EFFICIENT ALLOCATION OF ATTENTIONAL RESOURCES IN PATIENTS WITH ADHD: MATURATIONAL CHANGES FROM AGE 10 TO 29

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ABSTRACT

BACKGROUND: It is has been proposed that the neurocognitive basis of Attention Deficit-Hyperactivity Disorder (ADHD) resides in the executive control functions (ECF). One aspect of the study of ECF in ADHD individuals that has received little attention, however, is the evolution of ECF with maturation.

METHOD: A naturalistic, cross-sectional study of ADHD patients compared to normal controls on a computerized neurocognitive test battery, CNS Vital Signs.

SUBJECTS: 175 patients with ADHD, medication free, age 10-29, evaluated at the North Carolina Neuropsychiatry Clinics, compared to 175 age-matched normal controls,

RESULTS: ADHD patients were impaired, relative to normal controls, in measures of psychomotor speed, reaction time, cognitive flexibility and attention. Test score improvement was correlated with age in normals in all of the tests in the neurocognitive battery. The same was true in ADHD patients for most tests, but not for tests of ECF, the Stroop test and the shifting attention test. In the shifting attention test, performance of normals and ADHD patients improved with age. Normals, however, improved their performance with shorter reaction times. ADHD patients improved their performance, but by adopting a less efficient strategy: their reaction times increased with age.

CONCLUSIONS: These data support ECF as a “core deficit” in ADHD. In the Stroop and the shifting attention tests, ADHD patients proved to be inefficient in allocating their attentional resources.

BACKGROUND: It has been proposed that Attention Deficit-Hyperactivity Disorder (ADHD) is an executive control disorder. Little is known, however, about the maturation of executive control in ADHD.

METHOD: A cross-sectional study of ADHD patients compared to normal controls tested on a computerized neurocognitive test battery.

SUBJECTS: 175 patients with ADHD, age 10-29, compared to 175 age-matched normal controls,

RESULTS: In every age group, ADHD patients were impaired in measures of psychomotor speed, reaction time, cognitive flexibility and attention. Subjects in both groups improved with age. In tests of executive control, normals improved their performance with shorter reaction times. ADHD patients improved their performance, but by adopting a less efficient strategy: their reaction times increased with age.

CONCLUSIONS: These data support executive control as a “core deficit” in ADHD. In the Stroop and the shifting attention tests, ADHD patients proved to be inefficient in allocating their attentional resources.

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EFFICIENT ALLOCATION OF ATTENTIONAL RESOURCES IN PATIENTS WITH ADHD: MATURATIONAL CHANGES FROM AGE 10 TO 29

It is reasonable to assume that the pathology of Attention Deficit/Hyperactivity Disorder (ADHD) is related to an underlying neuropsychological deficit, and this assumption has driven a great deal of productive research in recent years. One assumes, as well, that understanding the nature of such deficits will help clinicians to understand patients who have the disorder. At one time, problems with sustained attention were thought to be central to ADHD. That belief is not only implied by the name, but also operationalized in the commercial popularity of tests for the disorder, like the TOVA and the Continuous Performance Test (CPT), that measure sustained attention. The primacy of sustained attention, however, has been gradually supplanted by a broader conception of the disorder: that the neurocognitive basis of ADHD is more diffuse, and resides in the broader domains of attentional and executive control functions (ECF).

The limitations of a unitary attentional model of ADHD are manifest. Impairment of sustained attention is not limited to ADHD. It seems to be common to all of the psychiatric disorders of childhood and adolescence, including anxiety and depression (Swaab-Barneveld et al., 2000). Patients with ADHD actually do better than normals in certain types of attention tasks (Koschack, Kunert, Derichs, Weniger, & Irle, 2003), and different subgroups of ADHD children are characterized by different attention profiles (Zalsman et al., 2003). In ADHD, various components of attention may be impaired, including the ability to focus upon or to “engage” a stimulus, the ability to encode stimulus properties, and the ability to disengage from a stimulus and shift one’s focus in an appropriate manner (Seidman, Biederman, Monuteaux, Doyle, & Faraone, 2001; Stearns, Dunham, McIntosh, & Dean, 2004). These particular components of the attentional system are closely integrated with the broader cognitive domain of executive control.

