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Aerobic Exercise Enhances Cognitive Flexibility

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Abstract *Introduction* Physical activity is believed to prevent cognitive decline and may enhance frontal lobe activity. *Methods* Subjects were 91 healthy adults enrolled in a wellness center. Over a 10 week intervention, controls were aerobically active 0–2 days per week. Half the intervention group was active 3–4 days/week and half 5–7 days/week. Outcome measures included memory, mental speed, reaction time, attention, and cognitive flexibility. *Results* Neurocognitive data were analyzed by repeated measures comparing minimal aerobic exercise (the control group) to moderate aerobic exercise (3–4 days/week), and to high aerobic exercise (5–7 days/week). Initial analyses noted significant improvements in mental speed ($p = .03$), attention ($p = .047$), and cognitive flexibility ($p = .002$). After controlling for age, gender, education, and changes in psychomotor speed, only cognitive flexibility still showed significant improvements ($p = .02$). *Conclusion* Over a 10 week period, increasing frequency of aerobic activity was shown to be associated with enhanced cognitive performance, in particular cognitive flexibility, a measure of executive function.

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Background

The association between physical fitness and cognitive health is as intuitive as "*mens sana in corpore sano*." Over time, this Latin phrase has come to mean that only a healthy body can produce or sustain a healthy mind. Today, this relationship receives much more attention as our aging population places a high priority on preserving cognitive acuity into our golden years. In fact, numerous observational studies have demonstrated that people who are fit perform better on cognitive tests, and people who are active suffer less cognitive decline as they grow older (Barnes, Yaffe, Satariano, & Tager, 2003; Heyn, Abreu, & Ottenbacher, 2004; Hillman, Belopolsky, Snook, Framer, & McAuley, 2004; Larson et al., 2006; Lautenschlager & Almeida, 2006; Mummery, Schofield, & Caperchione, 2004; Roth, Goode, Clay, & Ball, 2003; Singh-Manoux, Hillsdon, Brunner, & Marmot, 2005; Weuve et al., 2004).

The results of intervention studies evaluating the connection between exercise and cognitive functioning, however, are less consistent, and not every study has generated positive results (Kubesch et al., 2003; Pierce, Madden, Siegel, & Blumenthal, 1993; Rikli & Edwards, 1991; Small et al., 2006). The mixed results of clinical trials of exercise are only natural, however, given the variety of exercise regimes, the methods employed to measure fitness and exercise intensity, and the different measures that have been used to assess cognition. Yet in a recent article, Lautenschlager et al. (2008) showed in a randomized study that individuals with moderate cognitive impairment can increase some aspects of cognition with increased physical activity.

Important questions remain unresolved. Is any degree of exercise sufficient to improve cognitive performance, or is the effect dose-related, as noted by Barnes et al. (2003)? If there is an exercise effect on cognition, is it a general effect, demonstrable across all cognitive domains, or is it concentrated on particular functions? For example, several authors (Barnes et al., 2003; Churchill et al., 2002; Colcombe & Kramer, 2003; Colcombe, Kramer, McAuley, Erickson, & Scalf, 2004), have reported that high levels of aerobic exercise tended to affect performance on tests of attention and executive function. If this is true, how does increasing the frequency of aerobic exercise impact various aspects of cognition?

The purpose of this investigation was to address the fundamental question—does exercise improve cognition? Our second aim, using a technologically sophisticated method to assess a wide range of cognitive domains including memory, mental speed, reaction time, attention, and cognitive flexibility, was to clarify if the impact of aerobic exercise upon cognition is dose-related. Computerized neurocognitive testing provides a quick and efficient tool to measure the effect of an intervention like exercise on a broad range of cognitive functions. Studies that validate the efficacy of computerized neurocognitive testing have been described previously (Baker et al., 1985; Gualtieri & Johnson, 2006b, c; Gualtieri, Johnson, & Benedict, 2006).

Methodology

Procedure

This was an observational study of the effects of aerobic exercise on neurocognitive performance. First, a small study randomly assigned subjects to treatment and control groups. Having established that the treatment group would exercise at different levels of intensity, additional subjects were recruited, and the cognitive performance of no exercise, moderate exercise, and intense exercise was compared. The St Anthony's Institutional Review Board approved this research project.

Subjects and Methods

Subjects were recruited from the Carillon Wellness Center, St Anthony's Hospital, St Petersburg, Florida. Subjects were men and women, age 18–70, who were aerobically active on fewer than 3 days per week. Subjects with major health problems (e.g., heart or lung disease, major joint disease, or cancer) and those unable to exercise aerobically (achieve an elevated heart rate for at least 20–30 min) were excluded.

