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Enhancing Cognitive Function Using Perceptual-Cognitive Training

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Abstract

Three-dimensional multiple object tracking (3D-MOT) is a perceptual-cognitive training system based on a 3D virtual environment. This is the first study to examine the effects of 3D-MOT training on attention, working memory, and visual information processing speed as well as using functional brain imaging on a normative population. Twenty university-aged students were recruited and divided into a training (NT) and nonactive control (CON) group. Cognitive functions were assessed using neuropsychological tests, and correlates of brain functions were assessed using quantitative electroencephalography (qEEG). Results indicate that 10 sessions of 3D-MOT training can enhance attention, visual information processing speed, and working memory, and also leads to quantifiable changes in resting-state neuroelectric brain function.

Keywords

Multiple object tracking (MOT), cognitive enhancement, brain training, attention, qEEG

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Introduction

Cognitive enhancement is a domain of burgeoning interest, spanning the remediation of clinical disorders (eg, attention deficit/hyperactivity disorder), to enhancing the performance of healthy individuals, professional athletes, and CEOs, to combatting the deleterious effects of time on the growing aging populace. In 2012, despite a significant lack of credible evidence to support their use, the market revenues of computer-based training programs alone were more than 1 billion dollars.[1]

Many different kinds of interventions have been proposed, including rudimentary pencil-and-paper type tasks (eg, sudoku puzzles, crosswords), more advanced computer/video-game type programs (eg, Lumosity), brain-computer interfaces (eg, neurofeedback), nutritional supplements (eg, omega-3 fatty acids, caffeine), and even pharmacological drugs such as stimulants and cognitive enhancers/nootropics (eg, Ritalin, Nuvigil). Less invasive methods for enhancing cognition include adopting appropriate lifestyle habits related to nutrition, exercise, and sleep.

Arguments in favor or against each type of intervention are vast; suffice it to say significant issues plague each of these types of interventions. For a review, the authors suggest reading Dresler et al,[2] Jak et al,[3] the special report prepared by the Academy of Medical Sciences,[4] and Gruzelier.[5] Generally speaking, the complaints against these interventions are the following: Transfer effects are not consistently observed, the effects observed do not persist in time, the methods are invasive and include risk of significant side-effects, a significant monetary and time investment is required, and there are the ethical issues associated with the use of these interventions. While a thorough analysis of each individual cognitive enhancement tool is beyond the scope of this article, shown in Table 1 is a general assessment of each specific intervention type. As can be seen, little research has been conducted to support the widespread use of the majority of these methods, and much more is needed before definitive conclusions can be reached.

With these limitations in mind, the gold standard in cognitive enhancement would thus be an intervention that shows (*a*) robust effects with transfer, (*b*) no side effects or risk of toxicity, (*c*) minimal time and monetary investment, (*d*) lasting effects,

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Table 1. General Assessment of Various Methods of Cognitive Interventions.

	Pencil and Paper	Computer Games	Brain-Computer Interface	Nutritional Supplements	Stimulants and Nootropics
1. Robust effects with transfer	Inconsistent[3]	Inconsistent[2,3]	Yes[5]	Yes[2]	Inconsistent[2,4]
2. Side effects/toxicity	None reported	Insignificant[3]	Insignificant[5]	Signifcant[2,4]	Significant[2,4]
3. Investment	Continuous[3]	20+ hours[3]	10+ hours[5]; 30-40 hours[6]	Continuous[2,4]	Continous[2,4]
4. Lasting effects	Not reported	Unknown[3]	Yes[5,6]	No[2]; Tolerance[2]	No[2,4]
5. Ethical issues	None reported	None reported	None reported	None reported	Yes[2,4]
6. Mutually exclusive	No reported contraindications	No reported contraindications	No reported contraindications	Some contraindications[4]	Some contraindications[4]
7. Potential populations	Healthy aging[3]	Various	Various[5,6]	Various[4]	Various[2,4]

(*e*) no ethical issues, and (*f*) can be used in combination with others. In addition, this intervention should (*g*) apply to virtually any population. The current study aims at providing preliminary evidence for such gold-standard achievement using an intervention of perceptual-cognitive training: 3D-MOT.

3D-MOT

Three-dimensional multiple object tracking (3D-MOT) is a perceptual-cognitive training program adapted by Dr Jocelyn Faubert of the University of Montreal.[7] Initially devised by Pylyshyn and Storm[8] as a research tool, the multiple object tracking (MOT) task has since been adapted as a training tool called NeuroTracker.[7] So far, this tool has been used in aging populations to improve biological motion perception[10,11] and linking athletic performance levels and learning capacity on this task.[7,9]

As a cognitive enhancer, 3D-MOT has 4 defining characteristics essential to achieving the gold standard. First, the training uses (*a*) MOT, (*b*) a large visual field, and (*c*) binocular 3D. All these contribute to the ecological validity of the training. Daily, we must attend to multiple pertinent sources of information while inhibiting nonrelevant information (MOT) across our entire 3D perceptive field (large visual field and binocular 3D). By using speed thresholds, the training is adaptive and consistently maintains the difficulty level within the zone of proximal development.

The task also follows 2 principles fundamental to training cognitive abilities (for a comprehensive review, see Faubert and Sidebottom[7]). First, it is rudimentary and does not require a complex strategy but instead requires low-level cognitive systems. Second, it consistently asks the trainee to perform at and above their current level of functioning. The principles behind 3D-MOT training are thus to *isolate* and *overload*.

Isolation in this sense means that a number of functions solicited for the task should be limited and consistent. A training task should not draw on a random and inconsistent combination of cognitive functions to complete. If isolation does not occur, training effects are reduced.

Overloading a function means soliciting it beyond its current ability. To properly train any function, overloading must occur so that adaptation (in the brain: neuroplasticity) can take place. It is important to note that in any learning paradigm, overloading should be maintained within a range to ensure it falls within the zone of proximal development.[12] Speed thresholds ensure an appropriate level of *overload*.

Cognitive Functions

The cognitive functions engaged in 3D-MOT are theorized to be (*a*) attention, (*b*) working memory, and (*c*) visual information processing speed. The reason will become apparent in the description of the task in the methods section, and will be further explained in the discussion. The working definitions of each function are described in Table 2.

We hypothesize that the cognitive functions described above will demonstrate significant improvement following 10 sessions of 3D-MOT training. Quantitative changes in brain function should also be observed fitting the established patterns of these cognitive functions; namely we expect increased beta relative to slower brainwave frequencies, and increased gamma over the occipital cortex.