Executive control functions (ECF) refer to the capacity for autonomous behavior beyond the structure of external guidance. In clinical terms, this refers to initiative, motivation, spontaneity, planning, judgment, insight, goal-directed behavior, the ability to operate in favor of a remote or an abstract reward, the capacity for self-monitoring and the flexibility required for self-correction. The executive functions are activity-related behaviors that are necessary for appropriate, socially responsible and self-serving adult conduct. In the clinical literature concerned with deficits in executive behavior, lesions of the frontal lobes are most commonly implicated, although other cortical and subcortical structures may also be involved (Lezak, 1983; Gualtieri, 2002). As it happens, frontal lobe patients also have significant deficits in sustained attention. They are easily distracted by irrelevant stimuli, or they may be distracted by an immediate stimulus from the more important requirements of a remote goal. Deficits in sustained attention, however, are only one component of the frontal lobe syndrome.

ECF's are measured by special tests. The Stroop test, for example, is a test of cognitive flexibility, where appropriate responding entails the inhibition of an habitual response and the activation of an unaccustomed response. The Wisconsin Card Sort test and Halstead Categories measure "set-shifting," or one's ability to change cognitive sets quickly and accurately. ADHD patients, like patients with frontal lobe lesions, perform poorly on these tests (Homack & Riccio, 2004; Bedard, Ickowicz, & Tannock, 2002; Romine et al., 2004).

"Dual task" or "shifting attention" tests are also difficult for ADHD patients, just as they are for patients with frontal lobe lesions (Mehta, Goodyer, & Sahakian, 2004; McLean et al., 2004). Shifting attention tests require the patient to respond to different stimuli with different response patterns. They test the patient's ability to allocate their attentional resources efficiently in response to changing demands. Perseveration and distractibility are two symptoms of the failure to focus one's attention appropriately in response to environmental demands. If a shifting attention test is administered by computer, it is possible to record patients' reaction time. A slower reaction time indicates difficulty with shifting sets. Brain injury patients have slower reaction times on such tasks (Gualtieri & Johnson, 2004); and, as we shall see, so do patients with ADHD.

Barkley has proposed that the "core deficit" of ADHD is in one particular aspect of self-regulation, inhibitory control. According to this view, people with ADHD are impaired in (1) their ability to inhibit a "prepotent" response to an event; (2) their ability to interrupt an ongoing response; and (3) their ability to withstand disruptions from competing events (Barkley, 1997b). In order to perform at a comparable level to normal people, the ADHD patient has to trigger inhibitory processes earlier and more strongly than controls (Smith, Johnstone, & Barry, 2004).

Others have emphasized the regulation of response execution processes, and have suggested that ADHD cannot be fully explained by an inhibition-specific deficit (Banaschewski et al., 2004; Scheres et al., 2004). In fact, the supposition of a "core deficit" in ADHD is arguable. There are many components of attention and executive function, and it is possible that impairments in one, or several, of the components may be impaired in individuals with ADHD. This would account for the well-known heterogeneity of the syndrome. Factor analysis of neurocognitive test performance in a large group of young children with ADHD has suggested multiple early-appearing neurodevelopmental bases for ADHD (Sonuga-Barke, 2003).

Whether or not inhibitory control is the "core deficit" in ADHD, the evidence in support of ECF as central to the condition has had broad support. Studies using different measures of ECF have indicated executive dysfunction in the family members of ADHD children (Crosbie & Schachar, 2001; Sonuga-Barke, 2003). ECF deficits are associated with poor outcome in patients with ADHD, including academic failure (Biederman et al., 2004) and drug use in adolescence ((Aytaclar, Tarter, Kirisci, & Lu, 1999)).