Fifty-six subjects were randomly assigned to two groups, stratified by BMI. Those in the treatment group were assigned to an exercise program led by exercise instructors certified by the American College of Sports Medicine (ACSM). Following a fitness assessment with a trainer, VO_2max (maximum oxygen burning capacity) was predicted from peak MET (energy burning capacity) and heart rate levels achieved during a treadmill machine test using a Bruce Protocol (standard format with increasing speed and velocity every 3 min) with Physiologic® software. Subjects were then directed to undertake aerobic exercises 5–6 days per week for 30–45 min per day, at 70–85% of their anticipated maximum heart rate. The exercise program was undertaken for ten weeks. The subjects met with a trainer weekly one-on-one for a 1 h workout to ensure proper technique and effort. At this session weekly activity levels were logged into the database. Subjects in the pilot intervention group were also given recommendations to increase dietary fiber, reduce saturated fat intake, and for stress management. The details of this pilot study are reviewed elsewhere (Masley, Weaver, Peri, & Phillips, 2008).

Subjects in the control group were simply asked to continue their current activity level and dietary intake for 10 weeks. Of 28 intervention subjects, 1 dropped out the first 2 weeks for family related issues and 27 completed the study. Of 28 control subjects, 8 failed to follow up for their final evaluation and 20 completed the study.

After the pilot study was ended, preliminary analysis indicated a trend for aerobic exercise to improve neurocognitive performance. No relationship was noted for changes in fiber or saturated fat intake, or stress management with cognitive performance.

In the initial randomized pilot study, for cognitive function, there were no statistically significant changes in the control group from baseline to follow-up. In the intervention group, several of the cognitive scores showed a significant change from baseline: mental speed (4.6%, $p = .014$), reaction time (4.5%, $p = .023$), attention 4.6%, ($p = .18$), and cognitive flexibility (11.7%, $p = .019$). When only those intervention subjects who exercised at least 5–6 days per week were assessed for changes in cognitive function ($n = 13$), mental speed increased by 4.9%, reaction time improved by 9.1%, attention increased by 44.3%, and cognitive function improved by 24.6%; however, this limited sample size did not reach a statistically significant difference by independent t testing when compared to the control group.

It was also observed that about half the treatment subjects exercised 5 or more days per week, while the others reached only 3 or 4 days per week. It was decided, therefore, to recruit more subjects into the treatment group, in order to evaluate the possibility of a "dose–response" relationship between frequency of aerobic exercise and neurocognitive improvement. To this end, an additional 44 men and women meeting entry criteria participated in the same 10 week aerobic exercise program. Thus, a total of 71 subjects completed the 10 week fitness intervention. Because these 71 subjects reported exercise at different levels of frequency, we were able to do a post-hoc analysis of the comparative effects of moderate-frequency exercise (3–4 days/week) to high-frequency exercise (5–7 days/week).

Outcome Measures

At entry and following the ten week intervention, neurocognitive performance was assessed using a computerized battery, CNS Vital Signs®. This test battery is self administered in 30 min on a PC, and includes tests of visual and verbal memory, finger tapping, symbol digit coding, the Stroop test, shifting attention and continuous performance. The seven tests generate domain scores for memory, psychomotor speed, information processing time, attention, and cognitive flexibility. The tests in the CNS Vital Signs battery are standardized and are known to be valid and reliable, and sensitive to very small changes in neurocognitive performance (Baker et al., 1985; Gualtieri & Johnson, 2006a, b, c; Gualtieri et al., 2006). See Appendix. Normative data for the CNS Vital Signs battery have been published, in healthy subjects age 8–89 (Gualtieri & Johnson, 2006a).

Exercise logs were reviewed weekly by an exercise physiologist who recorded the frequency and duration of aerobic exercise; for example, the number of days per week when the subject performed at least 30–60 min of aerobic activity. As noted, measures of VO_2max were performed at entry and after completing the 10 week intervention.

Analyses

Descriptive statistics (means, frequencies) were assessed for baseline characteristics of study subjects. Changes between baseline and follow-up cognitive performance measures were assessed using paired samples *t*-tests. We used independent samples *t*-tests to compare changes in cognitive performance between the relevant study groups (e.g., intervention vs. control) and used ANOVA to assess changes in cognitive performance across three levels of physical activity (control, intervention low activity, intervention high activity). Analyses were performed using SAS version 9.1 (SAS Institute Inc., Cary, North Carolina).

