Improving executive function using transcranial infrared laser stimulation

Nathaniel J. Blanco¹,², W. Todd Maddox¹,²,³,⁴ and Francisco Gonzalez-Lima¹,³,⁵*

¹Department of Psychology, The University of Texas at Austin, Texas, USA
²Institute for Mental Health Research, The University of Texas at Austin, Texas, USA
³Institute for Neuroscience, The University of Texas at Austin, Texas, USA
⁴Center for Perceptual Systems, The University of Texas at Austin, Texas, USA
⁵Division of Pharmacology and Toxicology, The University of Texas at Austin, Texas, USA

Transcranial infrared laser stimulation is a new non-invasive form of low-level light therapy that may have wide-range neuropsychological applications. It entails using low-power and high-energy-density infrared light from lasers to increase metabolic energy. Preclinical work showed that this intervention can increase cortical metabolic energy, thereby improving frontal cortex-based memory function in rats. Barrett and Gonzalez-Lima (2013, Neuroscience, 230, 13) discovered that transcranial laser stimulation can enhance sustained attention and short-term memory in humans. We extend this line of work to executive function. Specifically, we ask whether transcranial laser stimulation enhances performance in the Wisconsin Card Sorting Task that is considered the gold standard of executive function and is compromised in normal ageing and a number of neuropsychological disorders. We used a laser of a specific wavelength (1,064 nm) that photostimulates cytochrome oxidase – the enzyme catalysing oxygen consumption for metabolic energy production. Increased cytochrome oxidase activity is considered the primary mechanism of action of this intervention. Participants who received laser treatment made fewer errors and showed improved set-shifting ability relative to placebo controls. These results suggest that transcranial laser stimulation improves executive function and may have exciting potential for treating or preventing deficits resulting from neuropsychological disorders or normal ageing.

Transcranial infrared laser stimulation is a novel, non-invasive low-level light therapy (LLLT¹) technique with promising potential for psychological and neurological applications (Gonzalez-Lima & Barrett, 2014; Naeser et al., 2014). LLLT consists of using directional low-power and high-fluence monochromatic or quasimonochromatic light from lasers or light-emitting diodes (LEDs) in the red to near-infrared wavelengths to modulate biological functions (Rojas & Gonzalez-Lima, 2011). LLLT has been shown to modify neuronal function in cell cultures, animal models, and clinical conditions (Eells

*Correspondence should be addressed to Francisco Gonzalez-Lima, The University of Texas at Austin, 108 E. Dean Keeton Stop A8000, Austin, TX 78712, USA (email: gonzalezlima@utexas.edu).

¹We use the term LLLT by convention to be consistent with previous research employing this technique, but it is important to clarify that the technique is used as an experimental manipulation, not a therapeutic intervention, in the current and some previous studies.
et al., 2004; Schiffer et al., 2009; Wong-Riley et al., 2005). It produces a wide range of neurobiological effects including the enhancement of cellular metabolic energy (ATP production) and gene expression (Rojas & Gonzalez-Lima, 2013). Recent research suggests that LLLT has exciting potential to enhance cognitive function in humans through transcranial laser stimulation (Barrett & Gonzalez-Lima, 2013). This highlights the need for further research into its potential neurocognitive enhancing effects and viability as treatment for cognitive dysfunction.

The idea of using red or infrared light to modify cognition in humans is novel, but research over the past decade has elucidated its neurophysiological basis and illustrated its potential for cognitive modulation in animal models. The primary mechanism of action of LLLT appears to be photobiomodulation of mitochondrial cytochrome oxidase (Karu, Pyatibrat, Kolyakov, & Afanasyeva, 2005; Rojas & Gonzalez-Lima, 2011; Rojas, Lee, John, & Gonzalez-Lima, 2008; Wong-Riley et al., 2005). Cytochrome oxidase is the enzyme that catalyses oxygen consumption in cellular respiration for metabolic energy production (Wong-Riley et al., 2005), and the primary photoacceptor of red to near-infrared light energy (Karu et al., 2005). Previous work has shown that transcranial LLLT can increase cytochrome oxidase activity in the rat brain (Rojas et al., 2008), which can provide neuroprotection and improve behavioural performance (Rojas & Gonzalez-Lima, 2011, 2013). In particular, Rojas, Bruchey, and Gonzalez-Lima (2012) demonstrated that transcranial LLLT can improve frontal cortex oxygen consumption and metabolic energy and thereby increase frontal cortex-based memory functions in rats. These findings in non-human animals suggest that the metabolic energy of tissue exposed to LLLT is enhanced and that this can result in enhancement of cognitive function.

