THE SCIENCE BEHIND LUMOSITY

Joseph Hardy, PhD
Michael Scanlon

November, 2009

www.lumosity.com

Table of Contents

Executive Summary

Until quite recently, most neuroscientists and psychologists believed that core aspects of cognitive processing were essentially fixed from a young age, with little or no room for improvement. Capacities like memory, attention, and sensory processing were thought to be largely determined after a relatively brief period of early development. In this worldview, those endowed with strong cognitive capacities through genetics and early development were destined to operate at a high level throughout much of their lives. Those not so fortunately endowed were out of luck.

The emerging science of the brain is dramatically changing the way we view these issues. We now understand that, with the right kind of stimulation and activity, the brain can dramatically change and remodel itself to become more efficient and effective in processing information, paying attention, remembering, thinking creatively, and solving novel problems.

Lumos Labs has used this cutting edge science to create a set of web-based software tools that empower people to exercise their brains and achieve their maximum performance. The assessments, games, and training courses on the Lumosity website (www.lumosity.com) are based on real science and are presented in an appealing, engaging form that make it fun to exercise the brain. Lumosity is being used as a platform technology for investigating the impact of cognitive training in a variety of populations. Results indicate that this training can improve a wide variety of core cognitive skills – from attention and memory to fluid intelligence and math skills. These improved abilities can help people do better in school, perform more effectively at work, and live a more productive life.

The Incredible Changing Brain

The capacity of the human brain to make new associations and acquire new knowledge has been appreciated for hundreds of years. However, the brain's ability to fundamentally reorganize itself when confronted with new challenges is a relatively recent discovery. In response to these challenges, the brain will adapt and change. Given the right kind of exercise, it will reshape itself to be more efficient and effective. This power of reshaping is referred to as neuroplasticity, and its consequences are only now beginning to be fully appreciated.

Behavior changes the brain

In order to obtain a license to drive one of the famous black cabs around the serpentine urban streets of London, one must first pass a rigorous exam testing knowledge of point-to-point routes throughout the city. These routes are referred to as The Knowledge, and would-be taxi drivers spend months "on The Knowledge," studying the map of London in hopes of passing the exam. In 2000, researchers at University College London published an intriguing brain imaging study involving these individuals (Maguire, et al., 2000). They sought to discover what happens to the brains of taxi drivers as they go on The Knowledge. If the brain is a relatively static receptacle, passively absorbing information, then researchers would have expected to see few, if any, major structural changes in the brain. What they saw was dramatic and surprising. Researchers observed differences in the size and shape of crucial brain structures in taxi drivers relative to control subjects. In particular, a part of the hippocampus, a brain structure critically involved in memory and navigation, was larger in those who were on The Knowledge compared to those who were not. In subsequent analyses, the research team showed that these changes were related to the amount of time drivers spent on the knowledge. This was an early look into the brain's incredible ability to change to meet the demands placed on it, and to respond with increased capacity for tasks that exercise it.

Throughout the past decade, researchers have observed similar structural and functional brain changes associated with specific task demands. Medical students studying for exams undergo brain changes similar to those observed in the London taxicab study (Draganski, et al., 2006). Learning to juggle results in functional changes in brain areas associated with visual processing, at least temporarily (Draganski, et al., 2004).

Cognitive abilities are affected by other kinds of activities as well, not just those traditionally associated with learning. Some interesting evidence of brain change comes from the world of video games. Green and Bavelier (2003) showed that video game players performed better in measures of visual attention than non-players. What's more, when they asked non-players to play an action video game intensively over a period of several weeks, those individuals' visual attention capacities improved to look more like

the gamers'. Tetris has also been implicated in the brain change literature. Haier and colleagues (2009) asked a group of adolescent girls to practice Tetris for a period of three months, taking brain recordings before and after training. The brains of these girls were changed both functionally and structurally from the training. Cortical thickness was increased in some areas, and levels of activation were increased in others.

Training can improve cognitive outcomes

Interactive multimedia software technology, like that used in video games, can be used to present specific task demands to individuals in a form that is intensive, repeatable, adaptive, and highly targeted. This advance in technology, combined with a new appreciation of the brain's ability to reshape itself, has led to an explosion in interest in using computer-based technology to train the brain. There are now several examples of studies performed with targeted brain training programs that have achieved positive outcomes.

Brain Training in Older Adults. One area of active research in brain training is the cognitive decline associated with the normal course of aging. The Advanced Cognitive Training for Independent and Vital Elderly (ACTIVE) study was a large, randomized, controlled trial testing the effects of three kinds of cognitive training (Ball, et al., 2002). The 2832 participants, all 65 years of age or older, were randomly assigned to one of four conditions. One group received no training, and served as the control. The three intervention groups received either memory, reasoning, or speed of processing training. Participants in each intervention underwent approximately 10 one-hour sessions of training over about six weeks. In the reasoning intervention, participants worked with trainers to learn and practice skills related to inductive reasoning and problem solving. The memory training focused on verbal episodic memory, and taught participants to use mnemonic strategies for remembering lists and other specific information. The speed of processing training involved a computer-based training procedure that required participants to simultaneously identify a central visual target and locate another stimulus in the periphery.

A number of interesting results have come out of this very large NIH-funded trial. Unsurprisingly, participants in all groups learned to perform the training tasks more efficiently. What was more impressive was that the effects of the training generalized to measures of real-world function. For example, those receiving training showed slower declines in instrumental activities of daily living (IADLs) than the controls, and these differences were significant for the speed of processing and reasoning groups (Willis, et al., 2006). These functional benefits were observed five years after training was completed, indicating that the benefits were sustained for a substantial period of time. The ACTIVE study demonstrates that cognitive training can have highly beneficial real-world benefits for seniors.

