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Effects of Transcutaneous Electrical Nerve Stimulation (TENS) on Cognition, Behavior, and the Rest-Activity Rhythm in Children with Attention Deficit Hyperactivity Disorder, Combined Type

Solveig Jonsdottir, Anke Bouma, Joseph A. Sergeant, and Erik J. A. Scherder

Objective. *The aim of this study was to examine the effects of transcutaneous electrical nerve stimulation (TENS) on cognition, behavior, and the rest-activity rhythm in children with attention deficit hyperactivity disorder, combined type (ADHD-CT).* **Methods.** *Twenty-two children diagnosed with ADHD-CT received TENS treatment during 6 weeks, 2 times 30 min a day. Neuropsychological tests were administered to assess cognition, parent/teacher behavioral rating scales were used to measure behavior, and actigraphy was used to assess the rest-activity rhythm.* **Results.** *TENS appeared to have a moderate beneficial influence on cognitive functions that load particularly on executive function. There was also improvement in behavior as measured by parent/teacher behavioral rating scales. Moreover, motor restlessness during sleep and motor activity during the day decreased by TENS.* **Conclusions.** *The effects of TENS in children with ADHD are modest but encouraging and warrant further research.*

Key Words: *Attention deficit hyperactivity disorder (ADHD)—Transcutaneous electrical nerve stimulation (TENS)—Actigraphy—Rest-activity rhythm—Children.*

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Attention deficit hyperactivity disorder (ADHD) is the most common neuropsychiatric disorder of childhood, affecting between 1% and 7% of children depending on the stringency of criteria used.^{1–3} The condition is manifested by excessive motor activity, impulsivity, and inattention and is associated with impairments in academic and social functioning. The etiology of the disorder is not known at this time, but several theories have been proposed to explain it. Barkley⁴ has argued that the various deficits observed in ADHD, including apparent attentional problems, are caused by one main feature: an impairment in the development of delayed responding, or response inhibition. He has put forth a theory that specifies that behavioral inhibition facilitates the effective performance of 4 executive neuropsychological functions: working memory, internalization of speech, self-regulation of affect-motivation-arousal, and reconstitution (behavioral analysis and synthesis). These 4 executive functions influence the motor system in the service of goal-directed behavior and originate within the brain's motor system (prefrontal and frontal cortex). The prefrontal cortex and its connections with the striatum play an important role in executive functions.⁵ A relation has been observed between the volumetric properties of the frontostriatal system and the performance on inhibition tasks.⁶ Abnormalities in the function and structure of the frontostriatal system have been observed in children with ADHD,^{5,7} and a decrease in inhibition is a main hallmark of ADHD.^{8,9} Sergeant,

Oosterlaan, and van der Meere¹⁰ have argued that it is an oversimplification to conclude that ADHD children uniquely suffer from an inhibition deficit that accounts for all of the experimental findings of impaired performance on a myriad of tasks. They have used information-processing theory and its associated energetic model (arousal, activation, and effort) for isolating the central deficits in ADHD within that paradigm. They emphasize the inadequate allocation of cognitive-energetic resources during the motor output stage of information processing. Douglas,¹¹ on the other hand, has viewed attentional and inhibitory deficits as different manifestations of an underlying regulatory control problem and believes this to be a more inclusive conceptual framework within which attentional, inhibitory, and motor-processing problems can be integrated.

Research has shown that ADHD is associated with various neuropsychological deficits, such as difficulties with planning and forethought, delay of gratification, resistance to temptation, and sustained goal-directed behavior.^{4,12} They also include deficiencies in problem solving, flexibility of responding, working memory, and self-directed private speech, which is believed to compose the phonological loop in verbal working memory.^{4,12} These deficits have in common their association with the concept of executive functioning.¹³

