation in higher level reasoning and problem solving (i.e., fluid intelligence, Gf; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Conway, Kane, & Engle, 2003;

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Engle, Tuholski, Laughlin, & Conway, 1999; Martinez & Colom, 2009; Redick, Unsworth et al. (2012)).

Given the fact that WM is assumed to be a core aspect of cognition, potential interventions aimed at improving WM have gained considerable interest in recent years. Many protocols involve targeted training of WM that spans several days or weeks. To date there have been mixed findings in the WM training literature, but a number of studies have suggested potential evidence of both "near transfer" and "far transfer" of training gains to other abilities. Near transfer refers to improvement in abilities that reflect largely similar psychological constructs as the training program (e.g., training on one WM task and finding improvement in a different WM task, or on a task of short-term memory). Far transfer refers to improvements on tasks or abilities that are substantially different than those engaged by the training program (e.g., finding improvement in Gf or cognitive control after training in WM). Evidence for near transfer effects after WM training has been observed in several age groups, including young adults (Chein & Morrison, 2010; Dahlin, Stigsdotter Neely, Larsson, Backman, & Nyberg, 2008; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Li et al., 2008), older adults (Borella, Carretti, Riboldi, & De Beni, 2010, 2013; Carretti, Borella, Zavagnin, & de Beni, 2012; Li et al., 2008; Richmond, Morrison, Chein, & Olson, 2011; Zinke et al., 2014), and in normally developing children or adolescents (Alloway, Bibile, & Lau, 2013; Dunning, Holmes, & Gathercole, 2013; Jaeggi, Buschkuehl, Jonides, & Shah, 2011; Roberts et al., 2016; Thorell, Lindqvist, Bergman Nutley, Bohlin, & Klingberg, 2009; Zhao, Wang, Liu, & Zhou, 2011; but see also Mansur-Alves & Flores-Mendoza, 2015; Redick, 2015). Evidence for far transfer also has been reported in a number of studies, most notably to measures of Gf (Jaeggi et al., 2008, 2010; Schmiedeck, Lovden, & Lindenberger, 2010), but also to measures of sustained attention (Klingberg et al., 2005; Klingberg, Forssberg, & Westerberg, 2002; Olesen, Westerberg, & Klingberg, 2004). Additionally, WM training has shown some promise for clinical populations. Transfer of training gains has been demonstrated in stroke patients (Westerberg et al., 2007), patients with Schizophrenia (Wexler, Anderson, Fulbright, & Gore, 2000), Multiple Sclerosis patients (Covey, Shucard, Benedict, Weinstock-Guttman, & Shucard, 2018; Mantynen et al., 2014; Vogt et al., 2009), dyslexics (Shiran & Breznitz, 2011), and children with Attention-Deficit/Hyperactivity Disorder (ADHD; Gibson et al., 2011; Holmes et al., 2010; Klingberg et al., 2002; Klingberg et al., 2005; Mezzacappa & Buckner, 2010; for a contrasting opinion on evidence of transfer of gains in children with ADHD, see Rapport, Orban, Kofler, & Friedman, 2013). Taken as a whole, there are a number of studies that suggest the possibility of near and far transfer of training gains after WM training, in both normal and clinical populations.

Despite the evidence suggesting cognitive benefits following WM training, the overall magnitude of benefits and of training-related effects is still very much in question. Some studies have reported null transfer results (e.g., Chooi & Thompson, 2012; Redick, Shipstead et al., 2012). Recent meta-analyses have suggested that near transfer of training gains are perhaps consistently observed, but far transfer of training gains to Gf measures are minimal (see Au et al., 2014; Bogg & Lasecki, 2015; Schwaighofer, Fischer, & Buhner, 2015; Dougherty, Hamovitz, & Tidwell, 2016; Karbach & Verhaeghen, 2014). There are also persistent methodological issues throughout the literature (for a review of these, see Moreau, Kirk, & Waldie, 2016). For example, many studies use a control group that may not adequately control for placebo/motivational effects, because the control protocol is considerably easier and less engaging than the WM training protocol it is being compared to. Other studies use a no-intervention control group (no-contact control), and many studies have no control group (for reviews see Boot, Simons, Stothart, & Stutts, 2013; Green & Bavelier, 2008; Morrison & Chein, 2011; Shipstead, Redick, & Engle, 2012).