To date, few studies have investigated the use of LLLT as a form of neuromodulation in humans in vivo, but preliminary research suggests it may have a broad range of applications. LLLT has been shown to improve neurological outcome after ischaemic stroke (Lampl et al., 2007) and mild traumatic brain injury (Naeser et al., 2014). Schiffer et al. (2009) found that a single LLLT treatment to the forehead using 810-nm LEDs resulted in a significant beneficial effect in patients with major depression and anxiety when measured 2 and 4 weeks later. Barrett and Gonzalez-Lima (2013) presented the first placebo-controlled study investigating the effects of transcranial laser stimulation on cognitive function in humans. They showed that transcranial LLLT in healthy young adults improved sustained attention, measured by reaction time in the psychomotor vigilance task, and short-term memory retrieval, measured by performance on a delayed match-to-sample task (Barrett & Gonzalez-Lima, 2013). These findings suggest promising applications of LLLT for enhancing cognitive functions, including treatment or prevention of cognitive and emotional dysfunction in patient populations.

In this study, we continued the investigation of LLLT’s capacity for neuromodulation by assessing the effect of transcranial infrared laser stimulation on executive function, an important frontally based cognitive faculty involved in a wide variety of common cognitive tasks and impaired in a number of neuropsychological disorders. We measured executive function using the Wisconsin Cart Sorting Task (Heaton, Chelune, Talley, Kay, & Curtiss, 1993; Milner, 1963), arguably the gold standard test of executive function in neuropsychology.

The Wisconsin Card Sorting Task
The Wisconsin Card Sorting Task (WCST) has been the standard of neuropsychological test of the prefrontal cortex (PFC) in humans (Mattay et al., 2003; Monchi, Petrides, Petre,
Worsley, & Dagher, 2001; Stuss et al., 2000) and is considered by many to be the gold standard of executive function tests (Delis, Kaplan, & Kramer, 2001). The WCST is a complex task that relies on a number of executive cognitive processes, including working memory, inhibition, abstraction, and set shifting (Goldberg et al., 2003; Head, Kennedy, Rodrigue, & Raz, 2009; Milner, 1963; Miyake et al., 2000). In the WCST, a participant’s task is to match a test card to one of the four reference cards. They are initially told nothing of the classification rule, which is to be acquired through feedback provided after each response. The cards have three dimensions (colour, shape, and number), and the rule is to match on one of these dimensions. After achieving 10 correct responses in a row, the rule is unexpectedly changed, requiring the participant to detect the change and adapt to the new task demands. Working memory is involved in maintaining the currently relevant rule, and set-shifting ability is necessary to switch between changing rules, which requires inhibiting the previously relevant rule. The WCST can also be seen as a measure of cognitive flexibility (Buchsbaum, Greer, Chang, & Berman, 2005), and so the WCST involves a wide array of the cognitive processes comprising executive function.

The WCST has proved a useful tool in evaluating executive processing deficits in a number of neuropsychological disorders as well as other special populations. For example, deficits are commonly found in patients with Parkinson’s disease (Monchi et al., 2004; Owen et al., 1992), schizophrenia (Berman et al., 1995; Daniel et al., 1991; Egan et al., 2001), Alzheimer’s disease (Binetti et al., 1996; Paolo, Tröster, Blackwell, Koller, & Axelrod, 1996), bipolar disorder (Martinez-Aran et al., 2002; Morice, 1990), and in depressed individuals (Channon, 1996; Davis & Nolen-Hoeksema, 2000; Harvey et al., 2004). There are also well-established effects associated with normal ageing (e.g., Fristoe, Salthehouse, & Woodard, 1997; Head et al., 2009; Salthehouse, Atkinson, & Berish, 2003).