Cognitive Development in Children. Research related to cognition in children is another area of intense interest. Researchers from the Karolinska Institute in Stockholm, Sweden conducted a series of experiments testing the effects of a working memory training program on children with attention deficit hyperactivity disorder (ADHD). The premise of this work is that increasing working memory capacity in these children will improve their ability to attend to and process information in their environments,

improving behavioral and school performance outcomes. By training on computer-based training tasks that challenge the child to remember a sequence of targets and hold on to and manipulate those memories, a variety of positive cognitive outcomes were achieved. The memory challenge wasadjusted adaptively to match the user's performance and improvement. In one study, improvements were seen in visual memory and response inhibition after training, relative to controls (Klingberg, et al., 2005). Increased levels of activation in the prefrontal and parietal cortices (the parts of the brain most responsible for working memory and attention) were seen in children following training (Olesen, et al., 2004). Improved mathematical reasoning performance has been observed following training, as well (Holmes, et al., 2009). This research lends more proof to the notion that the right kind of brain training can improve cognition, change the brain, and have positive impacts on young peoples' lives.

Intelligence Training in Young Adults. Computer-based brain training is not just for older adults or children, and one does not need to have a cognitive impairment to benefit. Recently, researchers from the University of Michigan examined the effects of a challenging working memory and divided attention task on fluid intelligence performance in young adults (Jaeggi, et al., 2008). This task, called the Dual N-Back, requires users to attend to simultaneously presented auditory and visual information and remember both streams, and the challenge adapts dynamically to the user's performance abilities. Fluid intelligence is the ability to creatively solve new problems, and it is measured as part of standard IQ tests. Conventional wisdom in psychology had said that intelligence is relatively fixed, without much potential for improvement. However, participants who completed the Dual N-Back training in this study showed improvements in working memory and fluid intelligence that were statistically significantly larger than those seen in the control group. The more participants trained, the larger the improvements in fluid intelligence were.

This research shattered the view that intelligence could not be changed in adults, and showed the potential for brain training to help even those who are already near the peak of cognitive performance. Lumos Labs has worked closely with Martin Buschkuehl and Susanne Jaeggi to make a version of the Dual N-Back task available on the Lumosity website (www.lumosity.com). This version is being actively used both by Lumosity customers and by the researchers who are widening the scope of their investigations into intelligence training.

Broad and Growing Base of Evidence that Cognitive Training Works. The studies presented here are merely a sample of some of the most compelling research showing that brain training can be effective in improving cognition and real-life outcomes for people of all ages and a wide range of conditions. Other notable studies include the IMPACT study, which examines the effect of an auditory-based training program on memory in older adults (Smith, et al., 2009), and the early studies in computer-based cognitive training in children conducted by Tallal, et al. (1996) and Merzenich, et al. (1996). Reviews are available that treat this literature in greater depth. Hertzog, et al. (2009) present an exhaustive survey of the evidence for enrichment effects in cognitive aging, treating lifestyle as well as physical and cognitive exercise outcomes. McGurk, et al. (2007) conducted a meta-analysis of cognitive remediation in schizophrenia, which touches upon computer-based training techniques as well as other techniques.

The evidence that "brain training works" is now sufficiently robust and compelling that it would be difficult for an objective, dispassionate observer to claim that there is no evidence that "brain training works." However, rather than being the end of the story, this is merely the beginning. There is a great deal more to learn about how this kind of training can be best applied and optimized for each individual's unique goals. At Lumos Labs, we have created a research platform that allows us to facilitate the exploration of these issues in collaboration with the top researchers and institutions around the globe. Completed and ongoing research using Lumosity will be described in greater detail below in the section Scientific Research with Lumosity.

The Lumosity Scientific Framework

Past systems of brain training have provided only splinters of a complete brain training solution. Among the scientifically rigorous solutions, each previous software package has addressed a single domain of brain function or a single condition. Disparate groups of researchers have viewed their specialties from their unique perspectives, and devised specific solutions from those perspectives. However, by focusing narrowly on a particular functional domain or problem, these approaches have obscured the overarching principles that make brain training effective. Previous serious cognitive training solutions have also typically been expensive, difficult to access, and boring to use. On the other hand, games such as Nintendo's *Brain Age* have eschewed scientific rigor in favor of commercial acceptability and ease of deployment.

Lumos Labs is committed to delivering an effective, complete, integrated, highly accessible, and engaging brain training solution. The Lumos Labs solution has been and continues to be developed in the context of a model of open innovation, in which the best researchers in the field are invited and encouraged to contribute to the brain training products through ongoing testing and contribution of the best ideas for novel brain training solutions. This model can flourish because there is a natural virtuous cycle between researchers, developers, and the users who benefit from training. The technological infrastructure of the hosted, web-based solution of Lumosity.com, and the back-end data solutions associated with it, make it easy for researchers to gather and analyze data from studies conducted with the software. This allows researchers to focus on the most interesting and important questions in the field of brain training research, rather than hassling with software development. In turn, this facilitation allows for rapid deployment of cutting edge solutions for a wide variety of populations who can benefit from these tools. The broad user base itself (at the time of writing, Lumosity.com had more than 1.5 million registered users) allows for investigation of basic aspects of brain function and brain change that could never have been answered in the past without such large samples.

What makes effective brain training?

There are many factors that are essential to creating an effective brain training solution. A few of the most critical characteristics that make the Lumosity training programs effective are targeting, adaptivity, novelty, engagement, and completeness.

Targeting. An effective training task must be carefully targeted to train brain functions that will lead to the maximum benefit for the user in daily life. Some exercises will lead to improvements on the specific tasks trained, but not to other cognitive tasks nor to the activities of everyday life. Highly effective brain training, on the other hand, will be characterized not just by improvements on the tasks themselves, but also on transfer of that improvement to performance of real world tasks. However, no one training task will improve all aspects of cognition; so, designing effective training tasks involves carefully crafting training tasks that target the most critical aspects of brain function.

