Enhancing visual attention and working memory with a Web-based cognitive training program

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Prior research has revealed that cognitive abilities are adaptable and improvable via targeted cognitive training methods; however, use of these methods is limited outside of research and clinical settings. Our objective was to investigate the efficacy of a web-based cognitive training program in enhancing the attention and memory of healthy adults. Volunteer participants (n=23, mean age=54) were given initial cognitive assessments, a training intervention or waitlist control, and then cognitive assessments again following the intervention period. Both training and testing were conducted online at each participant's home. Trained subjects completed 20-minute online cognitive exercise sessions once daily for 5 weeks, while control participants received no training during this period. The training program consisted of 4 exercises designed to enhance the brain's ability to dynamically allocate resources to visual attention and working memory. Results and compliance data were captured online automatically. The trained group improved significantly more than the control group on untrained measures of visual attention and working memory. Training reduced the average error in localization of transient and non-central visual stimuli while also improving performance on measures of spatial working memory. There were no significant performance shifts in the control group. Results indicate that improving cognitive abilities such as working memory and visual attention is possible via the use of web-based applications outside of a clinical setting.

INTRODUCTION

Until relatively recently, the conventional wisdom in the neuroscience and cognitive science communities held that cognitive capacity was essentially fixed after a relatively brief critical period of early development. In this view, little could be done to enhance cognition during the normal course of adult development. However, we now know that the adult brain – rather than being a fixed-capacity machine – is an adaptable, plastic organ capable of continual improvement in efficiency and effectiveness when exposed to the proper experiences (e.g., Buschkuehl and Jaeggi, 2010). It has been demonstrated that the human brain's inherent plasticity allows for the improvement, via targeted training exercises, of cognitive skills involving aspects of speed of processing (Ball *et al.*, 2002), attention (Green and Bavelier, 2003; Bherer *et al.*, 2008; Smith *et al.*, 2009), working memory (Wykes *et al.*, 2002; Valenzuela *et al.*, 2003; Hempel *et al.*, 2004; Olesen *et al.*, 2004; Westerberg *et al.*, 2007; Schmiedek *et al.*, 2010; Klingberg, 2010) and fluid intelligence (Jaeggi *et al.*, 2008).

The effects of cognitive training have been shown to extend beyond the context of cognitive performance testing. Demonstrated benefits of cognitive training include reduced age-related losses in the ability to carry out the activities of daily living (Willis *et al.*, 2006), reduced risk of motor vehicle accidents (Ball *et al.*, 2010), reduced predicted healthcare costs (Wolinsky *et al.*, 2009), and improvements in academic performance (Merzenich *et al.*, 1996; Holmes *et al.*, 2009).

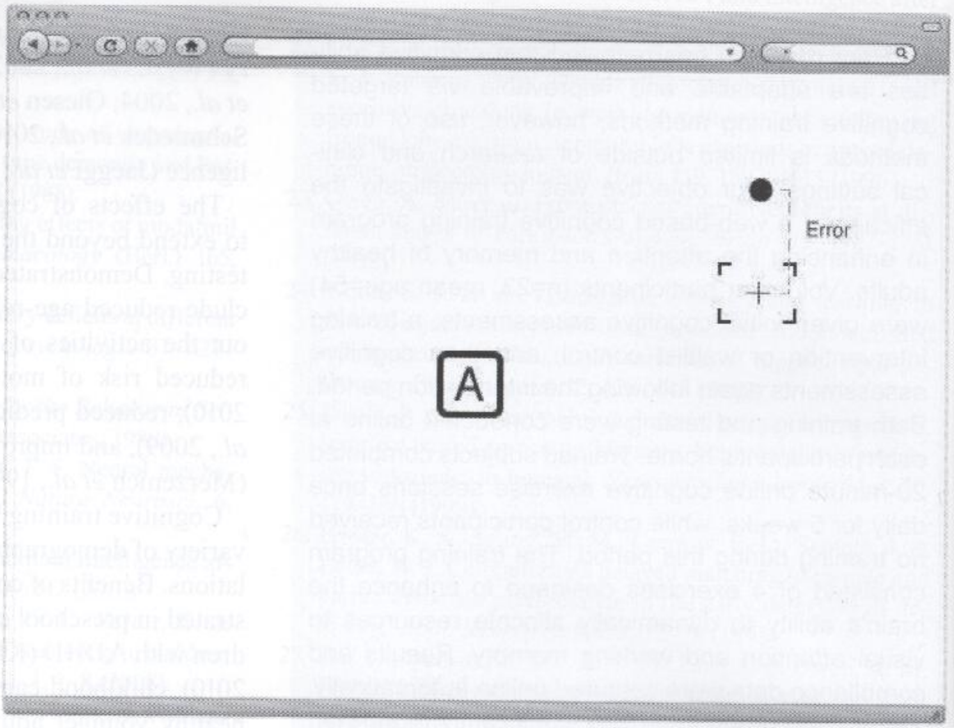
Cognitive training has been shown to be effective in a variety of demographically and clinically defined populations. Benefits of cognitive training have been demonstrated in preschool children (Thorell *et al.*, 2009), children with ADHD (Klingberg *et al.*, 2002; Holmes *et al.*, 2010), childhood cancer survivors (Kesler *et al.*, 2011), healthy younger adults (Jaeggi *et al.*, 2008), adult patients with schizophrenia (Fisher, *et al.*, 2009), healthy older adults (Ball *et al.*, 2002; Schmiedek *et al.*, 2010), and patients suffering from mild cognitive impairment (MCI) (Finn and McDonald, 2010).