Methods

Twenty university-aged students were recruited from the greater Montreal area and assigned randomly to either the 3D-MOT training (NT; n = 10) group or control (CON; n = 10) group. Both groups had an equivalent number of years of post-secondary education (NT = 4.40 ± 1.35), CON = 4.40 ± 1.17) and were similar in age (NT = 23.54 ± 2.56 years, CON = 23.02 ± 2.78 years). No individuals taking psychoactive medication, nor with a known diagnosis of a cognitive disorder were included in the study. The project was approved by the Université de Montréal ethics committee (CERES; Comité d'éthique de la recherche en santé). No high-level athletes were included in the sample because of their enhanced learning ability in this task.[9]

Table 2. The Cognitive Functions Involved in 3D-MOT.[a]

Cognitive Function	Definition
Attention	
Sustained	The ability to maintain selective attention over time
Selective	The ability to attend to/focus on/cognitively process a given thing
Divided	The ability to selectively attend to multiple loci at once (multifocal)
Inhibition	The ability to not attend/focus on/cognitively process a given thing
Short-term memory	The ability to retain information over a short time span (20-30 seconds)
Working memory	The ability to retain and transform information over a short time span
Information processing speed	The time needed to consciously integrate perceptual stimuli

[a]Adapted from Banich and Compton.[13]

Evaluation

All subjects underwent identical initial and final testing. The testing sessions lasted between 2 and 2.5 hours. Testing consisted of a quantitative electroencephalogram (qEEG), a battery of neuropsychological tests, and a 3D-MOT session. Neuropsychological measures included the Integrated Visual and Auditory Continuous Performance Test (IVA+Plus CPT; www.braintrain.com), selected subtests from the Wechsler Adult Intelligence Scale (WAIS-III),[14] including symbol search, code, block design, number sequence, letter-number sequence and spatial span, the d2 attention test,[15,16] and the Delis-Kaplan Executive Functions System Color-Word Interference Test (D-KEFS).[17] The 3D-MOT portion of the evaluation was identical to the training sessions described below.

The IVA+Plus is a computerized continuous performance task designed to measure attention. In this task, subjects are asked to identify target stimuli—the number "1" presented visually and auditorily—by clicking the left button on a mouse. Amid these target stimuli, are distracting stimuli—the number "2" presented both visually and auditorily—and subjects are asked not to respond to these stimuli. The task lasts approximately 20 minutes.

The WAIS-III symbol search is visual information processing speed test. A pencil-and-paper task, subjects are shown 2 target symbols followed by a string of 5 symbols. They are asked to answer either "Yes" or "No." A "Yes" answer means they have identified that 1 of the 2 target symbols is present in the string of 5 symbols.

The WAIS-III code task is also a pencil-and-paper task designed to measure visual information processing speed. In the code task, each digit from 1 to 9 has an associated symbol at the top of the page. Below this, the numbers 1 to 9 are displayed in random order in a grid with an empty space underneath. Subjects are asked to fill in the symbol paired with each digit in the space below each, provided for that purpose.

The WAIS-III block design is a visuospatial abilities task in which subjects are asked to recreate images displayed to them with the use of blocks. Each block has 2 fully red sides, 2 fully white sides and 2 half-white, half-red sides. For each item, the subject is shown the image and must recreate it as quickly as possible. The first 5 items require the use of 4 blocks; the final 5 items require the use of 9 blocks.

In the WAIS-III number sequence, a test to measure auditory short-term memory and working memory, subjects are read aloud a string of digits and are then asked to repeat them back. This is first done with subjects repeating the items in the same order in which they are given, and then they are asked to repeat the task using new items while giving the string back in reverse order. Items are grouped into levels of difficulty, with each level adding a digit to the length of the item.

The WAIS-III letter-number sequence is an auditory working memory task similar to the number sequence, with the addition of letters to the strings given for each item. Additionally, the subjects are asked to reorganize the digits and letters given as follows: letters first, in alphabetical order, followed by numbers, in ascending order.

The WAIS-III spatial span is a visual short-term memory and working memory task. It uses a rectangular board on which are 10 identical cubes. The cubes are numbered so that only the tester may identify them by number, while the subject must only rely on their location. The subject must repeat a sequence demonstrated by the tester by tapping on the correct blocks in the proper order. As in the number sequence task, items are grouped by 2 into levels, with each subsequent level adding one block to the string.

The d2 attention test is a pencil-and-paper type test, in which subjects are looking to cross out target stimuli amongst distractors. Targets are the lowercase letter "d" with 2 vertical dashes on top, 2 vertical dashes on bottom, or 1 vertical dash on top and another on bottom. Distractors consist of lowercase "d"s and "p"s with 1 to 4 vertical dashes above or below the letter, with a maximum of 2 dashes on either side.

The D-KEFS color-word interference test is a visual inhibition test composed of 4 different subtests. Each subtest is timed and the number of uncorrected and corrected errors is noted. The subtests consist of identifying 1 of 3 colors: red, blue, and green. For each subtest, the stimuli are presented listwise, and subjects proceed down the page from left to right, top to bottom. There are 2 lines of 5 items that serve as examples, followed by 5 lines of 10 items, which consist of the timed test. The first subtest is color naming: subjects must simply identify the colored squares. The next is word reading: subjects must

Table 3. 3D-MOT Trial.[a]

Phase	Description	Duration
Presentation (a)	Eight spheres appear, colored homogeneously in yellow	2 seconds
Indexation (b)	Four target spheres turn red with a surrounding white halo	2 seconds
Pause	Targets turn back to yellow, restoring homogeneity	2 seconds
Movement (c)	All spheres move along a linear path in the 3D cube. If a sphere contacts another sphere or a wall of a cube it bounces off and continues along its new trajectory	8 seconds
Identification (d)	All eight spheres cease movement and are labeled with numbers (1-8). Subjects verbally state their responses	User determined
Feedback (e)	The target spheres are revealed, and feedback (number of target spheres correctly identified) is given	2 seconds

[a]See Figure 1 for a visual representation of each phase.

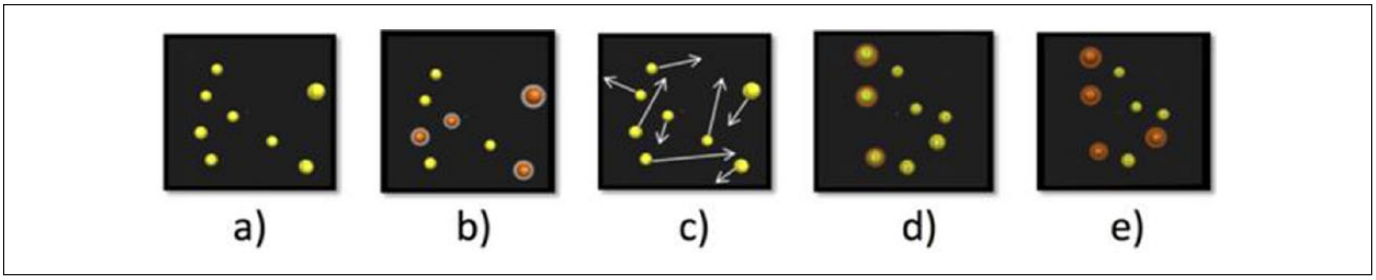

Figure 1. The phases of a 3D-MOT trial.

read the colors printed in black ink. The next is inhibition: subjects must identify each item based on the ink color and not read the word that is written. The final subtest is inhibition/switching: subjects must identify each item based on the ink color and not read the word that is written, unless the item is in a box and in that case they must read the word that is written.