The benefits of a particular training task will depend on the underlying brain mechanisms that are being trained by that task. For example, in the Lumosity game *Memory Matrix*, the mechanism responsible for encoding visual working memory is exercised by challenging the user to remember the location of a series of blocks. The parts of the brain that are responsible for this ability are also critically involved in a wide array of other tasks such as remembering faces, or where you left your keys. We would expect the improvement in visual memory to aid with the performance of these tasks, but not with tasks that involve very different cognitive abilities, such as the ability to inhibit unwanted responses. Response inhibition involves very different brain mechanisms, and must be trained with a different task, such as the Lumosity game *Color Match*.

Adaptivity. Each individual brings his or her own unique set of strengths and weaknesses to any new task. A task that is quite easy for one person might be impossible for another. In order to derive benefit from training, however, the level of difficulty must be set at a level that is challenging without being discouraging. This level is different for each individual, and it will change over time as performance improves. This response to challenge is a central component of how the nervous system operates, and shaping the response properties of the system progressively and adaptively is a part of all effective learning processes. The critical insight for the purposes of cognitive training lies in the precise methods by which task difficulty is adjusted. Each task needs to be adapted in a way that optimizes training intensity and improvement in that domain. The ability to adjust task difficulty in response to individual users' performance on a moment-to-moment basis is one of the key innovations in cognitive training that has been made possible by computer technology.

Each Lumosity game is designed to adaptively challenge the user. Responses are recorded and tracked dynamically over time, both within a session and across training regimens. The level of challenge is optimized continuously for each user.

Novelty. In order for the brain to be exercised effectively, it must be confronted with novel tasks and challenges. Many of the kinds of challenges that are typically recommended for brain health, such as crossword puzzles and bridge, are highly over-learned tasks that do not force the brain's processing systems to operate in new ways. Working in new ways that are not over-learned is critical for driving

nervous system remodeling. The brain creates specialized circuitry for doing particular tasks. Tasks that have been performed many times in the past simply reactivate the existing circuitry. This form of stimulation may be helpful in keeping the brain active, but it will not drive fundamental improvements in the way information is processed. Take the case of crossword puzzles as an example. In doing a crossword puzzle, we are recalling information we have already learned in the past, in the form of words. We are reactivating existing circuitry, not challenging the brain to work in new ways. Thus, crossword puzzles provide a relatively inefficient form of brain exercise.

Engagement. Engagement and reward are critical components of making brain games effective and encouraging people to do them. When the brain is in an engaged and rewarded state, it is much more open to learning and change. What's more, the very process of being rewarded for correct responses in a given task teaches the brain mechanisms to process that information more effectively. The reward for correct performance tells the brain, "That worked, do that again when confronted with the same situation in the future."

If you are rewarded for your hard work, for example by receiving praise from colleagues, friends, or family, you will be more likely to work hard in the future. This basic premise holds for both physical and mental exercise, as well. One of the biggest reasons why many of us do not exercise as much as we should is that it can really hurt. We are much more likely to engage in exercise if it is fun and feels good. All Lumosity games are designed with engagement and reward as critical components. These games are amusing and entertaining, making users much more likely to stick with the training over time.

Completeness. Many brain training programs previously available were developed in the context of a single, narrow academic framework, targeting a neural system with highly specialized training. However, the brain is a highly complex, interacting, and integrated system. Training on a limited aspect of brain function, such as visual attention, auditory processing, or working memory, in isolation is unlikely to yield optimal results for real world function. Engaging in the tasks of daily living – working, going to school, caring for loved ones, recreating, etc. – requires the proper functioning of *all* aspect of cognition. If information is not processed rapidly, then rapidly evolving events, such as the plot of an action movie, will fly past and be missed. If this information is never properly processed, then it will not capture one's attention, and will likely not be stored in memory. Similarly, if attention is limited, and cognitive energy and effort are not being properly allocated, then critical information and events, such as the key plot twists in the movie, will be missed. Finally, if memory systems are not functioning optimally, even attended-to information may not be retained over time, and it will be impossible to pull together disparate information - such as plot twists into a coherent whole. Even in the simple case of watching an action film, all aspects of brain function must work together to lead to optimal understanding and appreciation.

To achieve a complete brain training experience, Lumosity.com includes an integrated and ever-growing suite of web-based tools, including dozens of assessments, games, and courses. The games are developed to train five core areas of cognitive function: processing speed, attention, memory, flexibility, and problem solving. Training across these domains is coordinated in the form of courses. These

courses guide users through a training experience over 20-40 sessions in which complementary functional domains are exercised together to provide maximal benefit toward a specific goal, such as improving memory or getting better grades in school. The assessments allow users, researchers, and clinicians to assess cognitive function and direct training toward the greatest points of need. In this way, Lumosity represents a complete brain training solution that can yield benefits far beyond any single tool used in isolation. In a sense, this is similar to the difference between having a single piece of exercise equipment and having access to the whole gym, along with a personal trainer.

The Lumosity Product

The Lumosity product suite (www.lumosity.com) includes games, courses, assessments, and the supporting material that helps guide users through their training. Each element of this product experience is tailored to work as an integrated component of the complete brain training system. In addition to the Lumosity website, Lumos Labs has produced a cluster of complementary products that make it easy for users to train wherever they are, whenever they have a moment. These complementary offerings include iPhone, Palm Pre, Facebook, and Yahoo! applications.

Games

The centerpieces of the Lumosity brain training experience are the games. The principles of targeting, adaptivity, novelty, engagement, and completeness are embodied in this suite of games. Each game targets a critical component of brain function. The games are adaptive, increasing challenge as performance improves, and backing off when incorrect responses are made. The games are novel experiences challenging the brain in ways that encourage new connections and improved efficiency. The scientists at Lumos Labs work closely with game developers to create tasks that are both highly effective brain training and highly engaging games. Taken together, the entire suite of games represents a complete brain training system – an entire gym for the brain. There are games training speed of processing, memory, attention, mental flexibility, and problem solving. The best way to get a sense for how the games work is to look at a few examples.