The WCST was developed as a diagnostic test of frontal cortical pathology. Patients with lesions in the PFC show impairments in WCST performance (Demakis, 2003; Milner, 1963; Stuss et al., 2000). Imaging work has also sought to localize the brain regions engaged while performing the WCST and to isolate the areas associated with specific executive functions that are required. A wealth of evidence from fMRI, positron emission tomography, and transcranial magnetic stimulation (TMS) implicates lateral PFC in WCST performance (Ko, Monchi, Pito, Petrides, & Strafella, 2008; Monchi et al., 2001, 2004; Nagahama et al., 1996). Monchi et al. (2001, 2004) found increased activity in mid-dorsolateral prefrontal cortex (DLPFC) (areas 9/46) during feedback presentation and increased activity in mid-ventrolateral PFC (areas 47/12) specifically during negative feedback. Konishi et al. (1998) also found set-shifting-related activity in DLPFC (areas 44/45). Ko et al. (2008) found that applying repetitive TMS to the right DLPFC during feedback hindered WCST performance, suggesting that DLPFC plays an integral role in completing this task. Animal work has also implicated DLPFC in set-shifting tasks (Dias, Robbins, & Roberts, 1996, 1997; Passingham, 1972).

While other areas have been implicated (e.g., inferior parietal lobule, anterior cingulate cortex, and cerebellum; Buchsbaum et al., 2005), lateral PFC is the most consistently reported, and often strongest, area of activation. Many studies report bilateral activation, but activity in the right hemisphere is more consistently implicated in WCST performance (Ko et al., 2008; Konishi et al., 1999). For this reason, we chose to target right DLPFC and ventrolateral PFC (VLPFC) with our LLLT intervention. We applied active LLLT transcranially to two areas of the right forehead, targeting DLPFC and VLPFC, in an 8-min session before administering the WCST. Our results suggest that LLLT treatment improved overall WCST performance compared to placebo controls, with this being primarily due to an improvement in set-shifting ability.
Methods

Participants
Participants were 30 (13 female; 17 male) undergraduate students who participated in partial course credit. Participants’ mean age was 20.4 (SD = 1.64) years. As discussed below, participants were assigned to either an active or a placebo group. The active and placebo groups did not differ in terms of age (20.4 vs. 20.07 years, respectively), \( t(28) = 0.46, \ p = .65, \ d = .168 \), or gender (7/15 vs. 6/15 female, respectively), \( \chi^2 = 0.136, \ p = .713 \).

General procedure
The experimenter obtained informed consent from participants at the beginning of the experimental session. The consent form included details about the safety procedures relevant to the operation of the laser used to conduct the LLLT. Verbal explanation of these procedures was also given. Participants were told that they might be either in the active treatment or in placebo treatment groups and that they would not be told which group they were in. After the experiment was concluded, they were informed which group they were in if they wished to know. After the verbal explanation, participants were given the chance to opt out of the experiment with no repercussions, but all participants chose to participate.

Once consent was given, the LLLT session began. Half of the participants (15) received active LLLT administration, and the other half received placebo treatment. Condition assignment was counterbalanced between participants, with every other participant receiving active treatment. The LLLT session lasted 8 min, administered in eight 1-min treatments alternating between two locations on the forehead. Each location was 4 cm in diameter, with little overlap to cover the right lateral forehead in each subject (Figure 1). For the active LLLT group, administration began with location 1 (the lower right portion of the forehead), directly above the eyebrow, switched to location 2 (the upper right side of the forehead), and alternated between the two areas. In reference to the standard 10-20 EEG electrode placement system, the area stimulated covered the right frontal polar (FP2) and right frontal (F4) sites.

For the placebo group, the procedures were identical except that participants received only a brief (5 s) LLLT treatment to the intended site, followed by 55 s of no treatment, during each 1-min treatment session. Thus, the placebo group received approximately 1/12th of the cumulative light energy density as the active treatment group. This low energy has been found ineffective to improve cognition (Barrett & Gonzalez-Lima, 2013) and it was intended as a sham control to equate subjective experience between the active and placebo groups, as participants often report feeling a slight warm sensation at the start of a treatment session. Because the apparatus emits a sound at the start and end of each session, the laser remained on during the full 60-s session, but was simply directed away from the participant’s forehead towards a designated location on the wall for the remaining 55 s. Previous work has validated the effectiveness of this placebo control procedure (Barrett & Gonzalez-Lima, 2013), showing that participants were at chance when asked to indicate which group they believed they were in, with approximately half of the participants in each group believing they were in the active treatment condition. Immediately following the 8-min placebo or LLLT treatment, participants completed a computerized version of the WCST.
LLLT apparatus and procedure