Additionally, the relationship between the neurocognitive data and exercise was analyzed by repeated measures, controlling for the following covariates: age, gender, years of education, and psychomotor speed. These analyses were performed with SPSS.

As noted above, not all the intervention subjects were randomized, hence a comparison of the changes in cognitive performance between the randomized intervention subjects with the changes in the add-on intervention subjects was also performed.

Results

In Table 1, we present demographic and physiologic data comparing the control group to the combined intervention group, and the initial randomized intervention group to the add-on intervention group. There were no statistically significant differences between the control group and the combined intervention group in age, body mass index (BMI), years of education, gender, and VO_2max fitness at baseline. Likewise the randomized intervention group and the add-on intervention subjects showed no significant differences in any of these variables, except gender; there was a higher percentage of women in the add-on group compared to the randomized study groups.

Change in VO_2max over the study period affirmed the exercise-intensity data generated by the subject logs. VO_2max increased 6.5% in the control group, 12% in the moderate exercise intervention group, 17.3% in the combined intervention group, and 21.3% in the high exercise intervention group. While the changes in VO_2max did not reach statistically significant levels, an independent *t*-test comparison of the control group to the high exercise group was nearly significant ($p = .053$). Plus, a Spearman rank correlation coefficient comparing the change in VO_2max from the control, to the moderate exercise, to the high exercise groups noted a correlation coefficient = .23, which also showed a trend towards higher VO_2max with more frequent aerobic exercise ($p = .06$).

As shown in Table 2, the neurocognitive data were analyzed by repeated measures, MANOVA. Significant differences with more frequent exercise were observed in tests of psychomotor speed, attention and cognitive flexibility. However, when age, gender and years of education were introduced as covariates, only cognitive flexibility remained significantly different among the three groups. Because the two tests that contributed to this domain involved speeded responses, it was appropriate to control for psychomotor speed; as exercise might simply increase a subject's motor speed. When change in motor speed was introduced as a covariate, the effect of exercise frequency on cognitive flexibility was still significant ($p = .03$).

When an independent *t*-test compared changes in the combined intervention group with the control group, only cognitive flexibility showed a significant improvement:

Table 1 Demographic data of subjects at entry comparing the control group to the combined intervention group, and the randomized intervention group to the add-on intervention group

Baseline measures	Control group ($N = 20$)	Combined intervention group ($N = 71$)	*p* values*	Randomized intervention group ($N = 26$)	Add-on intervention group ($N = 45$)	*p* values**
Gender (% male)	45.0	32.4	.30	57.7	17.8	.00005
Age	45.4	47.8	.40	47.0	48.3	.65
Education (years)	16.3	16.5	.82	15.8	17.0	.34
BMI	27.5	29.6	.19	29.5	29.7	.91
VO_2max	41.0	38.8	.41	41.3	36.6	.07
Memory	97.0	98.3	.44	98.3	98.3	.98
Mental speed	169.7	170.1	.95	175.9	166.7	.13
Reaction time	690.8	667.7	.33	667.3	667.9	.98
Attention	8.2	9.8	.45	7.8	11.0	.15
Cognitive flexibility	43.2	40.3	.43	44.4	37.9	.08

* *p*-values for comparisons between control group and combined intervention group at baseline

** *p*-values for comparisons between randomized and add-on intervention groups

Table 2 Effects of increasing levels of aerobic exercise upon cognitive function, comparing the control group, the moderate exercise frequency group (3–4 days per week) and the frequent exercise group (5–7 days per week)

	Exercise effects by intensity		Covariates: age, gender and years of education		Age, gender, years of education and delta PMS	
	F	*p*	*F*	*p*	*F*	*p*
Memory	1.532	.222	2.569	.083	2.530	.086
Psychomotor speed	3.663	.030	1.840	.165	2.250	.112
Reaction time	.703	.498	.915	.404	1.005	.370
Attention	3.171	.047	2.245	.112	2.198	.117
Cognitive flexibility	6.821	.002	3.865	.025	3.860	.025

memory $p = .18$, mental speed $p = .4$, reaction time $p = .71$, attention $p = .16$, and cognitive flexibility $p = .02$. In comparing those intervention subjects who exercised 5–7 days per week with those who exercised 3–4 days per week, significant improvements were noted for reaction time ($p = .02$), attention ($p = .005$), and cognitive flexibility ($p = .002$).