Aside from the methodological concerns and mixed findings, the specific factors that drive training and transfer effects are still not well understood. Some training methods have used a "kitchen-sink" approach (Morrison & Chein, 2011), in which training consists of a number of training tasks that reflect related or overlapping constructs. This method provides variation in the training material and may train multiple aspects of WM and other cognitive domains. From an applications standpoint, this approach could be ideal; on the other hand, this approach does not lend itself well to strict experimental control, which would allow for more accurate interpretation of the specific mechanisms of transfer (Jaeggi, Buschkuehl, Jonides, & Shah, 2012).

Other studies have used a single task to train WM. In particular, the n-back paradigm has emerged as a widely utilized task for the purpose of training WM (see for example, Jaeggi et al., 2008, 2010, 2011). During the n-back task, participants must determine whether a presented stimulus matches or does not match a stimulus that was presented *n* trials back. A major advantage of using the n-back task as a training paradigm is that the level of *n* can be parametrically modified to place differential demands on WM. For example, a 1-back task places relatively minimal demand on WM; whereas a 3-back task places relatively high demand on WM. The difficulty of the n-back task can therefore be adaptively altered during training in order to consistently challenge the participant (as in Jaeggi et al., 2008), which presumably maximizes training gains. An experimental design using a single training task approach, such as the n-back – as opposed to a "kitchen-sink" approach – can potentially provide greater specificity for the domains targeted by training. The use of a single training task can also enable better control-task design. The design of the control/comparison task is key for determining the relative strength of transfer effects and for addressing specific hypotheses about the mechanisms targeted by a given WM training protocol.

Functional magnetic resonance imaging (fMRI) studies that have examined neural changes associated with WM training have revealed some of the potential neurocognitive mechanisms that may underlie training and transfer effects. These studies have generally found that the putative brain regions involved in WM are affected by training, including changes in the activity of prefrontal cortical regions and connectivity in the frontal-parietal network (for a review, see Constantinidis & Klingberg, 2016). However, most neuroimaging studies have generally not included control/comparison training tasks that placed similar demands on participants as the WM training task(s), and a number of these studies used no-contact controls or no control group. Recent work by Thompson, Waskom, and Gabrieli (2016) was one of the first fMRI studies to include a control task that placed demands on participants that were similar to the WM training task. In their study, one group trained on a dual n-back task, another group trained on a demanding visuospatial attention task, and a third group served as no-contact controls. They found that individuals that trained on the dual n-back task had distinct reductions in frontal-parietal network activity, in comparison to the control groups (including the group that did demanding visuospatial training).

While the identification of regions and pathways that are affected by WM training is critically important, the types of neuroimaging studies noted above (e.g., fMRI) may not reveal the full extent of the effects of WM training on neurocognitive processes – particularly those occurring at different stages of information processing that may be modulated dynamically over millisecond time-periods. Electrophysiological measures of information processing in the brain, such as the Event-Related Potential (ERP), which is derived from ongoing electroencephalographic (EEG) activity, can provide distinct, functionally dissociable indices of dynamic perceptual and cognitive processes that occur during WM. Components of the ERP waveform offer unique insight into the brain resources allocated to different types of brain processes. Earlier occurring, exogenously driven components such as the P1, N1, and P2 (occurring at approximately 100–200 m post-stimulus) are thought to reflect processing of the physical parameters of the stimulus, and, therefore, can offer insight into attentional demands during initial sensory input (for a review, see Key, Dove, & Maguire, 2005). Later occurring, endogenously driven peaks such as N2 (negative occurring