Although functional neuroimaging studies have been somewhat variable in their findings, there is consistency in their demonstration of abnormalities (or at least, slight deviations from normal) in the prefrontal cortex and the striatum, consistent with the primacy given to the broad domains of attention and executive function (Castellanos, 1997; Schulz et al., 2004). Functional MRI studies, for example, have indicated abnormal frontal-striatal activation in ADHD children on tests of cognitive inhibition (Vaidya et al., 1998). Underactivation in frontal regions during shifting attention tests suggest a core deficit in ADHD (Tamm, Menon, Ringel, & Reiss, 2004).

One aspect of the study of ECF in ADHD individuals has received little attention, however. That is the evolution of ECF with maturation. Patients' performance on neuropsychological tests like the Stroop test and tests of shifting attention are not static. They change as individuals mature, and then they change again as they age. For virtually every measure of ECF, performance improves dramatically from childhood through adolescence, and achieves an optimal level in early adult life (see below).

In order to develop this point, we took advantage of a large database of cognitive data in children, adolescents and young adults with ADHD. The cognitive data included a wide range of cognitive domains, but our particular interest was performance on tests of ECF, the Stroop test and the shifting attention test. The specific question was how ECF's change with maturation. If meaningful changes do occur (and we believe we have demonstrated that they do), how does that affect our understanding of the condition, and, more important, how does it improve our appreciation of the problems ADHD individuals face as they grow up?

MATERIALS & METHODS

This was a naturalistic, cross-sectional study of 175 ADHD patients compared to 175 normal controls who were tested with a computerized neurocognitive assessment battery.

SUBJECTS

The patients were 175 people with ADHD, age 10-29, evaluated at the North Carolina Neuropsychiatry Clinics. The diagnoses were conferred by experienced clinicians, according to DSM-IVr criteria, and reviewed by a senior psychiatrist. For all the subjects, ADHD was the primary diagnosis. Patients with comorbid disorders were excluded. As part of their diagnostic evaluation, the patients were administered a computerized battery of tests, CNS Vital Signs. All of the patients were drug-free at the time of evaluation.

Patients' performance was compared to that of 175 age-matched normal controls who had also taken the CNS Vital Signs battery. The normal controls had participated in standardizing the normative database for the computerized battery. The patients and the normal controls were all in good health, and taking no concomitant medications.

To illustrate the point that performance on the Shifting Attention Test changes with aging, we have drawn from data on normal individuals in the CNS Vital Signs Database, N = 556, age 8-89. "Normals" are people who are free of current or past neurological, developmental or psychiatric disorders, and who are taking no centrally-active medications.

COGNITIVE EVALUATION

Patient's neurocognitive performance was measured on a computerized battery of tests, "CNS Vital Signs" (CNSVS). CNSVS is a PC-based neurocognitive screening battery, comprised of seven familiar neuropsychological tests: verbal and visual memory (VBM, VIM), finger tapping (FTT), symbol-digit coding (SDC), the Stroop test (ST), the shifting attention test (SAT) and the continuous performance test (CPT). The test battery is self-administered in the clinic on an ordinary PC, and takes about 30 minutes.

The tests in the "Vital Signs" battery are highly reliable (test-retest, r = 0.63-0.88) (Gualtieri, Johnson, & Benedict, 2004b). Normative data from 556 normal subjects, age 8-89, indicates typical performance differences by age and gender (Gualtieri, Johnson, & Benedict, 2004a). Concurrent validity was established in studies comparing the Vital Signs battery to conventional neuropsychological tests (Gualtieri, Johnson, & Bendict, 2004; Benedict & Benson, 2004).

THE VITAL SIGNS SHIFTING ATTENTION TEST (SAT)

The special focus of this report is the SAT, a test of the subject's ability to shift sets quickly and accurately. Three figures appear on the screen, one on top and two on the bottom. The top figure is either a square or a circle. The bottom figures are a square and a circle. The figures are either red or blue; the colors are mixed randomly. The subject is asked to match one of the bottom figures to the top figure. But the rules change at random. For one presentation, the subject has to match the figures by shape; for another, by color. This goes on for 90 seconds.