Cognitive changes reflecting memory, mental speed, reaction time, attention, and cognitive flexibility for the control group, the combined intervention group, and the high frequency exercise group are shown in Table 3. Similarly, paired *t*-tests indicated that both moderate and intense exercise increased performance on tests of cognitive flexibility to a significant degree (See Table 4.)

As shown in Fig. 1, the dose–response relationship between frequency of aerobic exercise and magnitude of improvement in cognitive flexibility raw scores for the controls, moderate exercise group, and high exercise group was 0.1 (0.2%), 2.3 (4.8%), and 11 (31.7%), respectively.

To compare the improvements in the randomized intervention group to the add-on intervention group, the following findings were noted. In the randomized and the add-on intervention groups, the following respective cognitive improvements were noted in memory (2.8% vs. 1.8%), mental speed (4.9% vs. 4.2%), reaction time (9.1% vs. 2.6%), attention (44.3% vs. 38.1%), and cognitive flexibility (24.6% vs. 22.4%) suggesting the changes between these two types of intervention groups were very similar.

Discussion

The results of this observational investigation suggest that aerobic exercise has positive effects on neurocognition, and suggests a dose–responsive relationship between aerobic activity and executive function. The neurocognitive tests that were most responsive to the effects of exercise were the shifting attention test and the Stroop test; both are measures of what neuropsychologists refer to as “cognitive flexibility” or “executive function.” The improvement in cognitive flexibility was proportional to the degree of exercise undertaken by the subject; the validity of the different levels of activity frequency was affirmed by

Table 3 Changes in neurocognitive data in the control group, combined intervention group, and the frequently active intervention group

	Memory	Mental speed	Reaction time[a]	Attention[a]	Cognitive flexibility
Control group at entry	97.0	169.7	690.8	8.2	43.2
Control group post-10 weeks (% improvement)	95.5 (−1.5)	175.0 (3.1)	663.2 (4.0)	7.7 (6.1)	43.3 (0.2)
Combined intervention group at entry	98.3	170.1	667.7	9.8	40.3
Combined intervention group post-10 weeks (% improvement)	99.5 (1.2)	178.4 (4.9)	645.3 (3.4)	6.5 (33.7)	47.6 (18.1)
High exercise (5–7 days/week) intervention group at entry	97.5	164.2	680.5	12.2	34.7
Intervention group post-10 weeks, activity 5+ days/week (% improvement)	100.2 (2.8)	172.8 (5.2)	645.9 (5.1)	6.6 (45.9)	45.7 (31.7)

[a] A decrease in reaction time score and attention score indicates an improvement

Table 4 Effects of exercise upon changes in cognition using paired *t*-tests

	Controls		Moderate exercise		Intense exercise	
	t	*p*	*t*	*p*	*t*	*p*
Memory	.940	.359	.442	.662	−2.408	.021
Psychomotor speed	−1.385	.182	−2.929	.007	−4.432	<.001
Reaction time	2.111	.048	.637	.529	4.060	.001
Cognitive flexibility	−.048	.962	−2.062	.048	−5.197	<.001
Attention	.361	.722	.381	.706	3.577	.001

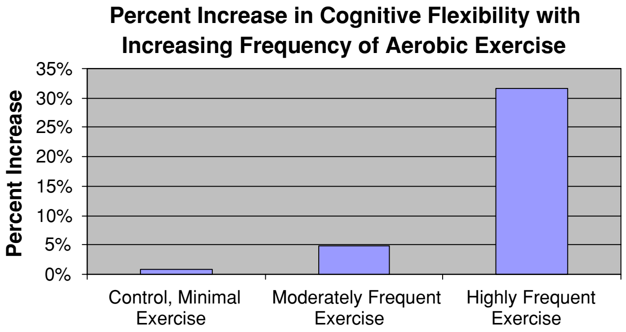

Fig. 1 Magnitude of increase in cognitive flexibility with increasing frequency of aerobic exercise

estimating change in VO_2max over the course of the study. Improved test performance was not simply a measure of improved muscle tone and motor speed; first, because psychomotor speed was not significantly improved by exercise, and, second, because controlling for change in motor speed did not influence the results. The data suggest, therefore, that the impact of exercise is mediated by central, not peripheral mechanisms.