Playing Koi. The goal of Playing Koi is to feed all the koi (a type of domesticated carp common in Japan), while avoiding the other fish (Figure 1). Also, each koi should be fed only once per round. The task is challenging because all the koi look exactly the same, and they are constantly moving around.This game is an exercise of visual divided attention and working memory. The player is challenged to focus on multiple targets simultaneously and follow them

Figure 1. Playing Koi screenshot.

throughout their journey across the screen. Focus must be maintained, or fish go unfed. As performance improves, more fish are added, and distractions are increased. Improving on this task will have real world benefits of improving the ability to process multiple streams simultaneously, such as attending to two computer windows at the same time. In addition, this training increases the ability to avoid outside distractions while concentrating on a task.

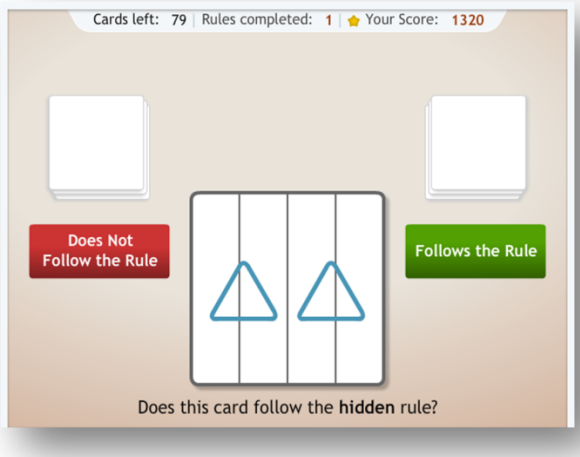
Familiar Faces. The game Familiar Faces challenges the brain's ability to create associations between visual and verbal information, such as associating a person's name with their face (Figure 2). The user's job in this game is to work as a server at a seaside restaurant. Each visitor has a name and places an order. You must remember the orders as well as the customers' names to earn large tips.

Figure 2. Familiar Faces screenshot.

This game is an exercise of associative memory that is closely related to the kinds of memory challenges that we all experience on a daily basis. As performance improves on this task, more characters and more complicated orders are presented. Not only does the user need to remember names during a single session, the user must also remember names from past sessions, mimicking the real life situation.

By the Rules. In By the Rules, users must identify the hidden rule in a dynamic card game (Figure 3). In this task, the user must indicate with each card whether the card follows the rule. For example, the card pictured in Figure 3 would follow the rule if the rule were "blue," "triangle," "number two," "vertical lines," or "solid border." If the user indicates that the card follows the rule, but it does not, then it is known that the rule is none of the aforementioned possibilities. It must be something else. However, if the user indicates it does follow the rule, and is correct, there are still five possibilities of what the rule could be. Only through multiple tries is it possible to determine the correct rule.

Figure 3. By the Rules screenshot.



This game is an exercise of mental flexibility and working memory. The user is challenged to formulate hypotheses about what the current rule might be and then dynamically update that hypothesis as new information becomes available. This type of reasoning ability involves the intersection of inductive and deductive reasoning, and in that way mimics the type of decision making that happens in a wide variety of real world contexts. For example, the judgments we make about people

involve this kind of continuous updating, particularly early on in a relationship.

Courses

An important feature of the Lumosity training experience is the course framework. Courses are clusters of games set to prearranged schedules. These tools are there to guide users through a training experience with a particular goal and timeframe in mind. The commitment associated with courses ranges from 20 to 40 daily sessions of between 15 and 30 minutes each, depending on the characteristics of the training goals.

The courses are organized into a four groupings – Core Brain Training, Peak Performance, Student, and Medical Conditions. The Core Brain Training starts with Basic Training, the general purpose starter course. Other Core courses include Speed Boost, Attention Boost, and Memory Boost. Each of these booster courses is designed to improve a particular core area of cognitive function. Peak Performance courses provide an extra challenge for users who have mastered the basic levels of Core Brain Training. The games in these courses will make anyone's brain sweat. Student courses are designed to help children and young adults achieve better performance in school. The games in these courses have been shown to help students improve on tests of reading and math. The final group of courses falls under the rubric Medical Conditions. The Medical Conditions courses include training aimed at improving outcomes in such conditions as attention deficit hyperactivity disorder (ADHD), traumatic brain injury, and chemofog.

The courses are designed to give users a discrete challenge. When starting a course, the total commitment is known, and expectations of benefits are set. Matching these with personal goals is a great way to motivate training. Also, these courses build on one another. Once a course has been completed, others are suggested based on the user's profile of progress and performance. An ongoing, dynamic brain training experience can be constructed using courses. Along the way, users can play any of the other games at any time.

Assessments

Another component of the Lumosity brain training experience is the assessment system. At the time of writing, there were 11 assessments on the Lumosity website. Each is based on clinically accepted measures of cognitive performance. For users of the site, they provide a way to measure performance with tests that are not being directly trained and that are based on concepts validated by external experts in cognition. For researchers, these tools allow a much more convenient way to assess cognition in their subjects, since these tests are substantially equivalent to the paper-and-pencil tests that are commonly administered in clinical and research settings. However, by being accessible online, these tests can be administered in a fraction of the time, and there are no scoring or data entry errors.

Supporting materials

A variety of other components support the training experience within the Lumosity web product. These include the Brain Performance Index (BPI), the Brain Profile, and Lumosity Points. The BPI is an aggregate measure of cognitive performance that allows users to track their improvement over time and

across games. It lets users know where they are with a single number. The Brain Profile breaks down the BPI into its component parts. Subscores are provided for performance across the main cognitive domains – Speed, Memory, Attention, Flexibility, and Problem Solving. The Brain Profile also indicates where the user sits in the overall distribution of similar users. In each cognitive domain, a percentile rank is graphed, indicating how the user compares to peers. Lumosity Points provide an effort-based measure of progress. The more games and courses completed, the higher the point total, encouraging users continue playing.