Scoring is correct responses, errors and average reaction time for all responses. "Number correct" is how many stimuli the subject was able to match correctly in 90 seconds. "Errors" are incorrect matches. Reaction time is measured for correct responses.

The SAT has been standardized in 500 normal subjects age 8-89. The test was proven reliable in a test-retest study of 107 subjects: SAT correct responses, r = 0.73, errors = 0.63, reaction time, r = 0.80.

RESULTS

Demographic data on the 175 patients and 175 controls are presented in Table 1. The data are presented for three age groups.

Table 1. Demographic and Clinical Data: Patients & Normal Controls

		NORMAL CONTROLS			ADHD PATIENTS		
AGEGROUP		10-14	15-19	20-29	10-14	15-19	20-29
N		43	52	80	40	54	81
MEAN AGE		12	15.2	23.4	12	17.2	22.6
RACE	**A**	2	2	0	1	1	0
	B	5	4	5	5	5	3
	H	1	1	2	0	0	0
	NA	0	0	0	0	0	0
	O	0	0	0	0	1	1
	W	35	45	73	34	47	75
GENDER	**M**	25	32	39	24	30	48
	F	18	20	41	16	24	33

TABLE 1: N, number of subjects. RACE: A, Asian; B, African American; H, Hispanic; NA, Native American; O, other; W, White.

The normal controls performed better than the ADHD patients on all of the tests in the computerized battery, except the memory tests. Two-tailed t tests indicated significant differences for thirteen of the primary variables (all except verbal and visual memory), on four of the five domain scores (all except memory domain) and for the Neurocognition Index (NCI) (Table 2). The ADHD patients were slower in tests of psychomotor speed (finger tapping and symbol digit coding) and in the four reaction time measures. They made fewer correct responses on symbol digit coding, the shifting attention test and the continuous performance test, and they made more mistakes in the Stroop test, the shifting attention test and the continuous performance test. Multivariate analysis yielded similar results when age, gender and race were considered as covariates (Table 2).

Table 2. Test Performance for ADHD Patients and Normal Controls

GROUP	NORMAL		ADHD			
	Mean	SD	Mean	SD	t	P<
N	175		175			
NCI	**100.00**	**11.35**	**90.47**	**17.36**	**6.06**	**0.0000**
MEMORY	**98.44**	**15.86**	**96.83**	**19.49**	**0.85**	**0.3970**
PMS	**101.33**	**23.70**	**92.70**	**22.82**	**3.47**	**0.0006**
RT	**100.78**	**15.16**	**89.72**	**23.56**	**5.22**	**0.0000**
COGN FLEX	**99.53**	**13.98**	**88.16**	**23.15**	**5.56**	**0.0000**
COMPL ATT	**99.92**	**12.48**	**84.14**	**36.44**	**5.39**	**0.0000**
VBM	52.51	4.42	51.62	5.69	1.64	0.1016
VIM	47.27	5.47	46.73	5.85	0.90	0.3713
FTT	114.64	18.70	108.48	21.52	2.86	0.0045
SDCcorr	58.83	13.98	54.17	13.48	3.17	0.0017
STsrt*	265.12	62.11	314.37	119.75	-4.83	0.0000
STcrt*	586.55	104.47	646.74	124.29	-4.90	0.0000
STstrt*	691.07	127.30	755.44	153.18	-4.28	0.0000
Sterr*	2.39	2.06	3.38	4.33	-2.75	0.0063
SATcorr	50.65	8.82	46.19	10.18	4.38	0.0000
SATerr*	8.85	7.33	12.43	11.38	-3.50	0.0005
SATrt*	992.85	164.95	1040.22	215.12	-2.31	0.0214
SATq*	1.19	0.28	1.36	0.44	-4.31	0.0000
CPTcorr	39.71	0.80	38.90	2.24	4.50	0.0000
CPTerr*	1.48	1.68	2.95	7.53	-2.50	0.0134
CPTrt*	409.91	51.65	460.49	74.48	-7.35	0.0000

Table 2: NCI Neurocognition Index, PMS Psychomotor speed, RT Reaction Time, COGN FLEX cognitive flexibility, COMPL ATT, complex attention, VBM Verbal Memory, VIM Visual Memory, FTT finger tapping test total right and left taps, SDC Symbol Digit Coding, ST Stroop Test, SAT Shifting Attention Test, Q Efficiency ((SAT RT/per cent correct)/1000), CPT Continuous Performance Test. An asterisk indicates that a lower score is better.