It should be noted that some of the tests used are typically not readministered in quick succession because of the possibility of test–retest effects, notably learning or practice. Considering the time frame of the current study, the tests most prone to test–retest effects include the WAIS-III and all included subtests,[14] and the D-KEFS Color-Word Interference Test.[17] The utilization of a control group should adequately control for these effects.

The qEEG data were acquired using a Mitsar 202 system (www.mitsar-medical.com) at 500 Hz using an augmented 10-20 system; however, only the data from the standard 10-20 electrode placement system[18] were retained for this analysis. The data were recorded using WinEEG (www.mitsar-medical.com) and were analyzed using the NeuroGuide qEEG normative database.[19]

Training

For the NT group, each training session was identical. For each trial, the speed and correct number of targets identified was recorded. Each session lasted between 45 minutes and 1 hour. Sessions were performed between 9 AM and 5 PM twice per week over a period of 5 weeks. The CON group was a nonactive control.

A training session consists of 3 series of 20 trials in which the trainee tracks 4 spherical targets among 4 identical distractors that move linearly through a virtual 3D cube. The cube was projected onto a square projector screen measuring 8 × 8 feet; each side of the cube measured 1.5 m while targets measure 10 cm diameter. The speed for each trial is measured in meters per second and initial start speed of each series is 0.3. All other methodological specifics can be found in Faubert and Sidebottom.[7]

During the first phase of each trial, all 8 spheres appear in yellow and are stationary. Next, the 4 target spheres that the trainee must track appear in red for 2 seconds, before switching back to yellow. The spheres begin movement and tracking then occurs over a period of 8 seconds. All 8 spheres move along a linear path through the cube; should any sphere encounter an obstacle it bounces off that obstacle and continues along its new path. At the end of this phase, each sphere is identified with a number and the trainee is asked to verbally state their responses. Table 3 outlines each phase of a 3D-MOT trial and a visual representation can be seen in Figure 1.

If all 4 targets are correctly identified the speed of the subsequent trial increases. If an incorrect response is given, the speed of the subsequent trial decreases. The speed changes are based on an adaptive staircase: Initial speeds vary more widely than later trials to ensure that the optimal zone for training is quickly attained. Ideally, in order to maintain a zone of proximal development, the majority of trials should be at and slightly

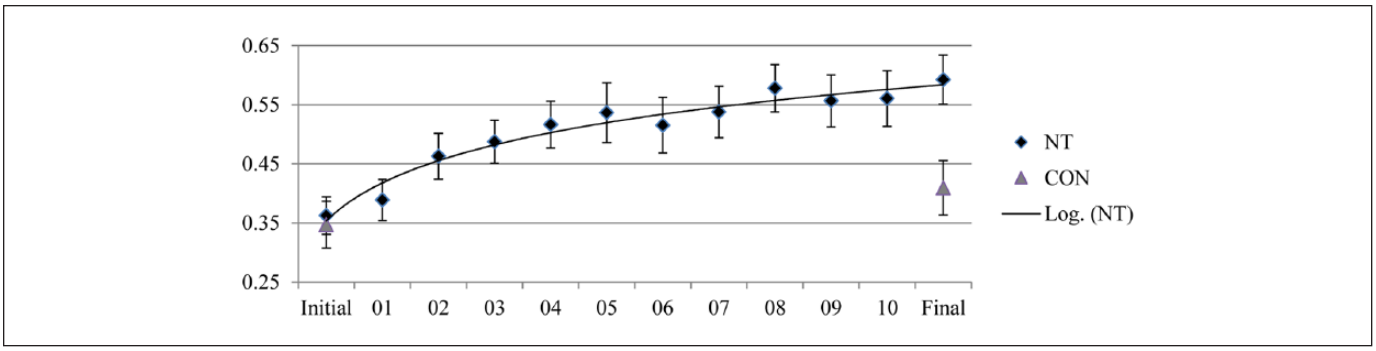

Figure 2. 3D-MOT session scores for NT (training) and CON (control) groups; GEO mean with standard error. The final session score for the CON group is statistically similar to the first training session of the NT group. Initial session scores were 0.36 for the NT group and 0.35 for the CON group. Standard errors were 0.03 and 0.04, respectively. The NT group's first session was 0.40 with a standard error of 0.03, while the CON group's final session was 0.41 with a standard error of 0.05.

above the trainee's current level of ability. An adaptive staircase[9,10] ensures this while adjusting for endurance and fatigue. At the end of a series of 20 trials, a final speed threshold score is given. A subject's session score comprises the average threshold score of the 3 series of 20 trials. Four targets are used as research has shown that most people can generally track four elements in such a context.[20]

Data Analysis

All the neuropsychological tests were scored and EEGs analyzed by the first author. One minute of artifact-free data from the pre- and post-qEEGs were selected by the author respecting a blind design using the NeuroGuide Normative Database (version 2.7.9, 2013). Test-retest and split-half reliability measures were kept higher than .90.

Results

3D-MOT

As expected, 3D-MOT session scores showed significant improvement ($P < .01$) from initial to final testing for the NT group. Interestingly, the CON group also showed a strong improvement ($P = .016$) from their initial to final testing session. The 2 groups differed significantly in their final session score ($P < .01$). Session scores for both groups along with log trend line for NT group are shown in Figure 2.

Cognitive Functions

A Levene test yielded no significant differences in homogeneity between groups ($P > .01$; only WAIS letter-number sequence was significant at $P < .05$) between groups prior to training. An analysis of variance of initial results demonstrated that there was no significant difference between groups on neuropsychological tests prior to testing. A repeated-measures analysis of variance was also performed with training condition (training or control) as the between-subject factor. A main effect of training was found ($F = 36.232$; $P < .01$), as was an interaction for training × group ($F = 13.201$; $P < .01$). As a consequence of the a priori hypotheses regarding cognitive functions, planned follow-up t tests were used to compare neuropsychological measures pre- and posttraining. Because of the exploratory nature of the research at hand and the accordingly lenient nature of the statistical tests used, a more stringent alpha of $P < .01$ was required to achieve significance. The mean pre- and posttraining, the degree of change, and results of the planned t tests can be seen in Table 4.