Sleeping disorders have been frequently reported in ADHD children and used to be a diagnostic criterion for ADHD.¹⁴⁻¹⁷ ADHD children have been shown to be more motor active in their sleep¹⁸ and to have a more unstable sleep-wake system¹⁹ than normal children. Thunström²⁰ found that approximately 1 in 4 children with severe sleep problems in infancy would later qualify for the diagnosis of ADHD. A recent study by O'Brien and colleagues²¹ found that both stimulant-medicated and nonmedicated ADHD children had more sleep disturbances than controls. They also found that children with ADHD spend less time in rapid eye movement (REM) sleep than controls. During REM sleep, most muscles of the body are relatively paralyzed, so there is no motor activity during that time. The fact that ADHD children spend less time in REM sleep than other children might be one explanation for more motoric activity during sleep. Studies have indicated that REM sleep may be associated with the secretion of brain-derived neurotrophic factor (BDNF), which in turn is believed to be involved in sleep regulation.^{22,23}

Stimulant drug therapy is the most frequently used and the most effective therapy known today for ADHD.^{14,24} The limitations of stimulant drug therapy are that although it helps 65% to 75% of ADHD children,²⁵ there are many nonresponders, there are some side effects, there is a need for frequent dosing, there is an abuse potential, there are wear-off or rebound effects,^{26,27} and many parents are reluctant to give their children drugs. In view of these limitations, it is of utmost importance to seek and develop safe alternative nonpharmacological types of stimulation for ADHD. One type of nonpharmacological neuronal stimulation is transcutaneous electrical nerve stimulation (TENS).

In a series of studies, the effects of TENS on memory, (affective) behavior, and the rest-activity rhythm were examined in patients with probable Alzheimer's Disease (AD).²⁸⁻³³ The results showed that visual short-term memory, visual and verbal long-term (recognition) memory, and verbal fluency improved with TENS. In addition, patients who were stimulated participated more independently in activities of daily life and showed an improvement in their mood and in their rest-activity rhythm. The improvement in the rest-activity rhythm of the AD patients implied that the nightly restlessness decreased.

One explanation for the observed treatment effects might be that TENS activates the hippocampus, the hypothalamus, and the hypothalamic suprachiasmatic nucleus (SCN), the "biological clock" of the brain, through direct spinoseptal and spinohypothalamic pathways.³⁴⁻³⁷ These areas are involved in memory processes,³⁸ affective behavior, and the rest-activity rhythm,^{39,40} respectively, and are affected in AD.^{39,41,42} Alternatively one could also argue that TENS stimulates the ascending reticular activating system (ARAS) through, for example, the locus coeruleus and the nucleus raphe dorsalis.⁴³ These brain stem areas, which are the origin of the noradrenergic and serotonergic system, respectively,⁴⁴ are part of the ARAS.⁴⁵ One of the end fields of the ARAS is the prefrontal cortex,⁴⁶ which plays a crucial role in executive functions, such as inhibition^{6,47-49} and working memory.

Based on the positive effects of TENS on cognition, behavior, and the rest-activity rhythm in AD patients and the rationale underlying those effects, that is, TENS might stimulate cortical activity through the ARAS, it was hypothesized in the present study that TENS could have a beneficial influ-

ence on cognition, behavior, and the rest-activity rhythm in children with ADHD.

METHODS

Subjects

The sample consisted of 22 children (21 boys and 1 girl), drawn from schools, from an ADHD advisory center, and from an ADHD patients' association. The children had been diagnosed with ADHD combined type (*DSM-IV*) by a pediatrician or a child psychiatrist on the basis of a clinical interview. To further support the diagnosis, the Disruptive Behavior Disorders Rating Scale,⁵⁰ Dutch version,⁵¹ was administered to the parents and the teacher. They filled in the questionnaire independent from each other. The items belong to 1 of 4 *DSM-IV* disorders: attention deficit disorder (9 items), hyperactivity/impulsivity disorder (9 items), oppositional defiant disorder (16 items), and conduct disorder (16 items). Raw scores were transformed into percentile scores. The cutoff score for inclusion in the present study was set at a percentile score of 90 for attention deficit and hyperactivity/impulsivity on questionnaires from both parents and teachers.

The patients ranged in age from 8 to 14 years, with a mean age of 10.59. Children were included if they had normal intelligence and when they were prepared to be medication free during the study period of 12 weeks. Individuals were excluded from participation in this study if they had a history of epilepsy, dyslexia, pervasive developmental disorder, schizophrenia, Gilles de la Tourette, or a personality disturbance.