The two groups, therefore, normals and ADHD patients, demonstrated the cognitive differences one should expect to see, and the computerized battery was sensitive to these differences. Having thus established the validity of the two groups and the sensitivity of the instrument, it was appropriate to proceed to the next level of analysis. The general question we posed was whether the cognitive abilities of ADHD patients changed with age, compared to normal adults. If differences did, indeed, exist, how were they reflected, specifically, in tests of executive control function?

The results of correlation analysis of the thirteen primary test variables with age are presented in Table 3. (The two memory tests, having proven to be insensitive to group differences, were excluded from this analysis.) In normal Ss, every variable is significantly correlated with age; that is, test scores improve in older patients, from age 10 to 29. This is consistent with the known standardization properties of the tests; as people mature, they get better on neurocognitive tests; age-related cognitive decline does not begin until past 30 years of age.

ADHD patients, however, demonstrate a slightly different pattern. Their performance improves with age in tests of psychomotor speed (FTT and SDC) and sustained attention (CPT), but not in the two tests of executive control, the ST and the SAT.

TABLE 3. TEST SCORES CORRELATED WITH AGE

	NML		ADHD	
	r	P<	r	P<
FTT	0.32	0.0000	0.28	0.0002
SDCcorr	0.45	0.0000	0.48	0.0000
STsrt*	-0.16	0.0309	0.01	0.9286
STcrt*	-0.48	0.0000	0.00	0.9567
STstrt*	-0.41	0.0000	0.03	0.6674
Sterr*	-0.36	0.0000	-0.26	0.0005
SATcorr	0.52	0.0000	0.35	0.0000
SATerr*	-0.49	0.0000	-0.51	0.0000
SATrt*	-0.21	0.0054	0.23	0.0024
SATq*	-0.50	0.0000	-0.14	0.0589
CPTcorr	0.20	0.0070	0.10	0.2028
CPTerr*	-0.42	0.0000	-0.31	0.0000
CPTrt*	-0.36	0.0000	-0.23	0.0022

On the finger tapping test, for example, tapping speed improves with age in both normals (r = 0.32, P < 0.00001) and ADHD patients (r= 0.28, P < 0.0002). The same pattern is observed in symbol digit coding and the continuous performance test. However, in the two tests of executive ability, the pattern does not hold.

On the Stroop test, reaction times improve with age in normal individuals but not in ADHD patients. In both groups, the number of errors decreases with increasing age. Normals are able to improve their performance, however, and also increase the speed with which they respond. ADHD patients are no faster at age 29, however, than they are at age 10.

This pattern is demonstrated more dramatically on the shifting attention test, a more rigorous test of cognitive flexibility. In both groups, the number of correct responses improves with age, and so does the error rate. However, normal individuals achieve better scores with faster reaction times. The correlation between reaction time and age in normals is r = -0.21. For ADHD patients, however, the correlation between reaction time and age is positive (r = 0.23). They are able to better their performance as they mature, but only by adopting a comparatively inefficient strategy. They go slower; they are less efficient.

This pattern is demonstrated in the scatterplots in Figures 1, 2 and 3. In the first figure, correct responses on the SAT, the slopes of the regression lines for normals and ADHD patients are both positive. In the second figure, SAT reaction time, the regression lines diverge. The slope of the regression line is negative for normal subjects and positive for ADHD patients. In Figure 3, complex reaction times on the Stroop test have a negative slope in normals, but the regression line is flat for patients with ADHD.