The NT group demonstrated significantly higher scores with regard to the IVA+Plus Auditory, WAIS Symbol Search, WAIS Code, WAIS Block Design, WAIS Letter-Number Sequence, d2 Test of Attention, and D-KEFS Color Naming, Inhibition and Inhibition/Switching subtests ($P < .01$). The NT group also displayed a couple of trends toward significance, including IVA+Plus Visual and WAIS Spatial Span ($P < .1$). With regard to the individual IVA+Plus subscales, there were significant improvements in Visual Consistency ($P < .01$), and Auditory Speed ($P < .01$). Auditory Stamina ($P < .05$), Auditory Focus ($P < .05$), and Visual Speed ($P = .068$) also showed a trend toward significance.

With regard to the CON group, only the D-KEFS Inhibition/Switching subtest attained significance, while WAIS Code, WAIS Block Design, d2 Test of Attention and D-KEFS Inhibition subtest demonstrated trends ($P < .1$).

Initial IVA+Plus testing demonstrated higher scores in the visual domain (97.57) contributing to a ceiling effect that is observed to a lesser extent in the auditory domain (93.40). This is likely the reason why visual attention comparisons do not attain significance but do trend toward significance; visual attention scores remained higher in posttraining measures (104.60 vs 101.58 for auditory).

Table 5 shows which tests demonstrate significant improvement, where relevant, related to each of the cognitive functions being assessed. This is discussed at length in the Discussion section.

Table 4. Neuropsychological Test Results: Pre–Post Within-Group *t* Tests.

	NT Group (n = 10)				CON Group (n = 10)			
Measure	Pre	Post	Change	Significance	Pre	Post	Change	Significance
IVA+Plus–Auditory	93.40	101.58	8.18[a]	.007	97.30	98.98	1.68	
IVA+Plus–Visual	97.57	104.60	7.03[b]	.071	97.80	97.92	1.12	
WAIS–Symbol Search	43.40	48.40	5.00[a]	.004	45.50	49.40	2.90	
WAIS–Code	91.40	101.10	9.70[a]	.000	88.00	95.50	7.50[b]	.015
WAIS–Block Design	51.20	59.20	8.00[a]	.000	56.10	58.60	2.50[b]	.024
WAIS–Number Sequence	20.00	19.90	–0.10		19.60	19.70	0.10	
WAIS–Letter-Number Sequence	13.90	15.70	1.80[a]	.008	12.20	13.30	1.10	
WAIS–Spatial Span	19.40	22.20	2.80[b]	.021	19.00	20.60	1.60	
d2 Test of Attention	437.70	498.10	60.40[a]	.000	465.10	509.30	44.20[b]	.017
D-KEFS Color Naming	27.30	23.60	–3.70[a]	.006	24.90	24.40	–0.50	
D-KEFS Word Reading	20.00	18.10	–1.90		19.10	19.30	0.20	
D-KEFS Inhibition	43.80	38.40	–5.40[a]	.004	44.10	40.20	–3.90[b]	.020
D-KEFS Inhibition/Switching	49.50	42.80	–6.70[a]	.004	50.80	45.60	–5.20[a]	.009

Abbreviations: IVA: Integrated Visual and Auditory Continuous Performance Test; WAIS, Wechsler Adult Intelligence Scale; D-KEFS, Delis-Kaplan Executive Functions System.
[a]Significant at $P < .01$.
[b]Trend toward significance $P < .1$.

Table 5. Improvements in Cognitive Functions as Measured by Neuropsychological Tests Following 3D-MOT Training.

Cognitive Function	Measure
Attention	
Selective	IVA+Plus (Consistency and Focus[a]), WAIS (Symbol Search), d2
Sustained	IVA+Plus (Stamina[a], Consistency, Focus, and Sustained Quotient), d2
Divided	d2 Test of Attention, D-KEFS (Inhibition/Switching)
Inhibition	D-KEFS (Inhibition and Inhibition/Switching[b])
Short-term memory	N/A
Working memory	WAIS (Spatial Span[a] and Letter-Number Sequencing)
Information processing speed	IVA+Plus (Speed[a]) WAIS (Symbol Search, Code, Block Design), d2, D-KEFS (Color Naming and Word Reading)

[a]Indicates a trend toward significance.
[b]Note that the CON group also demonstrated significant improvement in D-KEFS Inhibition/Switching.

Quantitative EEG

In considering the changes hypothesized with regard to cognitive functions, specific changes in qEEG were expected to occur. The figures below demonstrate significant differences in qEEG analysis following training for the NT group. The left figure shows the results of the planned paired 2-tailed *t* test while the figure on the right shows the direction of the change in percent differences in pre–post EEG power. The left figure shows the degree of significance of changes; white indicates no significant change, blue is a change at $P < .05$ and red $P < .001$. The color in the right image shows the direction of the change; blue indicates decrease and yellow-red indicates increase.

Since no consensus on the exact definition of frequency bands exists, the authors discuss specific individual frequencies. For the sake of conformity, the authors refer to the frequency bands as defined in the NeuroGuide database. These are delta (1-4 Hz), theta (4-8 Hz), alpha (8-12 Hz), beta (13-30 Hz), and gamma (30-50 Hz).

Decreased Delta, Theta, and Alpha. As hypothesized, the NT group demonstrated significant absolute power decreases in the theta and alpha frequency bands. The delta band also showed some lesser but still significant reduction. Specifically, decreases were observed across 2 to 11 Hz with eyes closed and 2, 5 to 6, 10 to 11 Hz with eyes open. The changes were noted primarily in the frontal lobes (electrodes FP1, Fp2, F7, F3, Fz, F4, F8, C3, Cz, and C4) while the changes in theta could also be observed over the parietal cortex, most dominantly in the left hemisphere (P3, Pz). These changes can be observed in Figure 3. The CON group did not demonstrate this trend.