The parents and the children were extensively informed about the goal and the procedure of the study and gave their informed consent. It was emphasized that a beneficial influence of TENS on cognition, behavior, and the rest-activity rhythm could not be guaranteed. Next, the patients were familiarized with the electrostimulation method by applying a trial treatment during which they could experience the electrical stimulus. The parents and the children subsequently gave their informed consent.

Materials and Procedure

To evaluate possible treatment effects on cognition, behavior, and the rest-activity rhythm, several

neuropsychological tests, a behavioral rating scale, and an actigraphy were applied, respectively, before the onset of the treatment period (pre), directly after the 6-week treatment period (post), and again after 6 weeks without treatment (delayed). The administration of the tests took place by an investigator who was not blind with respect to treatment. Similarly, the parents and the teacher who filled in the behavioral rating scale knew that the child received TENS treatment.

Neuropsychological Tests

The subtests Arithmetic, Digit Span, and Coding from the Wechsler Intelligence Scale for Children–Revised⁵² can be combined into one separate IQ factor, called Freedom from Distractibility,⁵³ also sometimes called the “Third Factor” (F31Q). The subtest Arithmetic implies that the children have to solve sums, for which fundamental arithmetical skills are required (e.g., subtracting) ($M = 10$). On the subtest Coding, the child is asked to associate a specific number with a specific symbol ($M = 10$). On the subtest Digit Span, the child has to repeat a number of digits in the same and in a reversed sequence. Besides a variety of cognitive functions, all 3 subtests may be considered to tap the executive function of working memory.^{4,13}

The Bourdon-Vos⁵⁴ is a task that requires sustained visual attention and visuomotor speed. The test consists of a sheet of paper with groups of dots printed on it. Each group has a varying number of dots, that is, 3, 4, or 5 dots, and moreover, the dots are differently situated in each group. The child is asked to cross out as quickly and accurately as possible the groups with 4 dots. Administration of the Bourdon-Vos results in 2 scores: 1) the mean time in seconds per line ($M = 10$) and 2) the total number of omissions ($M = 15$).⁵⁵ Test-retest reliability for the mean time per line appeared to be 0.87, and interrater-reliability was 0.91.⁵⁵

The Stroop Colour and Word Test, Dutch version,⁵⁶ is meant to measure executive (cognitive) processing. The test consists of 3 cards with 100 items each. All items relate to the colors red, yellow, blue, and green. On card 1, the names of these 4 colors are printed in black ink and the child is asked to read aloud the printed names as quickly as possible. Subsequently, card 2 is presented to the child. On card 2, the colors themselves are shown, and the child is required to name the colors as quickly as possible. On card 3, the color of the ink does not match the name of the color. For

example, the word *red* is printed in yellow ink. The child is asked to read aloud the color of the ink (e.g., yellow), instead of the name of the color (e.g., the word *red*), as quickly as possible. For an adequate performance, the child has to suppress the impulse to read the words themselves. The difference in time between card 2 and card 3 results in an interference score. A high interference score may point to a deficit in executive function. Children with ADHD have been shown to be slower than controls on the Stroop tasks.⁵⁷

Behavioral Measures

The Revised Conners Parent and Teacher Rating Scales⁵⁸ was used to rate the various behavioral symptoms. The scale includes 7 subscales, that is, conduct problems I (max. score: 30), learning problems (max. score: 12), psychosomatic problems (max. score: 15), impulsive-hyperactive (max. score: 12), conduct problems II (max. score: 9), anxiety (max. score: 12), and other items (max. score: 54). A lowering of the score implies an improvement in behavior.