Complementary products

In order for brain training to be fully effective, it needs to be highly accessible. Users must be able to train wherever they are, in whatever language they understand, whenever they have a few minutes. Lumos Labs is committed to making its training available to as many people as possible in as accessible a format as possible. With this in mind, Lumosity is currently available in French and Spanish (http://i.lumosity.com/), as was well as in English. In addition, Lumosity games are available on the iPhone and Palm Pre mobile devices. On the web, beyond Lumosity.com, games are accessible through the *New York Times* website, on Facebook, and on Yahoo!. Virtually ubiquitous access allows people to achieve much more than they ever could with a single-platform product.

Scientific Research with Lumosity

The Lumosity games, assessments, and courses are based on scientific research, and Lumos Labs is continually collaborating with independent research labs at top universities to validate and hone the effectiveness of the programs.

Completed research

There have been a number of studies conducted that show that the training available on Lumosity is effective in improving important aspects of cognition, across a variety of populations. The results of these studies demonstrate improvements in working memory, attention, executive function, and fluid intelligence, as well as improved performance in school and increased brain activity.

Figure 4. Improvement in working memory following training on Lumosity.

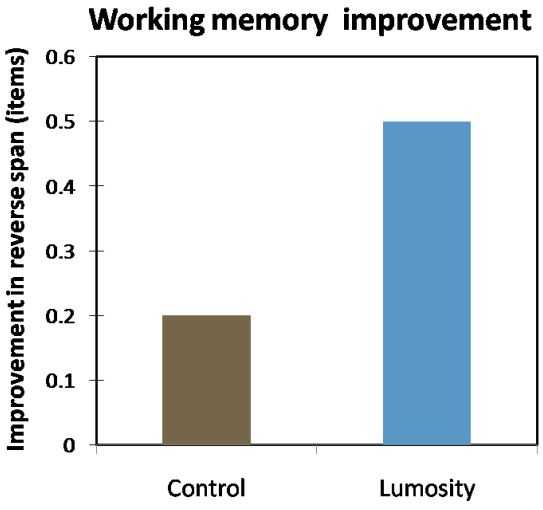


Figure 5. Improvement in visual attention following training on Lumosity.

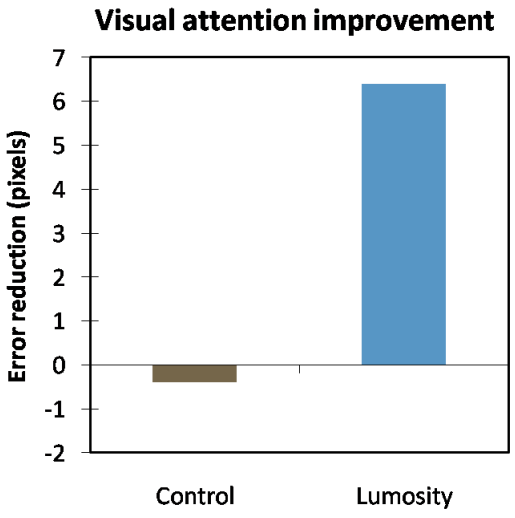
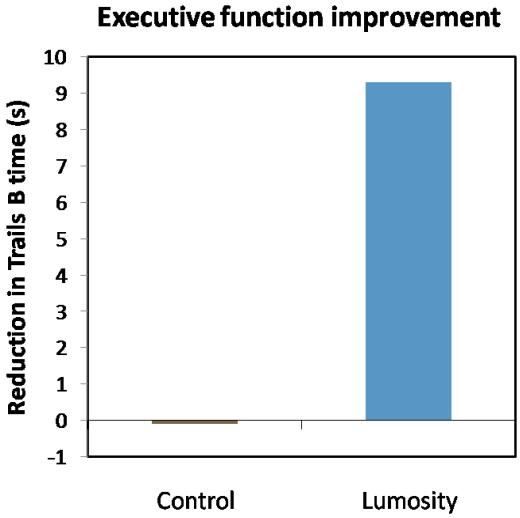


Figure 6. Improvement in executive funtion following training on Lumosity.



Lumos Labs Study. In 2006, the team at Lumos Labs conducted an experiment to evaluate the effect of Lumosity training on cognition in normal, healthy adults. There were 23 participants (mean age = 54) who were divided into a control group, who received no treatment, and a group who received Lumosity training. Training consisted of 20 minutes of Lumosity per day, once a day, for five weeks. All participants' cognitive abilities were assessed at baseline and at follow-up with measures of visual attention, working memory, and executive function. These assessments were versions of standard assessments of cognitive function, adapted for use on the web.

Results of this study have been presented at conferences and in an earlier white paper (Scanlon, Drescher, and Sarkar, 2006, 2007a, 2007b).

Working memory performance was measured before and after training using a test referred to as the reverse span board. In this assessment, participants must attend to and remember the order in which a set of blocks were lit up and respond my clicking on them in the opposite order. Participants who engaged in Lumosity training improved significantly ($p<0.01$, two-tailed t-test) on this working memory measure following training. Control participants did not improve significantly (Figure 4).

Similar results were seen in the assessments of visual attention and executive function, as well. The visual attention assessment measured participants' ability to accurately process multiple streams of visual information simultaneously. Participants who received Lumosity training showed improvement in this test that was significantly larger than that of the control group ($p<0.01$, two-tailed t-test) [Figure 5].

Executive function is a term that describes the ability to control the various aspects of cognition. This ability is critical for a wide variety of tasks including planning, creative thinking, and inhibiting inappropriate actions. A standard measure of executive function is the Trailmaking Part B test. In this test, participants must click on a series of icons, alternating between letters and numbers, while going in

Figure 7. Working memory training (Dual N-Back) improves fluid intelligence (after Jaeggi, et al., 2008).