LLLT treatment consisted of applying laser light of a specific wavelength (1,064 nm) that intersects with the absorption spectrum of cytochrome oxidase and maximizes tissue penetration (Sommer, Pinheiro, Mester, Franke, & Whelan, 2001). Treatment was administered using a laser diode supplied by Cell Gen Therapeutics, LLC (Cell Gen laser; HD Laser Center, Dallas, TX, USA). LLLT received approval by the FDA in 2002 for relief of pain in arthritis, head and neck pain, and carpal tunnel syndrome. Our device has not been evaluated or approved by the FDA for the specific uses tested in this study. Marketing of the Cell Gen laser in the USA is FDA-cleared as safe for various uses on humans, such as for improving circulation, temporary relief of muscle and joint pain, muscle spasm, stiffness associated with arthritis, and relaxation of muscle tissue. The laser received approval from the University of Texas at Austin Laser Safety Program, and a standard operating procedure and room for the laser were approved by the University Laser Safety Officer.

During placebo and active treatment, the experimenter and the participant remained inside the locked laser room, with a sign on the outer door indicating that the laser was in use, and wore protective eyewear (900–1,000 nm: 5+, 1,000–2,400 nm: 7+; 2,900–10,600 nm: 7+) at all times. As an additional precaution, participants were instructed to keep their eyes closed while the laser was in use.

The laser wave was continuous (not pulsed) with a uniform circular beam area that measured 13.6 cm². A button on the handle controlled the onset and offset of the photodiode. Each 1-min treatment cycle was marked by a timer counting down and by a beep from the apparatus. Each of the two forehead locations was exposed to an irradiance (or power density) of 250 mW/cm² (3,400 mW/13.6 cm² = 250 mW/cm²) for 4 min (3.4 W × 240 s = 816 J/location), which corresponded to a cumulative fluence (or energy density) of 60 J/cm² (0.25 W/cm² × 240 s = 60 J/cm²). The chosen energy density of 60 J/cm² is the same that showed psychologically beneficial effects in Barrett

Figure 1. Locations targeted by low-level light therapy (LLLT) administration. LLLT was applied to both locations for four 1-min treatments each, beginning with the location 1 (the lower location) and alternating between the two locations, for a total of eight 1-min treatments.
and Gonzalez-Lima (2013) and Schiffer et al. (2009). At the power level used (3.4 W), this laser dose is safe, exposure to it is not harmful to tissue, and it causes negligible heat and no physical damage. Higher powers (15–20 W) are used clinically by Cell Gen Therapeutics for the treatment of lower back pain, sciatica, and migraine headaches.

**Wisconsin Card Sorting Task procedure**
Participants completed a computerized version of the WCST. In the WCST, the participant’s task is to sort a target card into one of the four groups. The groups are represented by four reference cards that are fixed and presented at the top of the screen at all times during the experiment (Figure 2). On each trial, a target card was presented in the centre of the screen, and the participant clicked on one of the four reference cards to sort it into that group. Stimuli consisted of the standard WCST 64-card stimulus set. The set of cards was run through twice for a total of 128 trials. Each card contained elements that varied along three dimensions: Colour (red, green, yellow, or blue), shape (triangle, star, cross, or circle), and number (1, 2, 3, or 4). The reference cards were one red triangle, two green stars, three yellow crosses, and four blue circles – each differing from the others on every dimension. After a selection, feedback was provided indicating whether the response was ‘Correct’ or ‘Incorrect’. The correctness of the response was determined by a rule – matching along one of the three dimensions. Starting rule (shape, colour, or number) was counterbalanced between participants. Unbeknownst to the participant, after 10 consecutive correct trials the rule changed; the relevant dimension switched to one of the other two dimensions. The task continued in this manner until all 128 trials were completed, which took participants 10–15 min to complete.

**Results**
We first compared overall accuracy between the active treatment and placebo groups. The active laser treatment group had a significantly higher overall accuracy than the
placebo group (Figure 3a), \( t(28) = 2.068, p = .048, d = .755 \). The active group sorted correctly on 85.5% of trials, and the placebo group sorted correctly on 79.7% of trials. To better understand the nature of this performance difference, we then analysed the number of trials to criterion for the initial and subsequent rules. Figure 3b plots this measure for the first four rules learned, which was the minimum number of rules completed by any participant. A group by rule ANOVA (with participant as an error term) showed a main effect of group, \( F(1, 28) = 5.492, p = .026 \). The main effect of rule, \( F(3, 84) = 1.786, p = .156 \), and the interaction, \( F(3, 84) = 1.603, p = .195 \), were not significant. The two groups did not differ on the number of trials needed to learn the initial rule, \( t(28) = 0.15, p = .882, d = .055 \). However, the active laser treatment group learned the second rule significantly faster than the placebo laser group, \( t(28) = 2.268, p = .031, d = .828 \). Although the numerical learning advantage for the active laser treatment group remained for the third and fourth rules, these differences did not reach statistical significance, \( t(28) = 1.599, p = .121, d = .584 \), and \( t(28) = 1.087, p = .286, d = .397 \), respectively. We also examined response time data to determine whether the performance differences might be accounted for by differing speed-accuracy trade-offs between the two groups. The active (1,508 ms) and placebo (1,439 ms) did not differ in response times, \( t(28) = 0.514, p = .611, d = .188 \). All reported \( t \)-tests are two-tailed tests.