A notable gap in the existing literature on cognitive training concerns normal, healthy middle-aged adults. Cognitive deficits typically increase with age (Zelinski and Burnight, 1997; Finkel *et al.*, 2003; Sorel and Pennequin, 2008; Gazzaley *et al.*, 2008; Thorvaldsson *et al.*, 2008), and are of growing concern given the large population of baby boomers currently reaching retirement. Increasingly, the benefits of cognitive reserve are being appreciated (Verghese *et al.*, 2003). The ultimate outcomes of the cognitive aging process are mediated by experiences across the lifespan, particularly education and other cognitively stimulating activities (Hertzog *et al.*, 2008). If cognitive training programs can be shown to enhance cognition in normal, healthy middle-aged adults, this presents the possibility of greatly improving long-term outcomes in cognitive aging.

In addition, it is of interest to many adults to improve their cognitive performance for reasons that extend beyond improved outcomes in aging. Many seek to simply augment cognitive ability for the benefits this can yield in everyday life, such as improved performance at work or school.

This investigation seeks to evaluate the potential for a cognitive training program to benefit normal, healthy adults who are neither very old nor very young. In order for this training to be practical in the broad population, outside clinics and research laboratories, the training must be effective, engaging, and accessible. For these reasons a cognitive training program – referred to as Lumosity – has been implemented as an easy-to-use Internet-based system (www.lumosity.com) that incorporates engaging gaming characteristics into the exercises. Lumosity includes a variety of training exercises (36 at the time of writing this manuscript) targeting distinct cognitive domains including attention, memory, speed of processing, cognitive flexibility, and problem solving. The training regimen studied in this report includes a selection of four exercises from this training system specifically designed to enhance the brain's ability to dynamically allocate visual attention and working memory.

Figure 1: *Divided Visual Attention Assessment.* In this task, the participant responded by indicating the identity of a central target and the location of an eccentrically presented target. The dependent variable of interest was localization error (in pixels) for the eccentric target.



The ability to accurately and robustly process and mentally manipulate complex visual information is critical for a diverse array of tasks such as navigating the environment, reading, and remembering faces. These fundamental abilities are important in the everyday lives of normal, healthy adults as they engage in work, school, leisure and social activities. For this reason, improving these abilities is potentially of interest to a wide audience.

It is clear that not every seemingly cognitively stimulating activity is effective at improving cognitive abilities. For example, Owen *et al.* (2010) demonstrated a failed attempt to provide online cognitive training to a broad audience. For this reason, great care was taken to develop exercises that effectively engage and improve the targeted cognitive abilities – in this case the dynamic allocation of visual attention and working memory. These methods are described in greater detail below, in Kesler, *et al.* (2011) and in Hardy and Scanlon (2010).

Previous studies have shown that training with the exercises on the Lumosity website can enhance cognitive function in select patient populations. These training-related enhancements include improvements in visual attention in patients with MCI (Finn and MacDonald, 2010) and improvements in working memory and attention in survivors of childhood cancer (Kesler, *et al.*, 2011). Kesler, *et al.* (2011) also found that Lumosity training led to enhanced activation of the prefrontal cortex in trained participants.