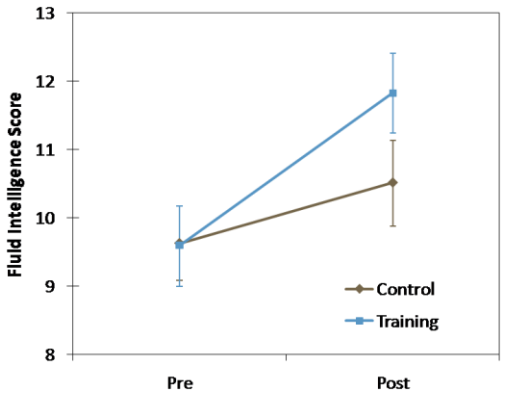
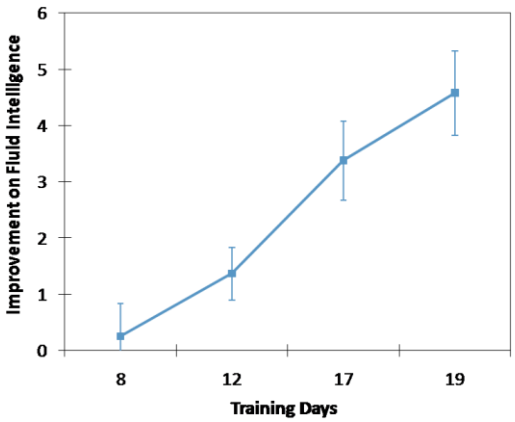


Figure 8. Fluid intelligence improvement by days of Dual N-Back training (after Jaeggi, et al., 2008).



order both numerically and alphabetically. Participants who trained with Lumosity improved significantly on this measure of executive function ($p<.01$, two-tailed t-test), while control participants did not (Figure 6).

Participants in this study improved on the games that they played, which is not surprising. What is more interesting is that these training gains transferred to measures of cognitive performance that were not directly trained. It was not that participants simply learned strategies to play the games; rather underlying brain mechanisms were fundamentally changed by the training. Due to the fundamental nature of this brain change, these gains will transfer to other real world tasks that rely on these cognitive abilities.

Fluid Intelligence Training Study. The benefits from training depend upon the underlying mechanism trained. Sometimes, this relationship can yield new fundamental understanding about the role of underlying brain mechanisms in certain tasks. As mentioned briefly above, Jaeggi, et al. (2008) found that training on the Dual N-Back task improved performance on a standard measure of fluid intelligence. This critical finding revealed several interesting things about intelligence. First and foremost, it revealed that fluid intelligence is not fixed, but can change with the appropriate training. This result also revealed an important relationship between working memory and fluid intelligence. In the past, researchers have suggested that there is a relationship between memory and intelligence (Halford, 2007), but this study demonstrates experimentally for the first time that the two constructs share underlying mechanisms.

This study involved 70 normal, healthy young adults (mean age = 25.6), divided into training and control groups. Participants trained for approximately 25 minutes per day, for 8, 12, 17, or 19 days. Participants who received training experienced gains in fluid intelligence that were significantly greater than those seen in the control group (Figure 7). This research also showed that the more subjects trained, the more their fluid intelligence improved, with average improvements increasing progressively for participants who completed more than eight training sessions (Figure 8).

Figure 9. Middle school students' improvements in standardized test scores in reading following training compared to controls.

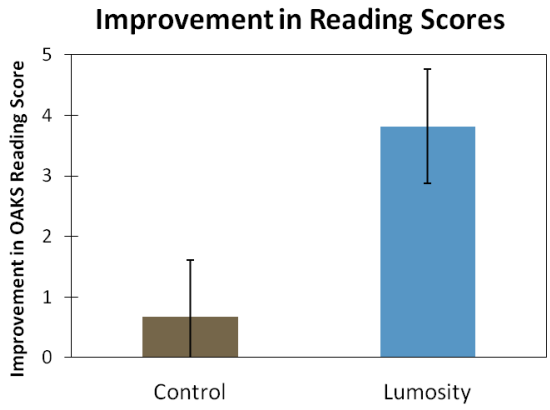
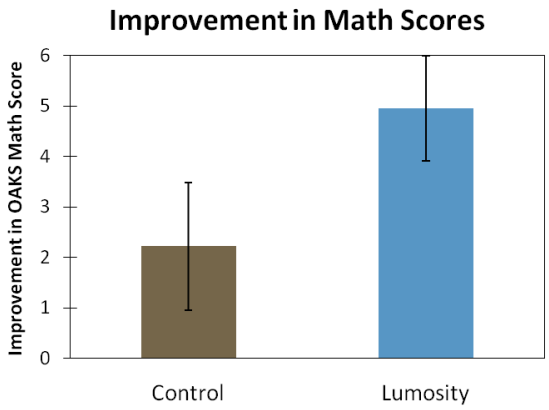


Figure 10. Middle school students' improvements in standardized test scores in math following training compared to controls.



As part of Lumos Labs' ongoing effort to support research in cognitive training, this training is now available on Lumosity. In addition to being available for Lumosity members, this training will be used by Martin Buschkuehl and Susanne Jaeggi to further study how intelligence can be improved with training. This type of collaborative effort exemplifies the Lumos Labs open approach to innovation.

School Preparedness Research. There is currently a great deal of interest among teachers, school administrators, and researchers in the potential for tools based in the principles of adaptive brain training to improve preparedness for school and academic performance in children. Lumosity contains a number of training tools that are useful in preparing children to learn and get ahead at school. Core cognitive abilities like attention and working memory serve as critical scaffolding for learning. Improving these abilities not only prepares the mind for taking in and processing information, it also prepares the student by improving the ability to focus and attend to classroom activities. In addition, several of the Lumosity games exercise cognitive functions by working on material such as basic math skills that students use directly in the classroom. In this way, the training is doubly productive, improving underlying brain mechanisms while simultaneously providing students with basic practice on needed skills. Lumos Labs encourages and facilitates research with Lumosity in schools and has documented a number of Lumosity success stories with students.

One such story comes from a public middle school in the Portland, Oregon Metropolitan Area. Several classes from the 7th and 8th grades participated in this study. The effects of Lumosity training on math performance were tested in the 7th graders and reading performance was examined in the 8th graders.