**Discussion**

This article reports the first study to investigate the effects of transcranial laser stimulation on executive function using the WCST, which is the gold standard measure of executive function in neuropsychology (Delis et al., 2001; Mattay et al., 2003; Monchi et al., 2001; Salthouse et al., 2003; Stuss et al., 2000). We applied LLLT transcranially using an infrared laser diode targeting the lateral PFC. Using transcranial infrared laser stimulation in humans to enhance neurometabolic activity as a means of treatment, neuroenhancement, or neuroprotection is a novel technology with exciting potential. Previous studies have

![Figure 3. Results. (a) Overall accuracy across all trials for the two groups. The active laser treatment group correctly sorted the cards more often than the placebo group. (b) Trials to criterion for each of the first four rules learned. The placebo treatment group took significantly longer to reach criterion on the second rule than the active laser treatment group, suggesting a benefit in set-shifting ability in the active treatment group. Error bars represent standard errors.](image-url)
shown increased cerebral metabolic energy production, oxygen consumption, and blood flow in animals and humans following transcranial LLLT (Gonzalez-Lima & Barrett, 2014; Lampl et al., 2007; Nawashiro, Wada, Nakai, & Sato, 2012; Rojas et al., 2008, 2012; Schiffer et al., 2009). Executive function is an important aspect of cognition that is compromised in a number of neuropsychological disorders such as depression (Channon, 1996; Davis & Nolen-Hoeksema, 2000; Harvey et al., 2004), schizophrenia (Berman et al., 1995; Daniel et al., 1991; Egan et al., 2001; Monchi et al., 2004), Parkinson’s disease (Monchi et al., 2004; Owen et al., 1992), Alzheimer’s disease (Binetti et al., 1996; Paolo et al., 1996), and bipolar disorder (Martinez-Aran et al., 2002; Morice, 1990), as well as by normal ageing (Head et al., 2009).

Our results demonstrate that WCST performance can be improved with a single 8-min LLLT session. We take this as further evidence in a growing body of evidence, suggesting that LLLT may have neuropsychological applications (Naeser et al., 2014; Rojas & Gonzalez-Lima, 2013), and see it as a first step towards investigating its efficacy in the treatment and prevention of conditions compromising executive function. Towards that end, a number of important questions remain that must be addressed with future research. While we have shown that transcranial laser stimulation can improve executive function in healthy young adults, its effectiveness in attenuating deficits in executive function resulting from disorders or ageing has yet to be investigated in placebo-controlled studies.

Another important issue in assessing whether it may serve as an effective clinical treatment is the duration of the effect. If the effect were only momentary, it would prove impractical. Currently, little is known about the durations of LLLT’s effects, although previous studies suggest the benefits could last for several weeks. For example, Barrett and Gonzalez-Lima (2013) found a significant benefit as compared to the placebo group in positive and negative affective states in healthy volunteers (n = 40) 2 weeks after a single laser treatment as described here. In depressed patients (n = 10), Schiffer et al. (2009) reported psychological benefits at 2 and 4 weeks after a single treatment. Light power density (250 mW/cm²) and energy density (60 J/cm²) used in these two studies were the same we used, but the study by Schiffer et al. (2009) used 810-nm LEDs instead of 1,064-nm laser and they did not use a placebo control group. Naeser et al. (2014) used similar LEDs in patients with mild traumatic brain injury (n = 11) for 18 treatments (3/week for 6 weeks). They monitored cognitive performance after 1 week, and 1 and 2 months after the 18th treatment, and reported a significant linear trend for the effect of LED treatment over time for the Stroop test for executive function and the California Verbal Learning Test. While these pioneering studies are promising, there are no placebo-controlled human studies investigating long-term cognitive effects after single or repeated LLLT treatments.