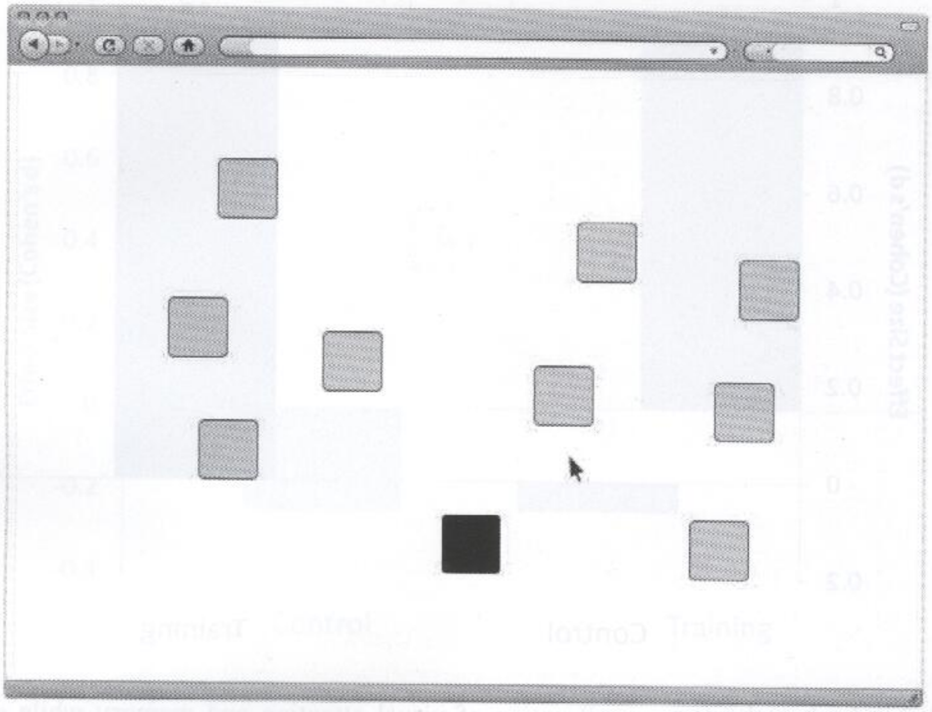
It is hypothesized that training intensively on web-based exercises designed to enhance the brain's ability to dynamically allocate resources to visual attention and working memory will transfer to improvements on untrained tasks that measure the fundamental operations of these cognitive domains in normal, healthy adults. Volunteer participants received an initial battery of cognitive assessments, training with Lumosity or a wait-list control, and then the cognitive assessment battery again following the intervention period. The assessment battery was constructed to measure transfer of training from the exercises to the fundamental underlying abilities of visual attention and working memory.

METHODS

Volunteers/Participants

Volunteers were recruited by email and word of mouth from locations across the United States. All participants

Figure 2: *Spatial Working Memory Assessments.* Two versions of the spatial working memory assessment were used. In the Forward Spatial Working Memory task, the participant watched as several squares were highlighted by changing from light blue to dark blue one at a time. The participant's task was to click on the squares in the order they were highlighted. In the Reverse Spatial Working Memory task, the participant needed to click on the squares in the opposite order to the way they were highlighted.



were mentally and physically healthy as determined via a short email questionnaire. Participants were compensated with continued access to the training program after the experiment concluded.

The trained group consisted of 14 participants (8 female, mean age = 57), while the control group consisted of 9 participants (3 female, mean age = 50). One control participant failed to complete the second assessment battery and was excluded from this analysis.

Design

Participants were randomly assigned to either the training intervention or a wait-list control group. Training participants completed a daily program of exercises delivered via the Internet from a secure server to a personal computer at home. Subjects trained an average of 29.2 sessions, each of which was completed within approximately 20 minutes. The intervention period lasted 5 weeks.

Both training and control participants completed a battery of cognitive assessments before and after intervention. The assessment tasks were distinct from the training tasks and were designed to specifically detect potential transfer of performance gains made during the training exercises. Each was completed in one session from home on a web browser communicating with the study's server.

TRAINING PROGRAM

The training program was developed by Lumos Labs and consisted of a set of 4 exercises designed to specifically train visual attention and working memory. Subjects completed these exercises through a web browser on the website www.lumosity.com.

