

Gaining control: Executive training and far transfer of the ability to resolve interference

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Abstract

A core assumption of cognitive brain imaging is that tasks that activate a common brain region share an underlying psychological component. We leveraged this assumption to develop a training regimen and a set of transfer tasks to examine the trainability of a putative executive control process: interference resolution. Training and transfer tasks were selected based on functional brain imaging data documenting overlapping sites of activation in prefrontal cortex. Eight days of training on high interference versions of three different working memory tasks increased the efficiency with which proactive interference was resolved on those particular tasks compared to low interference training. An improved ability to interference resolution was also transferred to different and relatively unpracticed working memory, semantic memory and episodic memory tasks. These results demonstrate that cognitive neuroimaging can guide the development of a process-specific training protocol that can improve a fundamental component of executive control.

Proactive interference is a major source of memory errors. For example, most drivers can relate to the following scenario: While searching for your parked car, you find yourself walking toward the spot where you parked yesterday or the day before, rather than where you parked today. To avoid such errors, we typically slow down, and employ deliberate strategies in an effort to resolve this interference from prior experience, and find *today's* parking spot. That is, we invoke “cognitive control.” Current theories consider cognitive control to fall under the rubric of central executive functions mediated predominantly by regions of prefrontal cortex (e.g. Braver & Barch, 2006; Miller & Cohen, 2001). This report examines whether the control needed to resolve interference can improve with intensive practice, and whether any training benefits can be transferred to relatively unpracticed, novel tasks.

In addition to several reports of successful training on attention tasks (Green & Bavelier, 2003), dual tasking (Oberauer & Kliegl, 2004; Schumacher et al., 2001), and working memory maintenance (Olesen, Westerberg, & Klingberg, 2004), neural correlates of improved performance (Kelly & Garavan, 2005; Rainer & Miller, 2000) and increases in neural efficiency have also been documented (Sayala, Sala, & Courtney, 2006). However, performance improvements may be modest in some cases (e.g., Olesen et al., 2004) and nonexistent in others (Sayala et al, 2006). Furthermore, demonstrations that benefits can be transferred to new materials or to new tasks are limited, thereby limiting current knowledge of the principles underlying transfer. (Ericsson & Kintsch, 1995; Moore, Cohen, & Ranganath, 2006). Here we report evidence indicating the ability to resolve proactive interference improves with training, and that this improved ability to

resolve interference can be applied to new materials and transferred to new tasks. We also propose a testable hypothesis about the neurocognitive bases of successful transfer.

Proactive interference in working memory has been examined in numerous behavioral and neuroimaging investigations using the “recent-probes” task in which participants must reject a probe that was a member of one or two immediately prior memory sets, but is not a member of the current set (e.g., Badre & Wagner, 2005; D'Esposito, Postle, Jonides, & Smith, 1999; Jonides, Smith, Marschuetz, Koeppe, & Reuter-Lorenz, 1998; Nelson, Reuter-Lorenz, Sylvester, Jonides, & Smith, 2003; Persson, Welsh, Jonides, & Reuter-Lorenz, 2007). Although there is debate about the precise mechanisms that resolve the interference in this task (see Jonides & Nee, 2006), the left inferior frontal gyrus (IFG), in the territory of Brodmann's area 45 and the 44 border, is consistently implicated as the critical neural substrate underlying this process.

One candidate mechanism that can account for a variety of relevant data and that builds on basic principles of selective processing shown to operate on perceptual representations is *biased competition* in which contextually relevant mnemonic representations are weighted most heavily, and thereby selected in favor of competitors (Kan & Thompson-Schill, 2004). Left IFG may provide the substrate for the biasing mechanism that resolves interferences among candidate representations (Jonides & Nee, 2006). An appeal of this potential mechanism is that it can plausibly account for interference resolution abilities in tasks other than the recent probes task that also activate left IFG. For example, left IFG activation is reliable in high selection conditions of the verb generation task, in which a noun stimulus, such as ball, evokes many verb associates (i.e., catch, throw, bounce) from which only one response must be chosen (Persson et al.,

2004; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). Within-subject data from our lab has documented that high interference conditions in the recent probes task and verb generation activate overlapping regions in the left IFG (Persson, Nelson, Jonides, & Reuter-Lorenz, 2006). Likewise, an episodic memory task that uses a paired-associate procedure to produce proactive interference also activates left IFG (Henson, Shallice, Josephs, & Dolan, 2002) in the high interference condition. A biased competition process, in which left IFG provides a biasing signal to select the contextually appropriate representation could conceivably account for the interference resolution demand that appears to recruit left IFG in these working memory, semantic memory and episodic memory tasks.