Increased Beta. Following the hypothesis of decreased slow-wave power, it was expected that the faster beta frequencies

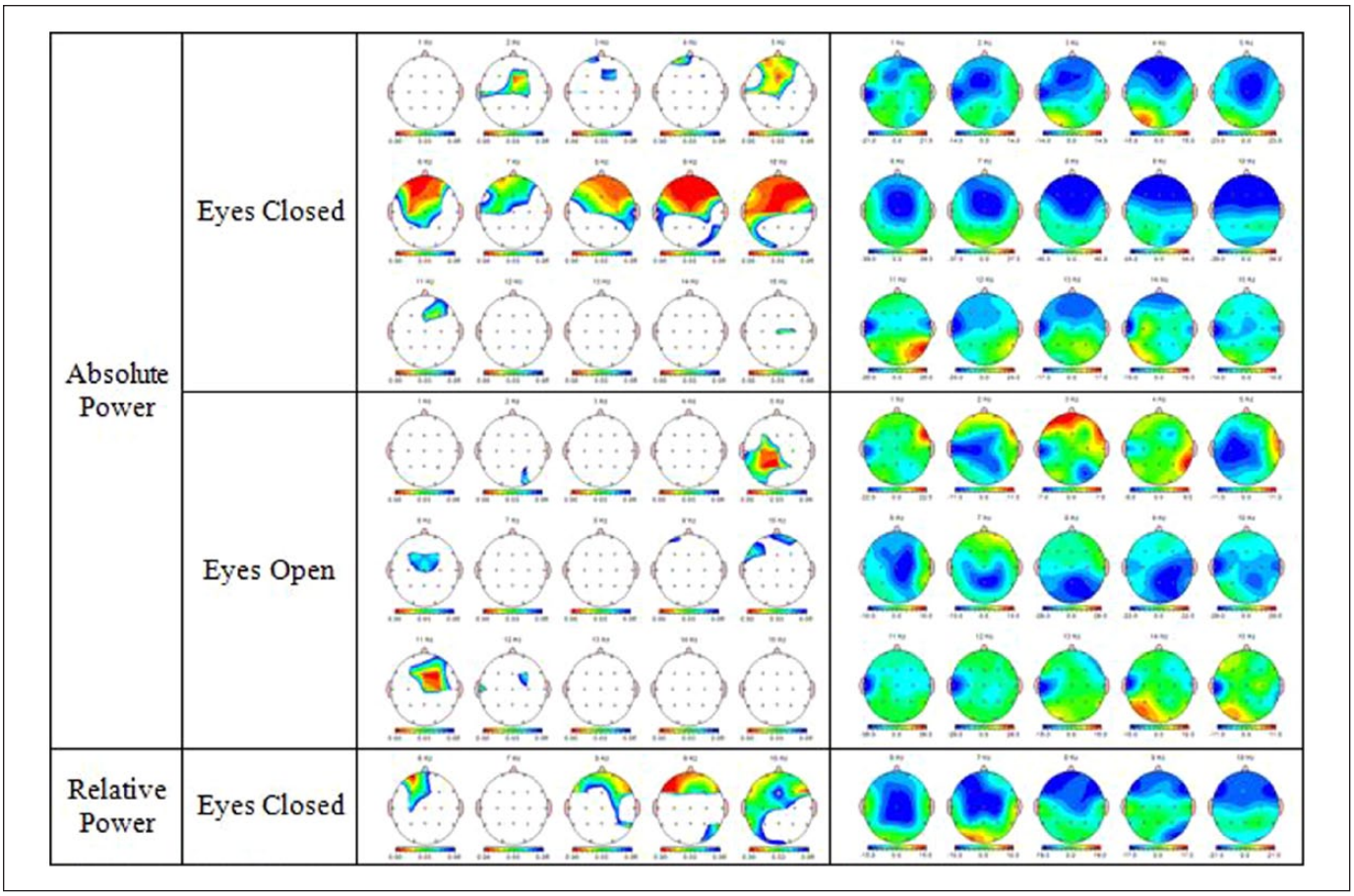

Figure 3. Pre–post changes in delta, theta, and alpha amplitude. Bandwidth segments cut to show significant changes only. Full qEEG maps are available in supplemental figures (available at http://eeg.sagepub.com/content/by/supplemental-data).

would show a more dominant presence. As expected, the NT group demonstrated significant relative power increases in various frequencies within the beta bandwidth, specifically 14, 16 to 18, 22 to 40 Hz with eyes closed and 20 to 23, 28, 34, 37 to 39 Hz with eyes open. These changes were observed across frontal regions (Fp1, Fp2, F7, F3, Fz, F4, F8, C3, Cz, and C4), and are shown in Figure 4. As these changes were limited to the relative power spectrum (there were no significant changes in corresponding frequencies in absolute power) these increases must be interpreted with caution as they may be the result of decreases in other frequencies. Once again, the CON group did not demonstrate this change.

Increased Gamma. The final hypothesis put forth was that the NT group would demonstrate significant increases in Gamma band frequencies, especially at occipital sites. This was the case with eyes open; as shown in Figure 5, the 40-50Hz bandwidth saw significant gains in occipital and parietal sites (O1, O2, Pz, and P4). Interestingly, and also shown in Figure 4, an unexpected trend occurred with eyes closed: the same bandwidth saw significant increases across frontal sites (Fp1, Fp2, F3, Fz, F4, and Cz). The CON group actually showed the opposite effect decreased gamma power at O1 and O2 with eyes open, and no significant difference with eyes closed.

Other Significant Changes. No other significant changes fitting any attentional theory were observed. Full qEEG maps for each testing condition are available in supplemental figures (available at http://eeg.sagepub.com/content/by/supplemental-data).

Discussion

3D-MOT

As expected, the NT group improved over time at the task and even the final session scores continued to show improvement. While the current study does not assess longevity, results suggest that the benefits observed may persist in time. This is demonstrated in the improvement in 3D-MOT scores of the initial and final testing sessions for CON group. The CON group significantly improved over 7 weeks and their session scores resemble the first 2 sessions of the NT group. It appears that the CON group is able to consolidate and maintain an effect from the first testing session despite a 7-week delay between sessions.