Twenty-two 8th graders received Lumosity training, while 34 8th grade students served as controls and received no training. The outcome measure used was the Oregon Assessment of Knowledge and Skills (OAKS) standardized statewide reading test. This assessment measures vocabulary and reading comprehension. The test was administered before and after the study period. Students in the Lumosity group received 10 sessions of training. Students in the control group received instruction as usual. Those students who received Lumosity training improved significantly on their standardized reading

scores ($p<0.01$, two-tailed t-test), while those in the control group did not improve significantly (Figure 9). In addition, the improvements in the training group were statistically significantly higher than those control group ($p<0.05$, two-tailed t-test).

The 7th graders were tested on the OAKS math test. This assessment measures grade 7 math proficiency, testing concepts in arithmetic, algebra, geometry, probability and statistics. Figure 10 shows the results of their testing. Students who trained on Lumosity improved significantly on the standardized math test ($p<0.01$, two-tailed t-test) while those in the control group did not. These results illustrate how Lumosity can be used in the classroom to improve outcomes on the standardized tests regularly used to assess student and school performance on such core abilities as reading and math.

A similar pattern of results has been seen in other schools as well. For example, middle school students at schools in Northern California and Eastern Pennsylvania were tested on measures of math fluency (the ability to solve math equations quickly) before and after Lumosity training. Substantial gains in this kind of math performance were observed following training.

Lumosity training is well suited to the classroom environment, with engaging and stimulating games that develop critical cognitive skills that prepare students for success in the classroom.

Research in Children with Learning Challenges. Lumos Labs has an ongoing collaboration with Professor Shelli Kesler at Stanford University. Dr. Kesler studies cognition in a few populations of individuals who are challenged due to medical conditions. She has been using Lumosity in this context to understand whether cognition can be improved in these populations.

One set of research studies from her lab involves children with Turner's syndrome. This is a genetic condition known to cause myriad issues, including cognitive challenge – particularly problems with executive function. In a study presented at the International Neuropsychological Society meeting in 2008, Kesler tested 12 girls with Turner's syndrome on a series of neurocongitive measures before and after four weeks of training with Lumosity. In addition, the girls were given functional magnetic resonance imaging (fMRI) scans at both time points to measure the effects of Lumosity training on brain activity. The girls who completed the Lumosity training demonstrated significant improvements in processing speed, numeration, algebra, geometry and mental flexibility ($p < .05$, two-tailed t-test) with a trend toward improvement in working memory ($p = .08$). In addition, fMRI brain scans revealed neuroplastic changes in brain function, with significantly ($p<0.001$) increased activation observed in frontal and parietal brain regions – areas associated with executive function. Brain training can help these children perform better cognitively, and changes in the brain corresponding to that cognitive improvement are observed (Kesler, 2008).

Research in Cancer Survivors. Chemotherapy and radiation therapy associated with cancer treatment can have negative effects on brain structures, and certain forms of cancer can directly impair brain function. Awareness of the negative effects of cancer and cancer treatment on brain function has been growing in recent years. Terms such as "chemobrain" or "chemofog" have been coined to describe the phenomenon. Dr. Kesler has been investigating the use of cognitive training in improving cognitive

outcomes in patients experiencing these negative effects. One completed study involved survivors of pediatric cancer. This study enrolled children with leukemia or posterior brain tumors in Lumosity training. Twenty-five children completed the training and demonstrated significant improvements in processing speed, visual memory and mental flexibility ($p < .01$). Dr. Kesler is actively engaged in testing the effects Lumosity training in a population of breast cancer survivors, as well.

Summary of Key Findings to Date. Results observed in studies conducted with the training on Lumosity show that this training platform can be used to improve cognition in a variety of ways in disparate populations. Improvements in memory, attention, and executive function have been seen in Baby Boomers. Fluid intelligence has been improved in young adults. Middle school students have improved their cognitive performance and school preparedness. Children with genetically based learning challenges have improved in a variety of cognitive domains. Cancer survivors have benefited from reduced impact of chemofog. These results demonstrate that training with the Lumosity tools can have wide-ranging and critical impacts in cognitive performance across the lifespan, regardless of one's starting point.

Ongoing research

The research described above is just the tip of the iceberg of scientific exploration using the Lumosity platform. Lumos Labs supports external, independent research by making available the Lumosity training and assessments, as well as offering data capture and analysis support. Groups currently using the platform span the range of interest in cognition from those engaged in research in school children to those interested in geriatric issues and from populations of normal, healthy participants to a variety of patient groups.

Here are just a few examples of ongoing research with Lumosity:

- Researchers at the University of New South Wales in Sydney, Australia led by Dr. Maurice Finn have been exploring the effects of Lumosity training in older adults suffering from mild cognitive impairment (MCI), a known precursor condition to Alzheimer's.
- Dr. Adam Gazzaley the Director of the Neuroscience Imaging Center at the University of California, San Francisco is using Lumosity to investigate age-related changes in memory function.
- Two groups are using Lumosity tools to conduct research on issues related to behavioral economics. These groups are headed up by Dr. George Lowenstein from Carnegie Mellon University and Dr. Eric Johnson at Columbia University. Dr. Lowenstein's group is using Lumosity training as a healthy behavior in their study investigating the effects of economic incentives in motivating healthy behaviors. Dr. Johnson's group is looking at correlates between decision making processes and performance on Lumosity games.

- A group at the Naval Health Research Center and University of California in San Diego led by Dr. Chris Johnson is using Lumosity to help activity duty soldiers recover from traumatic brain injury and post-traumatic stress disorder.

Conclusion

The understanding that the brain is dynamically changeable and remains plastic throughout life has revolutionized the way scientists view cognition. We no longer believe that children are stuck with the brain they were born with or that aging is an inevitable precipitous decline into memory loss. We understand that, while everyone is different and genetics do matter, there is a tremendous amount we can do to improve the way our brains function.