Key components of the program included 1) targeted training aimed at specific neural mechanisms; 2) adaptive difficulty changes to consistently challenge each individual and enhance progression; 3) game-like features and motivators such as scoring and unlocking of levels to improve motivation and to reward successful performance; 4) simple self-instruction without the need for human administration; and 5) a web-based platform ensuring ease and ubiquity of access.

The 4 exercises included in the training protocol for this study are described below. Further detail is provided in Kesler, *et al.* (2011) and Hardy and Scanlon (2010).

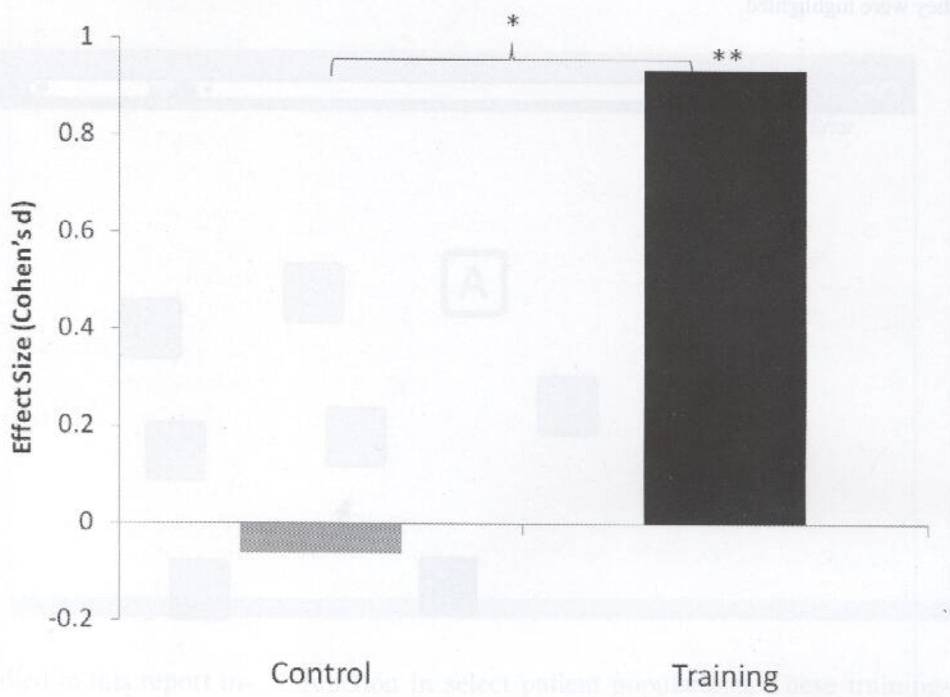
Birdwatching was designed to enhance the participant's ability to dynamically allocate attention across the visual scene. This task involved the identification of one visual stimulus and localization of another appearing briefly and simultaneously on the computer monitor. On each trial, a letter was presented in the center of the screen, and simultaneously a bird image was presented elsewhere on the screen. At higher difficulty levels, distracting elements (colored dots) were presented simultaneously. A forest scene served as the background and was continuously visible. The participant's task was to recall the identity of the letter and the location of the bird. Letter identity was indicated with a keyboard entry and bird location was indicated by a mouse click. The level of difficulty was adapted automatically in relation to performance by adjusting the stimulus duration (range: ~20-300 ms), the distance between the two stimuli, and the quantity of non-relevant distracting elements.

Speed Match is a timed visual n-back training task where participants compare a simple shape or pattern with one presented immediately beforehand (1-back). When correct matches occur, the participant indicates the match by a right arrow key press. Non-matches are indicated with a left arrow press. The goal is to make as many correct responses as possible in the time allotted (45 seconds per round).

Memory Match is a timed n-back (2-back) task where participants compare a visual stimulus with one presented two previously. The responses and goals are similar to those described for *Speed Match*. As with other n-back tasks (e.g., Buschkuehl and Jaeggi, 2010), these exercises were designed to enhance the ability to dynamically store and update information in working memory.

In *Monster Garden*, participants memorized the location of obstacles – "monsters" – appearing sequentially at 1-second intervals within a 4 x 4 or 5 x 5 grid. Participants were then required to navigate a character through the grid without running into the hidden monsters. Upon successful grid navigation, a secondary bonus task challenged the participant to recall the location of the monsters and click on them. In response to each participant's individual performance, the software automatically adjusted the number of monsters presented and the size of the grid in which they appeared. A given gameplay was ended after 3 incorrect responses (i.e., running the character into a monster) or successful completion of 10 grids. This exercise was designed to enhance visual working memory.