The effects of exercise were both physiologically objective and specific. That is, they were not simply a function of improved well-being, but rather individuals showed significant improvements on neurocognitive testing, demonstrated most robustly in tests of executive function, and not in tests of memory, reaction time or psychomotor speed. The data, therefore, suggest that central mechanisms are affected in the brain particularly in the prefrontal cortex, where the executive functions largely reside. This is consistent with published studies that demonstrate significant effects of exercise on executive function (Barnes et al., 2003; Colcombe & Kramer, 2003), but no effect of exercise on memory and reaction time (Pierce et al., 1993; Rikli & Edwards, 1991).

Our results support the work of previous studies demonstrating that aerobic exercise and greater levels of aerobic fitness are associated with less cognitive decline in older adults (Barnes et al., 2003; Heyn et al., 2004; Hillman et al., 2004; Larson et al., 2006; Lautenschlager & Almeida, 2006; Mummery et al., 2004; Roth et al., 2003; Singh-Manoux et al., 2005; Weuve et al., 2004). They are also consistent with the work of previously noted authors (Barnes et al., 2003; Colcombe & Kramer, 2003; Churchill et al., 2002) who suggest that that frontal lobe activities related to cognitive flexibility and attention showed the greatest improvement in cognitive performance with increasing aerobic exercise and fitness.

In comparison to our initial randomized pilot study (Masley et al., 2008), this larger observational study resulted in the same improvement in cognitive flexibility, a similar non-significant trend towards better attention, and no changes in mental speed or memory. Taken together these findings suggest that a dose response relationship may exist between aerobic exercise and cognitive flexibility.

This study also supports the work of Lautenschlager et al. (2008) and helps to clarify the exercise duration needed to enhance cognitive performance. This Australian intervention group increased physical activity by 142 min per week (or 20 min per day) more than the control group, while our intervention subjects averaged 150–210 min per week (or 20–30 min per day). Of interest, our subjects exercising 5 days per week appeared to have a greater improvement than those exercising only 3 days per week. However in contrast to our ten-week intervention which encouraged higher levels of aerobic activity, the Australian study increased activity for 6 months predominantly with walking. As our study did not directly control the amount of exercise performed, clearly further studies are needed to clarify how exercise duration, frequency, and intensity impact cognitive performance.

The results of this paper are also consistent with preclinical studies that have consistently shown that increased levels of physical activity are associated with less aging-related loss in brain tissue and enhanced cognitive performance (Neeper, Gomez-Padilla, Choi, & Cotman, 1995; van Praag, Christie, Sejnowski, & Gage, 1999).

Several biological mechanisms for improvements in cognition with exercise have been described. These studies have demonstrated that exercise enhances cerebral blood flow and oxygen delivery (Churchill et al., 2002; Rogers, Meyer, & Mortel, 1990; Taddei et al., 2000), induction of fibroblast growth in the hippocampus (Cameron & McKay, 1999; Churchill et al., 2002), decreased brain tissue loss (Colcombe & Kramer, 2003), and increased production of brain-derived neurotrophin factor (Cotman & Berchtold, 2002; Gómez-Pinilla, So, & Kesslak, 1998; Neeper et al., 1995). It is also feasible that non-biological mechanisms are associated with the improvements in cognition, such as improved well being. Future studies should consider pre and post study instruments to asses changes in well being and their impact on cognition.

The results of this study, while in agreement with previously published papers, are open to several limitations. First, what began as a random-assignment comparison of regular exercise versus minimal activity evolved into a larger study comparing minimal activity versus varying frequencies of aerobic exercise. In the transition, the advantage of random assignment was lost, and it is arguable that the results are no more than post hoc. On the other hand, the value of generating a dose–response curve for exercise and neurocognition seemed to us to be much more important than simply to demonstrate, as many others have done, that exercise is beneficial. There are reports, for example by Manini et al. (2006) that *any* sort of activity is beneficial for older adults, at least with respect to mortality. That may well be the case. But at issue here is not about mortality or morbidity, but about fitness and engaging in regular aerobic exercise, and whether an optimal exercise program has neurocognitive correlates. Our data suggest that it does. Plus the strong similarities in response between the randomized and add-on interventions groups make our findings more reassuring, given the limitations of this post hoc comparison. Lastly regarding the limitations of this study, there is always the potential that some of the observed effects could reflect a regression to the mean or a selection bias, hence further studies should be performed to validate these findings.

There are, of course, studies that have not found cognitive improvement in older adults on various exercise regimes (Pierce et al., 1993; Rikli & Edwards, 1991). Our study suggests a possible reason for why that may be the case. First, not every measure of cognition is sensitive to exercise effects. If one wished to examine the question of how exercise impacts cognition, one is advised to administer a broad range of cognitive tasks, especially those measuring executive function. It is also worthwhile to examine the effects of different levels of exercise, rather than just assuming that all exercise regimes are the same. The estimation of VO_2max is a way to ensure that exercise regimes are, in fact, as rigorous as they are supposed to be.