The current investigation leveraged the neuroimaging evidence for the co-localization of this specific control process, interference resolution, across a variety of tasks to test the possibility of training interactions between these tasks. We hypothesized that tasks that engage overlapping brain regions should be susceptible to process-specific transfer that could enhance or reduce performance depending in part on the training regimen. In previous work we have demonstrated process-specific interactions by demonstrating within-session fatigue effects between a subset of these tasks (Persson et al., 2007). In particular, we demonstrated that 30 minutes of intensive performance of high interference versions of the recent probes task produced a process-specific reduction in the ability to resolve interference on verb generation and episodic memory tasks, performed immediately afterward. The training protocols we adopt in the present study in which practice sessions occur daily, and are distributed across a two-week period (Figure 1), are designed to produce performance benefits, and thus positive transfer from

practiced to unpracticed tasks. Note that we do not expect this training to produce generalized improvement in memory performance. The high-interference training regimen is intended to improve the efficiency of a specific executive process. Therefore, unpracticed tasks that engage this process are expected to show transfer effects whereas tasks that do not engage this process will not show transfer.

Four different tasks were used in the current study, and by varying the stimulus materials six versions of these tasks were created. Three of these were used as training tasks, item-recognition with letters, item recognition with faces, and a 3-back task using words. The three transfer tasks were verb generation, paired associate learning, and item recognition with words. Each of these tasks can be rendered in high and low interference versions, and all high interference versions have been associated with activation in proximal if not overlapping sites in left IFG.

The experimental group practiced versions of the working memory tasks that involved high demands on interference resolution. There were two control groups. Control group 1 practiced the same working memory tasks as the experimental group but with minimal interference. A second control group performed task variants with minimal interference and with minimal memory requirements. For all groups, transfer was assessed by comparing interference resolution abilities after the training period to pre-training baselines.

Materials and methods

Participants

Forty-eight young adult (24 male; age range:18-30) native English speakers with normal or corrected to normal vision, were recruited from the University of Michigan community through posted advertisements. Participants gave informed consent and were paid \$10 per hour, totaling \$100 for the entire study. They were pseudo-randomly assigned in equal numbers to one of three groups (Fig. 1): the high interference training group, low interference control group 1, and low memory/low interference control group 2. This investigation was approved by the University of Michigan Institutional Review Board.

Tasks and stimuli

Experimentation occurred in a dimly lit, sound attenuated room. Stimuli were presented on a 15-inch monitor, at a 50 cm viewing distance. E-PRIME software was used (Psychology Software Tools, Pittsburgh). For all tasks, subjects had a short practice block before data collection began. Subjects were not informed about the interference manipulations for either the training or transfer tasks.

Testing procedure

Subjects participated in a total of 10 sessions across a two-week period. The transfer tasks described below were performed on the first and last testing day to obtain pre and post training measures of interference resolution performance. On training days 2-9 subjects performed approximately 30 minutes of the testing protocol designated for their group (high interference training, control group 1, control group 2).

Training tasks

Variants of three basic tasks were used in each of the eight training sessions. Two were item-recognition working memory tasks using faces and letters as stimuli. The letters used were 19 consonants, excepting l and y. The set of face stimuli consisted of 20 digitized gray-scale portraits of ordinary people (50% males; 50% females). The third task was an N-back task for which 72 concrete 4-8 letter nouns were selected from the MRC Psycholinguistic Database (http://www.psy.uwa.edu.au/mrcdatabase/uwa_mrc.htm) using the following criteria: Kucera and Francis written frequency: 10-100; familiarity rating 350-700; concreteness rating: 100-380; imagability rating: 350-700. None of the words appeared in any of the other tasks.