Figure 3: *Divided Visual Attention Assessment.* Effect sizes for the pre- vs. post-testing error scores on the Divided Visual Attention task are shown for the training and control groups. The pre- vs. post-testing improvements in divided visual attention were significant for the training group ($p < 0.01$, indicated by two *'s). The group-by-time interaction was significant as well ($p<0.05$, indicated by one *) with training participants improving significantly more than the control participants.



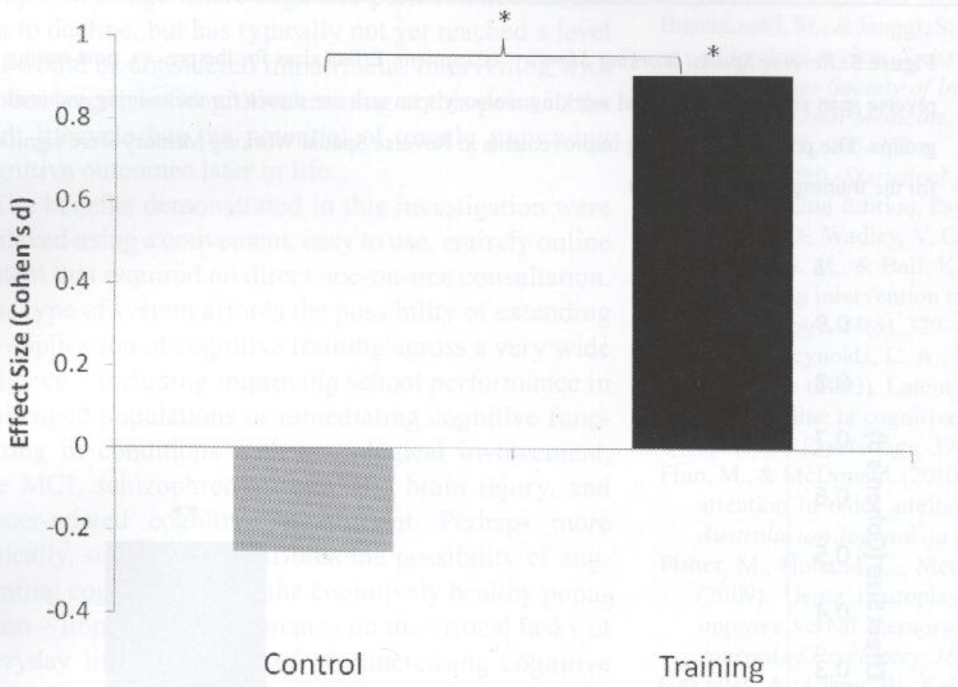
ASSESSMENTS

Spatial working memory and divided visual attention were evaluated with tasks designed to test transfer of training effects. The assessments challenge the dynamic allocation of visual attention and memory while employing stimulus and task demands clearly distinct from the training regimen. In this way, simple practice effects in the context of training would not be sufficient to enhance performance on the assessments. Only changes in the underlying neural mechanisms would support such changes. Since the training focused on visual attention and memory training, an assessment of semantically based working memory was used as a positive control, as well. Assessments were deployed in the context of the same website (www.lumosity.com) as the training.

Divided Visual Attention Assessment

Divided visual attention was assessed using a test of the ability to interpret information outside of the central field of view. In this task, subjects were required to fixate on and identify a stimulus in the center of the computer screen, while simultaneously locating stimuli (via a mouse click) presented for 100ms outside of their central view. The stimuli were presented in black on a white background to eliminate contrast variability and to prevent subjects from using visual anchors in the background – or other task-specific strategies they may have learned in the training period – as a localization

Figure 4: *Forward Spatial Working Memory Assessment.* Effect sizes for the pre- vs. post-testing forward span scores on the spatial working memory span task are shown for the training and control groups. The pre- vs. post-testing improvements in Forward Spatial Working Memory were significant for the training group ($p < 0.05$). The group-by-time interaction was significant as well ($p<0.05$), with training participants improving significantly more than the control participants.



strategy. The non-central stimulus was a small (10-pixel radius) solid black circle, which was visually unlike the training stimuli. On each trial, the non-central stimulus eccentricity varied unpredictably between 120 and 600 pixels in distance from the central stimulus. The distance between the target and location of the mouse click responses was recorded and treated as a measure of accuracy and localization error. Participants completed 40 trials of this test at the beginning and end of the experiment. See Figure 1.