Additionally, we need to investigate to what extent these effects generalize. The wide array of previously reported effects using LLLT suggests that its beneficial outcomes may be rather general, although targeted location is likely an important factor. Various effects may be elicited through targeting different brain regions. But, we may also expect that targeting the lateral PFC might have general beneficial effects, as executive function is an important cognitive process involved in myriad tasks. Indeed, the WCST is a complex task involving numerous executive processes. Due to the complex nature of the WCST and the variety of processes involved, the exact mechanism of the improvement in performance is unclear. That performance was higher for the active treatment group on the second, but not the first, rule suggests an improvement in set-shifting ability (i.e., cognitive flexibility), but there are other possible explanations. First, the WCST relies on working memory, and it is possible that improved working memory function is responsible for the performance improvement. This would be consistent with the improved working memory
performance found in a delayed match-to-sample task after the same infrared laser
treatment by Barrett and Gonzalez-Lima (2013). And, while WCST may be seen primarily
as a test of cognitive flexibility or set shifting, it is also a learning task. The possibility that
the beneficial effect of LLLT administration to the lateral PFC could improve other types of
learning warrants investigation. For example, an improvement of learning would be
consistent with the LLLT findings of Naeser et al. (2014) using the California Verbal
Learning Test. As a learning task, the WCST is essentially a rule-based categorization task
(Hélie, Paul, & Ashby, 2012), and so LLLT treatment may be able to provide a general
benefit during category learning. We see this as a particularly promising field of
investigation. Current theories of categorization typically posit (at least) two category-
learning systems: A frontally based, explicit system, and a striatally based, implicit system
(Ashby & Maddox, 2011). The frontal system excels at rule-based tasks, so it is consistent
with a dual-learning systems theory that enhancing metabolism in the PFC could improve
learning in the WCST. It remains to be seen whether LLLT targeted at PFC would also
improve other, non-rule-based categorization, or whether the benefit is specific to rule-
based tasks.

Another important question that needs to be investigated in future research is whether
there are cognitive costs to enhancing cognition using LLLT. A recent study using
transcranial electrical stimulation showed that enhancing one cognitive process may
come at the expense of other cognitive processes (Iuculano & Cohen Kadosh, 2013). It
remains to be seen whether the same type of cost to enhancing a cognitive process occurs
with LLLT given the differences in mechanism between the techniques. LLLT enhances
metabolic energy in neurons by a cytochrome oxidase photostimulatory mechanism that
is fundamentally different than the mechanism of other methods of brain stimulation such
as electric or magnetic stimulation. For example, during excitatory electrical stimulation
as used for transcranial direct current stimulation (tDCS), there is expenditure of
metabolic energy, while effective LLLT doses increase metabolic energy (Gonzalez-Lima &
Barrett, 2014). Animal studies have shown that LLLT upregulates the amount of brain
cytochrome oxidase for up to 2 weeks after light stimulation (Rojas et al., 2008), thereby
increasing brain capacity to produce metabolic energy to enhance cognitive functions
(Rojas et al., 2012).

**Conclusion**

Our study suggests that transcranial LLLT may have a range of potential benefits for
cognitive enhancement, but it also highlights the great need for future research to
establish the generalizability, duration, and specific cognitive mechanism of its effects.
Future controlled studies should also examine its efficacy as treatment for executive
processing and other cognitive dysfunctions in neuropsychological disorders and normal
ageing. Low-power LED arrays and laser diode sources are compact, portable, commer-
cially available, and have achieved non-significant risk status for human trials by the FDA
(Rojas & Gonzalez-Lima, 2013). If proven, effective LLLT could provide an affordable, safe
alternative to current treatment options for cognitive impairment and brain dysfunction.

**Acknowledgements**

The authors thank Raj Panesar for help with data collection. FGL gratefully acknowledges
support from an institutional research fellowship from the College of Liberals Arts of the
University of Texas at Austin. FGL holds the George I. Sanchez Centennial Endowed Professorship in Liberal Arts and Sciences. Research reported in this publication was supported by the National Institute on Drug Abuse at the National Institute of Health (DA032457 to WTM and DA032457-01A1S1 to NJB). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health.

References


Laser-enhanced executive function

catechol-O-methyltransferase Val158Met genotype and schizophrenia. *Archives of General Psychiatry, 60*, 889–896. doi:10.1001/archpsyc.60.9.889


Received 7 March 2015; revised version received 28 April 2015