INSERT FIGURES 1, 2 AND 3 AROUND HERE

FIGURE 1. SAT CORRECT RESPONSES IMPROVE WITH AGE IN BOTH GROUPS

FIGURE 2. SAT REACTION TIMES DIVERGE IN ADHD PATIENTS AND NORMAL CONTROLS

FIGURE 3. COMPLEX REACTION TIME ON THE STROOP TEST

In the first part of this paper, we wrote that patients' performance on neuropsychological tests like the SAT change as individuals mature, and then they change again as they age. To illustrate this point, the following figures show changes in performance on the SAT with aging. The data are taken from normal individuals in the CNS Vital Signs Database, N = 556, age 8-89. The jagged line represents the observed data, the extrapolated curve is smooth.

In Figure 4, correct responses on the SAT improve until about age 40, and then gradually decline. In Figure 5, SAT reaction times are fastest at about age 30, and then gradually slow down as people age.

INSERT FIGURES 4 AND 5 AROUND HERE

Figure 4. SAT Correct Responses by Age, Normal Subjects

Figure 5. SAT Reaction Time by Age, Normal Subjects

DISCUSION

We believe that our data support four conclusions. The first two have been remarked on many occasions before. Three and four are new.

1. In childhood, adolescence and young adulthood, untreated patients with ADHD are impaired, compared to normal controls, in measures of psychomotor speed, reaction time, cognitive flexibility and attention.
2. Test scores correlate with age in normals – correct responses increase, errors and reaction times decrease – in all of the tests in the neurocognitive battery.
3. Test scores improve with age in ADHD patients in most measures, but not necessarily in the two measures of ECF, the Stroop test and the shifting attention test. In these two tests, some test scores were de-correlated with age, or were correlated, but with the opposite slope.
4. In normals and ADHD patients, performance in shifting attention (correct responses, errors) improves with age. Normals, however, improve their performance with shorter reaction times. ADHD patients improve their performance, but by adopting a less efficient strategy: their reaction times increase with age.

The first conclusion simply reiterates that ADHD patients have diffuse cognitive dysfunction; the second, that as people grow up, they perform better on neurocognitive tests. Three and four indicate that there is something different about the maturation process in patients with ADHD. While they, too, improve with age in most of the tests on the CNS Vital Signs battery, in tests of executive control, something different happens.

The authors acknowledge that one should exercise caution is drawing conclusions from a cross-sectional, naturalistic study such as this. The ideal method to study maturational changes in neuropsychological functions is a longitudinal study, with multiple measures over time. It would also be important to examine whether treatment exercised any effect on the development of cognitive strategies in people with ADHD. These weaknesses, however, are balances by the strengths of the study: the large number of subjects and the precision of the computerized test battery. Even in the face of these limitations, however, it is not inappropriate to consider the psychological impact of our findings.

As people mature, they learn to solve complex problems with increasing efficiency. As ADHD patients mature, they also learn to solve complex problems better. In normals and ADHD patients, correct responses on the SAT, and error rates on the SAT and the Stroop test, improve with age. The crucial difference is the time that ADHD patients have to devote to information processing in both of these tests. This is reflected in the reaction time data, which, in fact, is “complex reaction time” or a form of information processing speed. As normals mature, their complex reaction time scores on the Stroop test grow faster. As ADHD patients mature, their Stroop reaction times stay the same. As normals mature, their complex reaction time scores on the SAT grow faster; among ADHD patients their SAT reaction times actually grow longer.

Considering the SAT data, ADHD patients perform better as they grow up, but in order to do so, they have to adopt a less efficient cognitive strategy. At age 20-29, ADHD patients’ reaction times on the SAT are, on average, 142 msecs slower than normals. This represents a significant cost in information processing speed. Considering the Stroop test, ADHD patients perform better, but, unlike normals, their efficiency does not improve.