Forward and Reverse Spatial Working Memory Assessments

Visual working memory span was measured via 2 visual memory span tests (see Figure 2). In each version, the participant watched as several squares changed from light blue to dark blue, changing in random order and one at a time. In the Forward Spatial Working Memory version of test, the participant's task was to click on the squares in the order they were highlighted. In the Reverse Spatial Working Memory test, the participant needed to click on the squares in the opposite order to the way they were highlighted. After each correct trial, a new level was presented with the number of revealed squares increasing by one. The task ended after the subject failed to complete a level twice.

Letter Memory Assessment

In the Letter Memory test, the participant observed a series of letters presented simultaneously on the screen. Subsequently, memory for the letter string was assessed by having the participant type in the observed string. The letters were chosen randomly. Upon correct performance, the span was increased by one. The test ended when the participant missed two consecutive trials.

RESULTS

All participants were able to successfully use the testing and training software from a personal computer without personal guidance.

Visual Attention

In the visual attention test, the average distance between target location and the location of the mouse click response was treated as the measure of error in locating the non-central stimulus (Figure 1). All participants were close to ceiling performance on the letter-identification component of the task, so localization error for all trials was included in the analysis. Training participants' accuracy was significantly better after the training intervention (pre-test = 32.8, post-test = 25.5 mean pixels of error; $p < 0.001$, two-tailed paired-samples t-test). The control subjects did not experience gains from the pre-test to the post-test (pre-test = 33.8, post-test = 34.2 mean pixels of error; $p = 0.882$). In addition, there was a significant testing-time-by-group interaction, with the improvements experienced by the training group being significantly greater than those of the control group ($p = 0.027$; two-tailed t-test of the difference scores). Effect sizes (Cohen's d; Cohen, 1988) for the pre- vs. post-test scores for both training

Table 1: ***Pre- and post-training scores and effect sizes for training and control groups.***

	Training Group						Control Group						Between Groups
Assessment	Pre-test Mean	Pre-test SD	Post-test Mean	Post-test SD	Cohen's *d*	*p* value	Pre-test Mean	Pre-test SD	Post-test Mean	Post-test SD	Cohen's *d*	*p* value	*p* value
Divided Visual Attention	32.8	8.5	25.5	6.9	0.94	**p<0.001****	33.8	3.7	34.2	8.3	-0.06	p=0.882	**p=0.027***
Forward Spatial Working Memory	5.9	1.1	6.7	0.4	0.91	**p=0.032***	6.5	1.7	6.0	2.2	-0.25	p=0.160	**p=0.012***
Reverse Spatial Working Memory	5.3	0.8	5.8	0.8	0.51	**p=0.008****	5.4	1.0	5.6	0.7	0.19	p=0.471	p=0.330
Letter Memory	26.1	5.1	27.0	5.6	0.16	p=0.517	24.4	3.3	26.4	4.0	0.54	p=0.105	p=0.506

and control participants are shown in Figure 3. See Table 1 for a summary of results.

Spatial Working Memory

Forward Spatial Working Memory. In the forward spatial working memory task, training subjects were able to remember significantly longer spans after training than they were prior to training (mean span before training = 5.9, mean span after training = 6.7; $p = 0.032$). Control subjects did not improve from pre- to post-testing (mean span before training = 6.5, mean span after training = 6.0; $p = 0.160$). The group by time interaction was significant for this difference as well ($p = 0.012$) with training participants increasing their spans significantly more than the control participants from pre- to post-testing. Effect sizes are shown in Figure 4.

Reverse Spatial Working Memory. The reverse spatial working memory task revealed that training participants had a significantly longer reverse spatial working memory span following training (mean span before training = 5.3, mean span after training = 5.8; $p = 0.008$). Control participants showed no significant changes from pre- to post-testing (mean span before training = 5.4, mean span after training = 5.6; $p = 0.471$). There were no significant group-by-time interactions for this task ($p = 0.330$). Effect sizes are shown in Figure 5.

Letter Memory. No significant changes were seen in the letter memory task for either group ($p = 0.517$ for the training participants and $p = 0.105$ for the control participants for the pre-post testing comparisons). The group-by-time interaction was also not significant ($p = 0.506$).