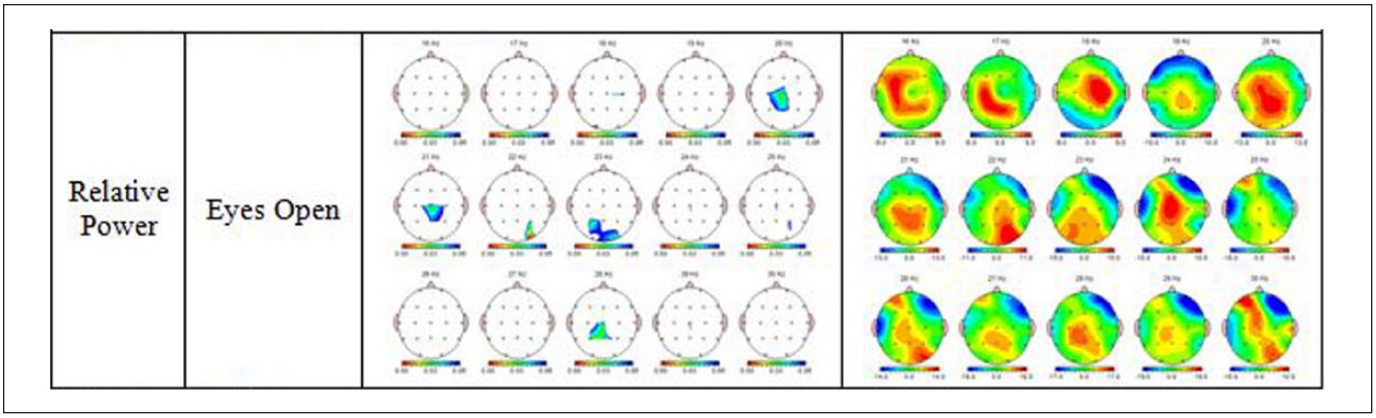

Figure 4. Pre–post changes in beta amplitude. Bandwidth segments cut to show significant changes only. Full qEEG maps are available in supplemental figures (available at http://eeg.sagepub.com/content/by/supplemental-data).

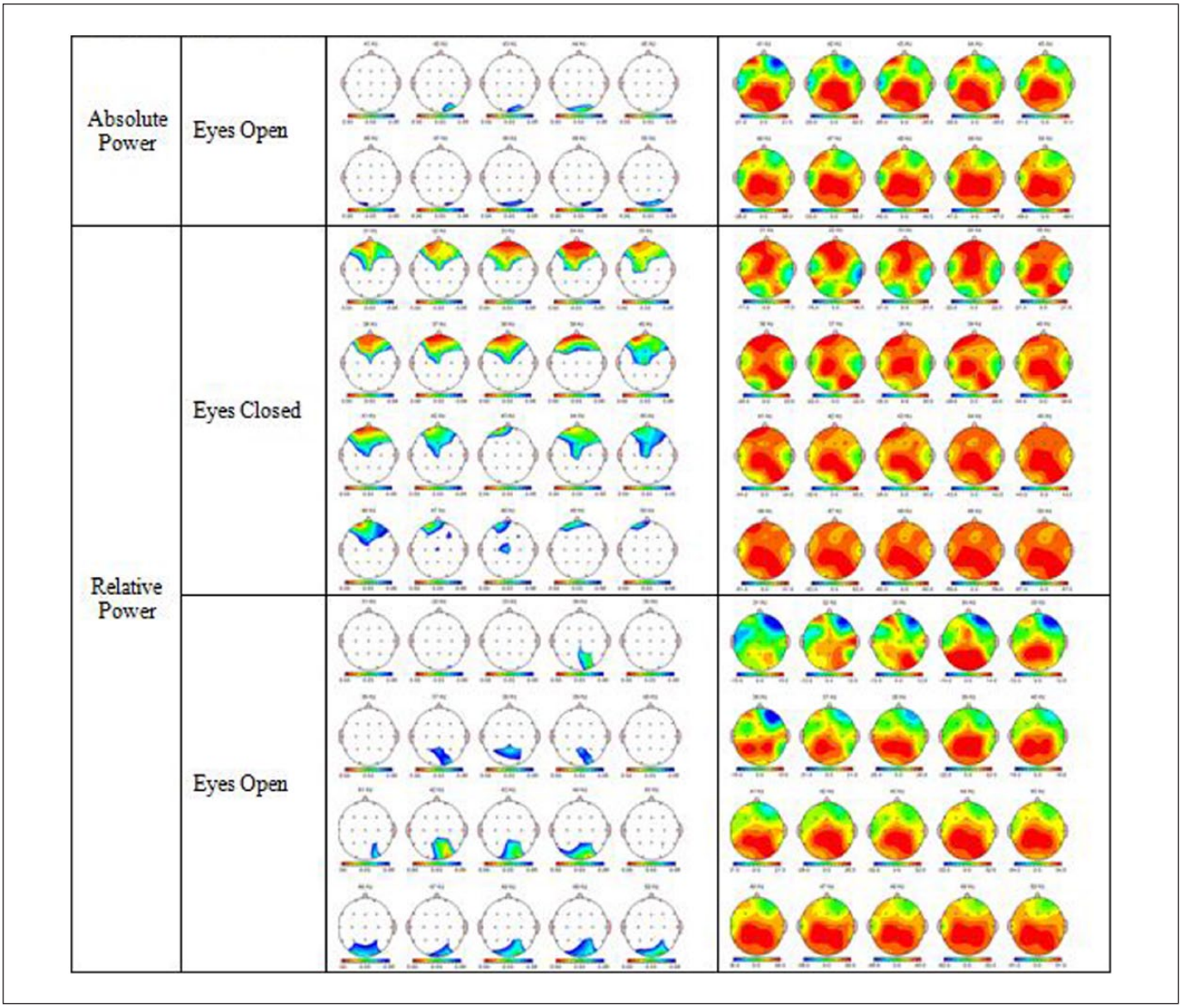

Figure 5. NT group pre–post changes in gamma amplitude. Bandwidth segments cut to show significant changes only. Full qEEG maps are available in supplemental figures (available at http://eeg.sagepub.com/content/by/supplemental-data).

Table 6. 3D-MOT as a Gold-Standard Cognitive Enhancer.

Standard	Status	Details
1. Robust effects with transfer	Yes	Attention, working memory, visual information processing speed; corresponding changes in brain function
2. Side effects/toxicity	Insignificant	Occasional mild fatigue immediately following training, dissipating within 20-30 minutes
3. Investment	5 hours	Optimal training frequency and duration is unknown; 1 hour per week is sufficient
4. Lasting effects	Unknown	
5. Ethical issues	None	
6. Mutually exclusive	Unknown	Further research to examine training in combination; no contraindications were observed
7. Potential populations	Known	Healthy, healthy aging, athletes
	Unknown	Clinical domains

Cognitive Functions

Attention. The 3D-MOT task most heavily solicits attentional resources, and results indicate that sustained, selective and divided attention as well as inhibition can be enhanced with 10 sessions of training. Attention is essentially the gateway of perception into consciousness, it is what "decides" what we see, hear, feel, taste, and smell. Attention modulates our ability to learn and communicate with others, and is a fundamental component of the human mind and consciousness.[21,22]

Since 3D-MOT is purely visual, it begs the question: Why are gains observed in the auditory domain? As described by Wickens,[23] attentional capacities across different modalities are limited by a common resource pool. For example, when performing a complex visual procedure (eg, a complex driving scenario), auditory tasks (eg, maintaining a conversation) become more difficult.[24] It stands to reason that when the substrates of this shared pool are improved all implied modalities would show gains.