Subjects performed all three tasks in separate counterbalanced blocks on each training day. Item-recognition was performed in three 48-trial blocks with a one-minute rest period between blocks, yielding a total of 154 item-recognition trials with faces, and with letters, lasting approximately 18 minutes for each task. Each trial began with a central fixation cross and four items arranged in a square configuration for 1500 ms. After a 3000 ms delay a single probe appeared for 1500 ms. On 50% of the trials, the probe was a member of the current target set, and on 50% of the trials it was not. Subjects responded “yes” for a match with their right index finger, or “no” for a mismatch, with their right middle finger. The ITI was 1500 ms and no more than 2 consecutive trials required the same response.

In the non-recent probes version of these tasks, negative probes were neither members of the current target set nor the target set of the previous two trials. In the recent-probes version, only one third of the negative probes were non-recent, whereas the other two thirds were recent in that they had appeared in the target set of the previous

trial or the previous two trials. Positive probes were non-overlapping with targets on the previous two trials.

The *high interference* training group performed the recent probes versions with faces and words. *Control group 1* performed item-recognition without recent probes. *Control group 2* performed a non-recent probes, minimal memory version of each task, in where each memory set consisted of 4 identical, and subjects judged whether or not the probe matched the set.

In the N-back task, a series of 96 words appeared at a 2s rate (6 ½ minutes total). Subjects indicated pressed the mouse button as quickly and accurately as possible when a word matched the one presented three words earlier. Half of the words matched the three-back item, and half did not. The high interference version included a critical distinction among the non-target trials: 3-back trials were intermixed with 2-back, 4-back, and 5-back trials which increased the familiarity from recent words (and hence increased demands for interference resolution). These non-target words are classified as lures (comprising 50% of trials), and all other non-target words are classified as non-lures (comprising 25% of task trials). For control group 1, no lures were presented and words were either targets (presented 3 words previously) or non-lures (not previously presented). Control group 2 performed a 1-back task without lures which required simply indicating whether a word was repeated or not.

Transfer tasks

The three transfer tasks included a high interference and a low interference condition thereby permitting the assessment of interference resolution efficiency before and after

training: paired-associates task, an item-recognition task, and verb generation. The same transfer tasks were used for each training group.

Paired associates were formed using the three most frequent associates for 64 common nouns from the Edinburgh Associative Thesaurus (<http://www.psych.rl.ac.uk/>). Each subject completed four blocks of 8 word-associate sets before and after training. Each block consisted of a study phase and a test phase. During the study phase, a cue word and an associate were displayed simultaneously for 3s, with a fixation cross presented during the inter-stimulus interval (ITI). Each cue word appeared three times. For non-interference trials, the cue-associate pairings stayed constant. In high interference trials, cue words were re-paired with different associates (e.g. QUEEN – KING; QUEEN – BEE; QUEEN – CROWN), and others were repeated with the same associate. Constant-pair and re-paired trials were randomized and counterbalanced across subjects. Each word-associate set included 4 re-paired (high interference) and 4 repeated (low interference) trials. During the test phase, cue words appeared in a random order for 4s. Subjects were instructed to retrieve and report the most recently studied associate of that cue, and to say “pass” if they could not remember it. Response times were recorded using a voice key, and verbal responses were digitized, subsequently transcribed and scored for accuracy.

For the item-recognition task, 20 concrete four-letter nouns were used (Kucera and Francis written frequency: 30-100; familiarity rating 400-700). None of the words appeared in any of the other tasks. Using the same timing and task parameters described for the training versions of the item-recognition tasks, all subjects performed 3 blocks that included recent-negative and non-recent negative probes.

For the verb generate task, participants were asked to generate silently a verb in response to a visually presented noun. The nouns were obtained from Thompson-Schill et al. (1997) and we refer to this paper for a full description of word selection and evaluation. The subjects were instructed to press the left mouse button when they had generated a verb. The nouns appeared for 3400 ms each and button responses were recorded during the presentation of the noun. The high selection condition (MANY) used nouns with several appropriate associated responses (e.g., BALL – THROW, KICK, BOUNCE) but which lacked a clear dominant response. In the low selection condition (FEW), nouns had one dominant response, or only a few associated responses (e.g., SCISSORS – CUT). Sixty-four nouns were presented in total; 32 were presented before and 32 were presented after the training phase. Each of the 32-item lists included 16 high and 16 low selection items presented in a random order. Participants were not informed of the high/low selection manipulation. Although no overt responses were made in this version of the task, previous data from our lab using a voice key show that the interference effect is similar for overt and covert responses (paired sample t-test; $t(14)=1.92$, n.s; see also Persson et al., 2007, for equivalent negative transfer effects) and that subjects are generating verbs covertly in correspondence to task instructions.