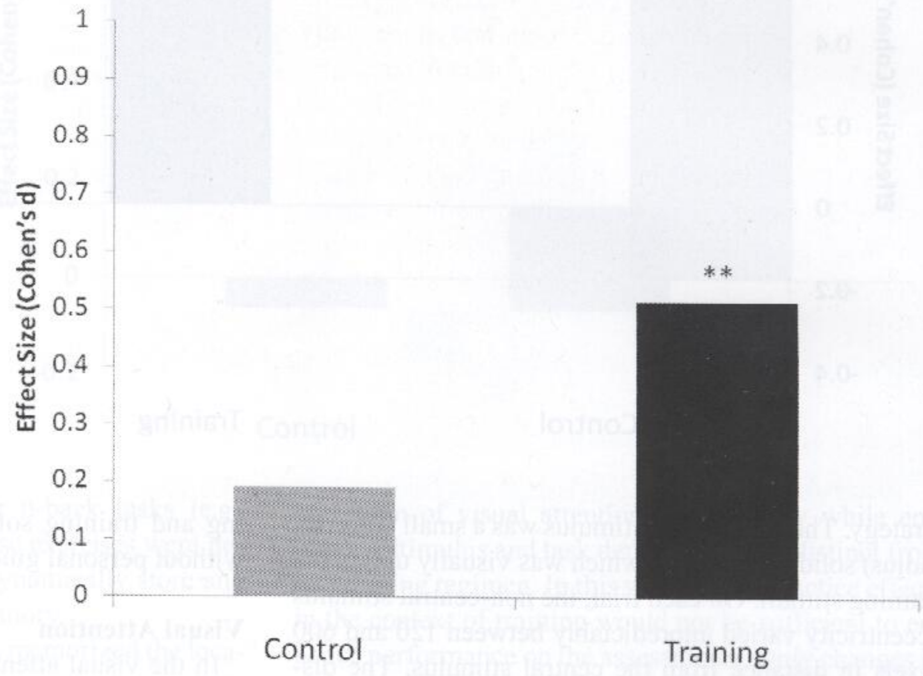


Figure 5: *Reverse Spatial Working Memory Assessment.* Effect sizes for the pre- vs. post-testing reverse span scores on the spatial working memory span task are shown for the training and control groups. The pre- vs. post-testing improvements in Reverse Spatial Working Memory were significant for the training group ($p < 0.01$).

DISCUSSION

In this study, participants who trained with the online cognitive exercise program Lumosity (www.lumosity.com) improved significantly more than the wait-list control group on untrained measures of visual attention and working memory. Training reduced the average error in localization of transient and non-central visual stimuli while also improving performance on measures of spatial working memory. There were no significant performance shifts in the control group. The benefits of cognitive training transferred to untrained measures of core cognitive abilities. Compliance and qualitative feedback suggest that the game structure motivated frequent training.

Customized versions of the online training system here described (www.lumosity.com) have already been demonstrated to improve cognitive functioning in childhood survivors of cancer-related brain damage (Kesler, *et al.* 2011) and older adults diagnosed with MCI (Finn and McDonald, 2010). Here we show that a group of normal, healthy, middle-aged adults can benefit from training as well. This finding is important, as it fills a gap in the existing literature. This demographic group is at an age where cognitive performance has begun to decline, but has typically not yet reached a level that would be considered impairment. Intervening with a robust regime of cognitive training at this point in the adult lifecycle has the potential of greatly improving cognitive outcomes later in life.

The benefits demonstrated in this investigation were achieved using a convenient, easy to use, entirely online system that required no direct one-on-one consultation. This type of system affords the possibility of extending the application of cognitive training across a very wide audience – including improving school performance in challenged populations or remediating cognitive functioning in conditions with neurological involvement, like MCI, schizophrenia, traumatic brain injury, and cancer-related cognitive impairment. Perhaps more critically, such a system affords the possibility of augmenting cognition across the cognitively healthy population – improving performance on the critical tasks of everyday life in a world of ever-increasing cognitive demands.

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FINANCIAL INTEREST DISCLOSURE

Joseph L. Hardy is employed as the Senior Director of Research and Development at Lumos Labs, Inc., makers of Lumosity, the training platform described in this manuscript. David Drescher, Kunal Sarkar, and Michael Scanlon are the co-founders of Lumos Labs, Inc. Each of these authors holds stock options in the company.

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