Sustained attention. Traditionally, sustained attention tasks require that attention be maintained over a relatively long period of time. The 3D-MOT task taxes this as a session is approximately 30 minutes. More, sustained attention tasks must also be sensitive to slight variations on the scale of fractions of a second. The movement phase of a 3D-MOT lasts only 8 seconds per trial; however, the trainee must consistently maintain attention on all 4 targets. If a target is lost, it cannot be reobtained; Even the slightest lapses in attention result in the failure of the trial.

Selective attention. A trainee must also selectively focus on targets and not on distractors. As the speed of trials increases there are more interactions between targets and distractors. The distribution of attentional resources must remain fluid; a target close to a distractor demands more attention than a target in relative isolation.

Inhibition. Inhibition, in contrast to selective attention, is the ability to not focus on nonpertinent information. They are complementary processes although are considered different constructs.[25] In 3D-MOT, inhibition is regularly called upon: Targets and distractors interact often during the movement phase and one must inhibit focus from distractors.

Divided attention. In MOT, divided (multifocal) attention plays an important role.[26] The 3D-MOT trains an ability to dynamically shift attention along multiple loci, a fundamental principle of divided attention.[27]

Short-Term Memory and Working Memory. Short-term memory is the ability to temporarily retain a limited amount of information in consciousness.[28] Working memory is the ability to manipulate information stored in a temporary bank to suit the task at hand.[29] Previous research has shown a strong link between short-term memory and working memory, the former often posited as being a limiting factor of the latter.[28] Working memory is a higher order task, often being considered a necessary precursor to executive function.[30] Attention is strongly implied in working memory, as is seen in the deficits in working memory in attention deficit populations.[31]

In 3D-MOT, targets must be retained in temporary memory stores (short-term memory) while the targets' movement is internally processed (working memory). The task may affect working memory by improving attention or may directly improve working memory. Once again it appears that shared resources are at play as auditory working memory shows gains similar to those seen in the visual modality; the research of Saults and Cowan[32] supports a shared resource pool.

Visual Information Processing Speed. Perceptual stimulus first enters through sensory organs before being transferred to primary processing areas and then through higher order processing or "association" areas. The speed at which this "bottom-up" transfer occurs is referred to as information processing speed, and can impact decision making and reaction time.[33]

The speed thresholds directly evoke visual information processing speed capacities. Previous work[9] has demonstrated that as individuals progress through training their speed threshold scores increase.

Quantitative EEG

Theta/Beta and Attention. In examining attention using qEEG, studies observe high amplitudes of slow wave activity (2-11 Hz) and relative deficits in faster beta activity (12-20 Hz) in those with attention deficits.[6,34] Psychostimulant pharmacological and neurofeedback interventions for attention deficits have a normalizing effect on the EEG in that they decrease excessive slow waves and increase deficient beta and note resulting improvements in attention.[6,34,35] These findings are concurrent with those observed in this study: improvements in attention in the NT group corresponded with decreases in 2 to 11 Hz slow-wave activity and relative increases in beta.

Gamma, Binding, and Neuroplasticity. The gamma band is relatively new to the family of EEG analysis.[36] The gamma band is traditionally seen as the "binding rhythm" in the brain responsible for the coordination and mobilization of cognitive resources for the task at hand.[37] It is said to reflect underlying large-scale cortical cooperation and phase synchrony triggered by thalamic pacemakers, playing a large role in attention and memory, and a critical role in synaptic plasticity.[37]

The changes observed here in the gamma band are focused on the occipital cortex, the region of the brain responsible for visual processing.[38] The parallel improvements in visual attention, visual working memory, and visual information processing speed are thus reflected in these gamma band increases.

Limitations of the Study and Suggestions for Further Research

This study employed a relatively small sample size; however, considering the promising results of the current study, the authors suggest replication with a higher number of subjects. Different neuropsychological tests and brain imaging techniques as well as questionnaires regarding observed changes in day-to-day life could be used to verify transfer as well as control for test–retest effects. A greater number of sessions, longer training periods, and longer test–retest intervals could yield information on the ideal frequency and duration of training as well as shed light on longevity. The use of an active control group could ensure that observed changes were indeed due to 3D-MOT and not due to nonspecific factors. These changes would ensure stronger statistical significance, and further understanding of the cognitive functions and neural substrates at play in 3D-MOT.

Conclusion

This preliminary study demonstrated that 3D-MOT improves cognitive functions in a healthy population and corresponding changes in brain function were observed. The current study is a first step toward establishing 3D-MOT as a gold-standard cognitive enhancer. Training 5 weeks with 3D-MOT demonstrated robust effects on attention, working memory, and visual information processing speed as measured by neuropsychological tests while corresponding changes measured by qEEG were also observed. Together, these findings suggest that transfer to daily life should be observed; however, further research could include real-world variables for verification. No side effects were noted other than anecdotal reports of mild fatigue immediately following training, and dissipating within 20 to 30 minutes following a session. In terms of time investment, 1 hour per week is sufficient; however, more research is needed to determine the optimal frequency and duration of training. It is currently unknown whether or not the effects of training persist over extended periods of time. No negative ethical issues were observed with regard to 3D-MOT training. Combining 3D-MOT with another type of cognitive intervention could yield superior results; further research is needed. No contraindications for 3D-MOT were observed. Finally, in terms of appropriate populations, this study further solidifies findings of transfer in healthy populations. Clinical populations exhibiting deficiencies in cognitive functions associated with those shown to improve following training would be good candidates for further research. 3D-MOT training could be beneficial for populations suffering from deficits in attention, working memory, and/or visual information processing speed, for example those with attention deficit disorder[39,40] or autistic spectrum disorder.[41] Table 6 resumes the findings of this study to that end.

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Author Contributions

BP was responsible for the design of the project, trained, and supervised the research assistants administering training, performed all pre- and posttesting, and performed all analysis. Authors JF and MB provided supervision and contributed to the design of the research project. TM, AB, MZ, KZ, SB, and OS, performed training sessions. B. Parsons was responsible for redaction and all authors approved the final version of the article.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: BP is a scientific advisor of CogniSens Athletics Inc., which produces the commercial version of the NeuroTracker used in this study. JF is Director of the Visual Psychophysics and Perception Laboratory at the University of Montreal and he is the Chief Science Officer of CogniSens Athletics Inc, which produces the commercial version of the NeuroTracker used in this study. In this capacity, he holds shares in the company.