Results

For all analyses, medians were used to minimize the effect of extreme values and average response time was calculated for correct responses only.

Training tasks

To verify the effectiveness of the interference manipulation in item-recognition (faces and letters), we examined the interference effects for the HIGH training group on training day 1. Paired sample t-tests indicated that subjects were slower to respond “no” to recent probes compared to nonrecent probes ($t(15)=4.91, P<.001$) for letters, and for faces ($t(15)=6.31, P<.001$). Because subjects only responded to targets in the 3-back task, no within-group measure of interference was available for this task.

To measure changes in the interference effect across the training period we calculated an interference resolution (IR) score for each session by subtracting each subject’s median RT for non-recent negatives from the median RT for recent negatives (Fig. 2). In the item-recognition task with letters the interference effect was reduced with training ($F(7)=2.28, P<.05$; Figure 2A), and a trend for reduced interference effects was found for item-recognition with faces ($F(7)=1.67, P=.12$; Figure 2B). Comparing the average training effects from the first half of training (1-4) with the second half (5-8), however, resulted in a significant training effect for both task conditions (letters: $F(1)=5.69, P<.05$; faces: $F(1)=5.13, P<.05$). Also, by the final training session the interference scores were not statistically different from 0 (letters: $t(15)=.422, P=.671$; faces: $t(15)=.367, P=.719$).

Transfer tasks

The primary scores for each of the tasks and trial types are presented in Table 1. Pre-training and post training IR-scores for accuracy and for RT were calculated for each transfer task. Preliminary analyses indicated that neither RT nor accuracy for the two control groups differed from one another on either pre or post measures of interference ($F<1$ for each of the three tasks using group by time ANOVAs), or any of the primary

measures before or after training ($F < 1$ for all measures using one-way ANOVA) and we therefore collapsed the data across the two groups. Figure 3 clearly illustrates that the high interference training group shows less post training interference on RT than controls on each of the three tasks. Separate analyses of covariance (ANCOVA) on the post-training IR-scores (using the pre-training scores as covariates) for each of the three tasks indicate that the difference between the training and control group was significant for each of the three transfer tasks: verb generation: $F(1)=7.32, P < .01$; item-recognition: $F(1)=6.18, P < .05$; and paired associate learning: $F(1)=4.35, P < .05$. These results indicate a significant reduction in the magnitude of interference that was specific for the group who trained for two weeks on the high interference tasks. Moreover, an ANOVA performed on only the non-interference RTs for each task indicated that improvement from pre to post training did not differ between groups ($F < 1$ on all trial types), indicating training differentially influenced interference rather than non-interference processes. Finally, accuracy was uniformly high (greater than 88%) and did not differ reliably between tasks, groups or testing sessions.

Interactions between training and transfer performance

In order to examine the relationship between successful training and subsequent transfer effects, we used regression analyses to identify, for each subject, the slope (i.e. rate of change) of IR-scores across the training sessions. Beta values (i.e. the slope of the regression line) provided a training index, such that larger betas reflect increased performance (lower IR-scores) with training. Transfer scores were derived by subtracting the post-IR-scores from the pre-training IR-scores, and then correlated with beta-scores.

This analysis indicates whether larger training benefits on the training tasks are associated with greater transfer effects. Based on these analyses we found that improved performance (reduced IR-scores) on the item-recognition tasks with faces was positively correlated with a positive transfer effect for the item-recognition with words ($r=.528$, $P<.05$; uncorrected for multiple correlations).

Discussion

Eight days of one-hour practice improved performance on working memory tasks with high levels of proactive interference and significantly improved the ability to resolve interference on relatively unpracticed tests of working memory, semantic memory, and episodic memory.

Several general conclusions can be drawn from these results. First, executive control is plastic and adaptive and can be improved by training. Training on tasks with high interference reduced interference across the training sessions. We infer that this reduction results from increased efficiency of the interference resolution process. Second, the ability to resolve interference improved not only for the training tasks themselves, but also for the transfer tasks, indicating that training was not task-specific and that more efficient executive skills can be utilized in new task contexts.