Finally, it might be asked "Is cognitive flexibility important for older adults, who are usually more concerned about their memory than any other cognitive function?" In fact, deficits in executive functions are among the earliest signs of dementing diseases (Colcombe et al., 2003). Preserving or enhancing executive functions like flexibility, initiative, self-regulation, and motivation are worthwhile in their own right. The executive functions of the frontal lobes mediate or participate in all of the higher cognitive functions and are essential to optimizing and maintaining function in daily life.

Are these findings generalizable to the wider population? People willing to volunteer for a fitness study are probably more motivated than the average person. People who were willing to exercise at an intense level showed the best results, and the average person may be disinclined to exercise aerobically 5–7 days a week, even if it is going to make him or her mentally sharper. On the other hand, our aim to enroll wellness center members who used the facility either rarely or not at all yielded a study population at baseline that had a fairly typical American fiber and saturated fat intake, average activity levels, average BMI and body fat percent, and average fitness levels. Also, the study population who were assigned to the control group did not show significant improvements in weight, body fat percentage, aerobic fitness, eating habits, or cholesterol profile (Masley, Weaver, Peri, & Phillips, 2005; Masley, Weaver, Peri, & Phillips, 2006; Masley et al., 2008) not an overly "motivated" group, to be sure. So, perhaps the results of the study are relevant to the average person after all. (Or at least to Caucasian college graduates, who represented the majority of the subjects in this investigation.) Certainly, further studies of subjects with diverse ethnic and educational backgrounds are indicated to validate these findings.

In spite of the limitations of this study, we have demonstrated that aerobic activity was associated with improved neurocognitive performance, and that more frequent aerobic activity was associated with greater cognitive flexibility in our sample. That this effect is seen after only ten weeks is encouraging, and provides added motivation for the public to exercise regularly.

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Appendix: The CNS VS Battery: Psychometric Properties

The CNS Vital Signs Battery contains seven tests that are widely used by neuropsychologists, and known to be reliable and valid (Baker et al., 1985; Gualtieri & Johnson, 2006b, c; Gualtieri et al., 2006). The tests embrace an appropriate span of cognitive domains, and are known to be sensitive to most of the causes of mild cognitive dysfunction.

Verbal memory (VBM) and visual memory (VIM) are adaptations of the Rey Auditory Verbal Learning Test and the Rey Visual Design Learning Test (Rey, 1964; Taylor, 1959) VBM and VIM are recognition tests, however, not tests of recall. Correct responses from VBM and VIM are summed to generate a composite memory or memory domain score.

The finger tapping test (FTT) is one of the core tests of the Halstead-Reitan Battery. Symbol digit coding (SDC) is based on the symbol digit modalities test (Smith, 1982), itself a variant of the Wechsler digit symbol substitution test. The total of right and left taps from the FTT and total correct responses on the SDC generates a composite score for "psychomotor speed."

The Stroop Test (ST) in the CNS VS has three parts that generate simple and complex reaction times. Averaging the two complex reaction time scores from the Stroop test generates a domain score for "reaction time." It might be more precise to refer to this domain as "information processing speed."

The Shifting Attention Test (SAT) measures the subject's ability to shift from one instruction set to another quickly and accurately. Color-shape tests like the SAT have been used in cognitive imaging studies (Le, Pardo, & Hu, 1998; Nagahama et al., 1998) A domain score for cognitive flexibility is generated by taking the number of correct responses on the SAT and subtracting the number of errors on the SAT and the Stroop test.

The Continuous Performance Test is a measure of vigilance or sustained attention (Rosvold & Delgado, 1956). A domain score for "complex attention" is generated by adding the number of errors committed in the CPT, the SAT and the Stroop.

Because the presentation of stimuli is randomized, no two presentations of CNS VS are ever the same; so, the test battery is appropriate for serial administration. Several of the tests draw stimuli from a "reservoir" of words or figures (VBM, VIM, SDC). Several tests record reaction times with millisecond accuracy (VBM, VIM, FTT, ST, SAT, CPT).

The CNS VS battery has been normed in 1,069 normal subjects. Test–retest reliability of the CNS VS battery is comparable to those reported for similar, traditional tests and to similar tests in other computerized test batteries.

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