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References

1. The Economist. Commercializing neuroscience: brain sells. Cognitive training may be a moneyspinner despite scientists' doubts. *The Economist*. August 10, 2013. http://www.economist.com/news/business/21583260-cognitive-training-may-be-moneyspinner-despite-scientists-doubts-brain-sells. Accessed December 3, 2014.
2. Dresler M, Sandberg A, Ohla K, et al. Non-pharmacological cognitive enhancement. *Neuropharmacology*. 2012;64:529-543.
3. Jak AJ, Seelye AM, Jurick SM. Crosswords to computers: a critical review of popular approaches to cognitive enhancement. *Neuropsychol Rev*. 2013;23:13-26. doi:10.1007/s11065-013-9226-5
4. Academy of Medical Sciences. *Brain Science, Addiction and Drugs*. London, England: Academy of Medical Sciences; 2008. http://www.acmedsci.ac.uk/index.php?pid=99&puid=126. Accessed January 11, 2014.
5. Gruzelier JH. EEG-neurofeedback for optimising performance I: a review of cognitive and affective outcome in healthy participants. *Neurosci Biobehav Rev*. 2014;44:124-141.
6. Arns M, Heinrich H, Stehl U. Evaluation of neurofeedback in ADHD: the long and winding road. *Biol Psychol*. 2014;95:108-115.
7. Faubert J, Sidebottom L. Perceptual-cognitive training of athletes. *J Clin Sport Psychol*. 2012;6:85-102.
8. Pylyshyn ZW, Storm RW. Tracking multiple independent targets: evidence for a parallel tracking mechanism. *Spat Vis*. 1988;3:1-19.
9. Faubert J. Professional athletes have extraordinary skills for rapidly learning complex and neutral dynamic visual scenes. *Sci Rep*. 2013;3:1154.
10. Legault I, Faubert J. Perceptual-cognitive training improves biological motion perception: evidence for transferability of training in healthy aging. *Neuroreport*. 2012;23:469-473.
11. Legault I, Allard R, Faubert J. Healthy older observers show equivalent perceptual-cognitive training benefits to young adults for multiple object tracking. *Front Psychol*. 2013;4:323.
12. Van Merriënboer JJ, Kirschner PA, Kester L. Taking the load off a learner's mind: instructional design for complex learning. *Educ Psychol*. 2003;38:5-13.
13. Banich MT, Compton RJ. *Cognitive Neuroscience*. 3rd ed. Belmont, CA: Wadsworth/Cengage Learning; 2010.
14. Wechsler DA. *Wechsler Adult Intelligence Scale*. 3rd ed. San Antonio, TX: Psychological Corporation; 1997.
15. Brickenkamp R. *Aufmerksamkeits-Belastungs-Test (Test d2)* [The d2 Test of Attention]. 1 ed. Göttingen, Germany: Hogrefe; 1962.
16. Brickenkamp R, Zillmer E. *The d2 Test of Attention*. Seattle, WA: Hogrefe & Huber; 1998.
17. Delis D, Kaplan E, Kramer J. *Delis-Kaplan Executive Function Scale*. San Antonio, TX: Psychological Corporation; 2001.
18. Jasper HH. The ten-twenty electrode system of the International Federation. *Electroencephalogr Clin Neurophysiol*. 1958;10:371-375.
19. Thatcher RW. *NeuroGuide Manual and Tutorial*. St. Petersburg, FL: Applied Neuroscience; 2008.
20. Fougnie D, Marois R. Distinct capacity limits for attention and working memory evidence from attentive tracking and visual working memory paradigms. *Psychol Sci*. 2006;17:526-534.
21. Cohen MA, Dennett DC. Consciousness cannot be separated from function. *Trends Cogn Sci*. 2011;15:358-364.
22. Dijksterhuis A, Aarts H. Goals, attention, and (un)consciousness. *Annu Rev Psychol*. 2010;61:467-490.
23. Wickens CD. Multiple resources and mental workload. *Hum Factors*. 2008;50:449-455.
24. Wickens CD. Multiple resources and performance prediction. *Theor Issues Ergon Sci*. 2002;3:159-177.
25. Tipper SP, Cranston M. Selective attention and priming: Inhibitory and facilitatory effects of ignored primes. *Q J Exp Psychol*. 1985;37:591-611.
26. Cavanagh P, Alvarez GA. Tracking multiple targets with multifocal attention. *Trends Cogn Sci*. 2005;9:349-354.
27. Spelke E, Hirst W, Neisser U. Skills of divided attention. *Cognition*. 1976;4:215-230.
28. Cowan N. What are the differences between long-term, short-term, and working memory? *Prog Brain Res*. 2008;169:323-338.
29. Baddeley A. Working memory: looking back and looking forward. *Nat Neurosci*. 2003;4:829-839.
30. Carpenter PA, Just MA, Reichle ED. Working memory and executive function: evidence from neuroimaging. *Curr Opin Neurobiol*. 2000;10:195-199.
31. Barkley RA. Behavioral inhibition, sustained attention, and executive functions: constructing a unifying theory of ADHD. *Psychol Bull*. 1997;121:65-94.
32. Saults JS, Cowan N. A central capacity limit to the simultaneous storage of visual and auditory arrays in working memory. *J Exp Psychol Gen*, 2007;136:663-684.
33. Vernon PA, Jensen AR. Individual and group differences in intelligence and speed of information processing. *Pers Individ Diff*. 1984;5:411-423.
34. Sterman MB. EEG markers for attention deficit disorder: pharmacological and neurofeedback applications. *Child Study J*. 2000;30:1-24.
35. Clarke AR, Barry RJ, Bond D, McCarthy R, Selikowitz M. Effects of stimulant medications on the EEG of children with attention-deficit/hyperactivity disorder. *Psychopharma-cology*. 2002;164:277-284.
36. Basar-Eroglu C, Struber D, Schurmann M, Stadler M, Basar E. Gamma-band responses in the brain: a short review of psychophysiological correlates and functional significance. *Int J Psychophysiol*. 1996;24:101-112.
37. Jensen O, Kaiser J, Lachaux JP. Human gamma-frequency oscillations associated with attention and memory. *Trends Neurosci*. 2007;30:317-324.
38. Herrmann CS, Mecklinger A. Gamma activity in human EEG is related to high-speed memory comparisons during object selective attention. *Vis Cogn*. 2001;8:593-608.
39. Alderson RM, Kasper LJ, Hudec KL, Patros CH. Attention-deficit/hyperactivity disorder (ADHD) and working memory in adults: a meta-analytic review. *Neuropsychology*. 2013;27:287-302.
40. Shanahan MA, Pennington BF, Yerys BE, et al. Processing speed deficits in attention deficit/hyperactivity disorder and reading disability. *J Abnorm Child Psychol*. 2006;34:584-601.
41. Liss M, Saulnier C, Fein D, Kinsbourne M. Sensory and attention abnormalities in autistic spectrum disorders. *Autism*. 2006;10:155-172.