In contrast with previous studies reporting only moderate training-related improvements in working memory, we found proactive interference to be negligible by the eight training session, indicating the plasticity of the interference resolution process. The present results suggest that training regimens aimed at improving executive control processes may be more fruitful interventions. Note also that while the greatest

improvement appears between training days 1 and 2 training benefits were also evident in the final training sessions. This pattern argues for the potential benefits of extended training periods for achieving optimal levels of performance.

A long-standing issue in cognitive training is the extent to which the benefit of training generalizes to different stimuli and tasks (e.g. Kramer & Willis, 2003). The transfer effects we report are between similar tasks using different materials (i.e., item recognition with faces/letters and item recognition with words) and between different tasks (item-recognition/N-back and verb generation/paired associates). The assumed commonality between these tasks was the demand for interference resolution, an assumption that was based in part on neurocognitive evidence for a shared substrate mediated by left inferior prefrontal cortex. We might hypothesize then that in the domain of executive functions shared neural circuitry is a necessary condition for training effects to be transferred from one task to another.

Although the distinction between near and far is open to debate, we view the present results as evidence for far transfer because the memory demands of verb generation and paired associate learning differ markedly from each other and from item recognition. The present observation of functional interactions between working memory, semantic memory, and episodic memory domains does however converge with the growing body of evidence indicating that these memory “systems” share common executive components (e.g., Duncan & Owen, 2000; Marklund et al., 2007; Nyberg et al., 2003). The evidence that interference resolution training can generalize across cognitive domains is potentially quite important because it suggests that process-specific training regimens may be especially effective for demonstrating transfer to novel tasks.

Although the exact properties of the mechanism(s) recruited and trained in the present high interference conditions remain to be specified, a biased competition process (Kan & Thompson-Schill, 2004) could conceivably mediate selection in the variety of domains represented in the training and transfer tasks we employed. Importantly, a biased competition process that operates on representations that are active in working memory could be utilized across memory and task domains. Thus, the control processes implicated here could potentially be involved in a variety of tasks that extends beyond those used in the present study. On this note, it is possible that interference training may transfer to other cognitive domains, and even to everyday activities.

Although our findings provide important new insights into the mechanisms that underlie training and transfer of executive components, a number of questions remain unanswered. First, even though we demonstrated successful training and transfer of a control process, we have yet to determine the extent to which such skills can be retained over days, weeks, or months. Second, it is unknown whether the training effects we demonstrate would transfer to other interference tasks or to everyday activities with high interference between competing stimuli. Also, because all transfer tasks involved verbal stimuli, it could be argued that transfer effects may not translate to tasks involving other types of stimuli. However, executive functions are widely viewed as amodal processes which argues for their potential involvement across material types and stimulus modalities. Finally, because several tasks were used for the training sessions, we cannot tease apart the contributions of each task, leaving questions unanswered about whether training influenced the same executive process and the relative effectiveness of each training task.

We believe our results constitute an important first step in evaluating the efficiency and transfer effects derived from theoretical and neurocognitive models of executive functioning. The present results raise the possibility that fundamental executive functions are amenable to training and because these are abilities purported to underlie performance across a wide range of cognitively demanding tasks, training effects can be expected across cognitive domains. Understanding the dynamics of executive functions is of great interest, not only because of its role in higher level cognition (Duncan & Owen, 2000) and cognitive declines with age (Schretlen et al., 2000; West, 1996), but also due to the wide array of disorders in which deficits in executive processing deficits have been implicated (e.g. McEvoy, Rogers, & Pennington, 1993; Morice & Delahunty, 1996). Further research is required, however, to demonstrate whether executive process training can improve performance in more practical, everyday situations and particularly whether the benefit of training can be maintained over time. Nevertheless, our work demonstrates the utility of neuroimaging evidence for identifying tasks with likely functional overlap, to develop process-specific training protocols.

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Figure captions

Fig. 1 Schematic depiction of the basic experimental design.

Fig. 2 Mean interference resolution scores for the high interference training group across training sessions for item recognition with letters and faces respectively. Error bars show standard error of the mean (SEM)

Fig. 3 Mean interference resolution scores (reaction time in ms), as a function of group (high interference training versus controls), and time (before/after training) on the transfer tasks; A = Verb generation task; B = episodic memory task; C = Sternberg working memory task. Error bars show standard error of the mean (SEM).