Set-shifting tasks like the SAT are measures of one’s ability to shift from one instructional set to another quickly and accurately. In neuropsychology, the appropriate term is “cognitive flexibility.” In everyday life, we refer to it as “multitasking.” “Shifting attention” simply means the ability to attend to one task and then to another. The ability to multitask depends on one’s ability to shift attention quickly, accurately and with facility. Hsieh ((Hsieh, 2002)) noted that the shifting of attention between two different types of tasks causes an increase in reaction time to both tasks. The degree to which set-shifting increases one’s reaction time is a measure of what we should term “cognitive efficiency.”

Cognitive inhibition has been proposed as a “core deficit” in ADHD (Barkley, 1997a). The Stroop test is a measure of one’s ability to inhibit an over-learned response and to activate an unfamiliar response. Our Stroop test data indicate that ADHD individuals learn to do that better as they grow up, but they are not able to improve their cognitive efficiency. Our data is fully in accord with those of Smith et al (Smith et al., 2004) who studied a similar phenomenon in ADHD children. The ADHD patient is capable of performing at a level comparable to normals, but in order to do so, has to trigger inhibitory processes earlier and more strongly than controls ((Smith et al., 2004)).

Our data support ECF as a “core deficit” in ADHD. The importance of cognitive inhibition, as measured by the Stroop test, is also supported, although more dramatic differences in cognitive efficiency between ADHD patients and normals are expressed in the SAT. Doing well on the SAT entails efficient regulation of response execution processes, which some have suggested are at least as important as cognitive inhibition (Banaschewski et al., 2004; Banaschewski et al., 2004).

In fact, the ECF comprise a superordinate command structure that regulates the various cognitive, motoric, social and emotional systems. Cognitive inhibition is one component of that structure; response execution is another. In speaking of ECF it may be more appropriate to speak in terms of the whole rather than the parts. In fact, the single principle around which the cognitive and behavioral components of the frontal lobe unite, is what Bekhterev called "psychoregulation" of Bekhterev ((Bekhterev, 1907)) and Luria, “behavioral regulation” ((Luria, 1973)). Fronto-striatal control systems regulate the mechanisms of arousal and of attention, the coupling of sensory information to autonomic activity, and the integration of complex goal-directed behavior. The actions of regulation and modification are in the service of stability of behavior and mood, and towards the successful execution of complex behaviors. Conversely, a relative weakness in the regulatory apparatus would be associated with instability in behavior and mood, and inefficiency in the execution of complex goal-directed behaviors; in other words, the clinical picture of the ADHD patient.

In this study, we have proposed that the efficency of the regulatory apparatus – the efficiency of ECF – can be inferred by looking at changes in cognitive performance during a period of time, from age 10 to 29, when the apparatus is maturing. (The prefrontal cortex is not completely myelinated until the fifth decade of life ((Yakovlev, 1970; Yakovlev, 1962)), but our sample did not reach quite that far.) We took complex reaction time, or information processing speed, as an indirect measure of cognitive efficiency. In both tests, the Stroop and the SAT, we are studying how the individuals are able to allocate their attentional resources efficiently. ADHD patients are inefficient in the way they allocate their attentional resources.

To discuss the efficiency ECF in terms of msecs is somewhat obscure. One hundred and forty-two msecs is not a very long time. In a car driving 60 MPH, it is only 12.5 feet. Activating a response on your PC by pressing a key takes 17 msecs. In the life of a neuron, though, it is a long time. In the life of an individual, what is the cumulative impact of a 142 msec increment in every complex mental operation he or she undertakes? What is the bio-energetic cost? What is the opportunity cost? And how is that reflected in the psychology of a person?

It is appropriate to emphasize the real-world importance of executive functions. Even the most prosaic tasks, like playing videogames and finding one's way to a designated point are impaired in ADHD children, and their impairments are correlated with poor performance on a neuropsychological test of set-shifting (Lawrence et al., 2004). With respect to our finding, we propose that the cumulative effect of slower information processing speed represents a significant burden to the ADHD adult. An organism so heavily taxed might be prone not only to cognitive difficulties, but behavioral and emotional complications as well.

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