Training designed around the key principles of targeting, adaptivity, novelty, engagement, and completeness can lead to real changes in the brain and be fun at the same time. Lumosity is helping people all over the world improve the way they process, think, focus, solve problems, and remember. Over a 1.5 million users from dozens of country have registered with Lumosity, and thousands more join each week. The Lumosity platform has been proven to provide benefits in a variety of studies conducted by leading researchers, and there is a great deal more research on the way. However, this is only the beginning for Lumosity and for brain training in general. There is still much more to be learned about the ways in which training can help specific populations with particular goals. This is why Lumos Labs is committed to making Lumosity and associated tools available to researchers worldwide.

References

Ball, K., Berch, D. B., Helmers, K. F., Jobe, J. B., Leveck, M. D., Marsiske, M., Morris, J. N., Rebok, G. W., Smith, D. M., Tennstedt, S. L., Unverzagt, F. W., & Willis, S. (2002). Effects of Cognitive Training Interventions With Older Adults: A Randomized Controlled Trial. *JAMA*, *288*(18), 2271-2281.

Draganski, B., Gaser, C., Busch, V., Schuierer, G., Bogdahn, U., & May, A. (2004). Neuroplasticity: Changes in grey matter induced by training. *Nature*, *427*(6972), 311-312.

Draganski, B., Gaser, C., Kempermann, G., Kuhn, H. G., Winkler, J., Buchel, C., et al. (2006). Temporal and Spatial Dynamics of Brain Structure Changes during Extensive Learning. *J. Neurosci.*, *26*(23), 6314-6317.

Green, S. C., & Bavelier, D. (2003). Action video game modifies visual selective attention. *Nature*, *423*, 534-537.

Haier, R., Karama, S., Leyba, L., & Jung, R. (2009). MRI assessment of cortical thickness and functional activity changes in adolescent girls following three months of practice on a visual-spatial task. *BMC Research Notes*, *2*(1), 174.

Halford, G. S., Cowan, N., & Anrews, G. (2007). Separating cognitive capacity from knowledge: a new hypothesis. *Trends in Cognitive Sciences*, *11*(6), 236-242.

Hertzog, C., Kramer, A. F., Wilson, R. S., & Lindenberger, U. (2008). Enrichment Effects on Adult Cognitive Development: Can the Functional Capacity of Older Adults Be Preserved and Enhanced? *Psychological Science in the Public Interest*, *9*(1), 1-65.

Holmes, J., Gathercole, S. E., & Dunning, D. L. (2009). Adaptive training leads to sustained enhancement of poor working memory in children. *Developmental Science*, *12*(4), F9-F15.

Jaeggi, S. M., Buschkuehl, M., Jonides, J., & Perrig, W. J. (2008). Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences*, *105*(19), 6829-6833.

Kesler, S. R. (2008). Cognitive intervention and neuroplasticity in children with neurodevelopmentally based executive function deficits. Presented at the International Neuropsychological Society Meeting.

Klingberg, T., Fernell, E., Olesen, P. J., Johnson, M., Gustafsson, P., Dahlstrom, K., Gillberg, C. G., Fossberg, H., & Weterberg, L. P. (2005). Computerized training of working memory in children with ADHD: A randomized, controlled trial. *Journal of the American Academy of Child & Adolescent Psychiatry*, *44*(2), 177-186.

Maguire, E. A., Gadian, D. G., Johnsrude, I. S., Good, C. D., Ashburner, J., Frackowiak, R. S. J., & Frith, C. D. (2000). Navigation-related structural change in the hippocampi of taxi drivers. *Proceedings of the National Academy of Sciences of the United States of America*, *97*(8), 4398-4403.

McGurk, S. R., Twamley, E. W., Sitzer, D. I., McHugo, G. J., & Mueser, K. T. (2007). A Meta-Analysis of Cognitive Remediation in Schizophrenia. *Am J Psychiatry*, *164*(12), 1791-1802.

Merzenich, M. M., Jenkins, W. M., Johnston, P., Schreiner, C., Miller, S. L., & Tallal, P. (1996). Temporal Processing Deficits of Language-Learning Impaired Children Ameliorated by Training. *Science*, *271*(5245), 77-81.

Olesen, P. J., Westerberg, H., & Klingberg, T. (2004). Increased prefrontal and parietal activity after training of working memory. *Nat Neurosci*, *7*(1), 75-79.

Scanlon, M., Drescher, D., and Sarkar, K. (2006, October). Improvement of visual attention through a web-based training program. Poster presented at Society for Neurosciences Annual Meeting in Atlanta, GA.

Scanlon, M., Drescher, D., and Sarkar, K. (2007a, January). Improvement of visual attention through a web-based training program. Poster presented at Bay Area Neuroscience Gathering in San Francisco, CA.

Scanlon, M., Drescher, D., and Sarkar, K. (2007b). Improvement of visual attention and working memory trough a web-based cognitive training program. A Lumos Labs White Paper.

Smith, G. E., Housen, P., Yaffe, K., Ruff, R., Kennison, R. F., Mahncke, H. W., & Zelinski, E. M. (2009). A cognitive training program based on principles of brain plasticity: Results from the Improvement in Memory with Plasticity-based Adaptive Cognitive Training (IMPACT) study. *Journal of Geriatrics Society*, *57*, 594-603.

Tallal, P., Miller, S. L., Bedi, G., Byma, G., Wang, X., Nagarajan, S. S., Schreiner, C., Jenkins, W. M., & Merzenich, M. M. (1996). Language Comprehension in Language-Learning Impaired Children Improved with Acoustically Modified Speech. *Science*, *271*(5245), 81-84.

Willis, S. L., Tennstedt, S. L., Marsiske, M., Ball, K., Elias, J., Koepke, K. M., Morris, J. N., Rebok, G. W., Unverzagt, F. W., Stoddard, A. M., & Wright, E. (2006). Long-term Effects of Cognitive Training on Everyday Functional Outcomes in Older Adults. *JAMA*, *296*(23), 2805-2814.