Actigraphy

The rest-activity rhythm was assessed using actigraphy,³³ for 3 periods: 5 days before treatment (pre) during which the children were medication free, 5 days immediately following a 6-week treatment period (post), and again 5 days after a treatment-free period of 6 weeks (delayed). On each occasion, the child wore an actigraph around the right wrist. The actigraph registers arm movements. From the resulting rest-activity rhythms, 5 variables were calculated: 1) The interdaily stability (IS) quantifies the strength of coupling between the rest-activity rhythm and supposedly stable zeitgebers. In normal cases, the activity patterns of individual days resemble each other very much, whereas days may differ considerably with rhythm disturbances. 2) The intradaily variability (IV) quantifies the fragmentation of the rhythm, that is, the frequency and extent of transitions between rest and activity. In normal cases, one has a major activity period during the day and a major inactivity period during the night, whereas brief alternating bouts of rest and activity are characteristic of rhythm disturbances. 3) The relative amplitude (RA) quantifies the difference between the main activity (day) and rest (night) periods. 4) M10

reflects 10 h of the child's maximum activity within 24 h. 5) L5 represents the 5 least active hours within 24 h. In normal cases, the daytime activity is high and the nighttime activity is low, resulting in high amplitude. With circadian rhythm disturbances, nighttime activity may increase, whereas daytime activity may decrease resulting in a low amplitude.

TENS Treatment

Frequency and intensity. The children were treated with an electrostimulator, type Premier 10s. This stimulator generates transcutaneous electrostimulation that consists of asymmetric biphasic square impulses, applied in bursts of trains, 9 pulses per train, with an internal frequency of 160 Hz, a repetition rate of 2 Hz, and a pulse width of 100 μ s. This type of TENS is known as BURST-TENS.⁵⁹ The intensity of the stimulation triggered visible muscular twitches, which were painless. A flickering green light placed on the electrostimulator indicated stimulation.

Location. Two 2 $\times$ 3 cm (h $\times$ w) self-adhesive carbon rubber electrodes were fixed on the patient's back between Th1 and Th5, each on one side of the spinal column.

Duration. The children were offered a stimulation time of 30 min, twice a day, that is, early in the morning between 0700 and 0800 before going to school and after school, in the afternoon between 1600 and 2000. TENS was applied at home, by one of the parents, 7 days a week during a 6-week period.

Trial treatment. The children were familiarized with the electrostimulation method by applying a trial treatment during which they could experience the electrical stimulus. During the trial period, no negative reactions to TENS were observed.

Data Analyses

For each of the neuropsychological tests, the (subscales of the) observation scale, and the actigraphy variables (IS, IV, RA, L5, and M10), 1-

Table 1. Means, Standard Deviations, and the Wilcoxon Signed Rank Tests (*Z* Scores, *P* Values) with Respect to the Scores on the Various Neuropsychological Tests, Administered before and after a Treatment Period of 6 Weeks and after a Treatment-Free Period of 6 Weeks

Neuropsychological Tests	Pre		Post		Delay		Wilcoxon Pre-Post		Wilcoxon Post-Delayed	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>Z</i>	<i>P</i>	<i>Z</i>	<i>P</i>
Third factor total score	85.73	13.20	88.59	13.33	90.53	9.74	1.83	0.03	1.22	0.22
Arithmetic	7.23	2.43	7.19	2.08	7.16	2.46	0.16	0.44	0.35	0.73
Digit Span	8.41	3.12	8.59	2.17	9.00	2.56	0.65	0.26	1.29	0.20
Coding	7.77	3.53	8.68	3.40	9.58	2.36	1.98	0.02	1.15	0.25
Bourdon-Vos Time (seconds)	17.92	4.15	16.76	4.83	14.72	3.37	2.69	0.004	1.89	0.06
Bourdon-Vos Omissions	21.67	30.66	9.24	7.01	7.84	7.76	2.37	0.009	0.88	0.38
Stroop Card 3 – Card 2	96.41	44.60	73.72	30.87	60.44	29.38	1.82	0.03	1.60	0.11

tailed nonparametric Wilcoxon signed rank tests were used at a 0.05 significance level on 2 contrasts: pre versus post and post versus delayed. In addition, effect sizes were calculated, $d' = .20$ is small, $d' = .50$ is moderate, and $d' = .80$ is large.⁶⁰

RESULTS

Cognition

The third factor (Freedom from Distractibility). Data-analyses by means of the nonparametric Wilcoxon signed rank test showed that after a treatment period of 6 weeks, the children showed a significant improvement in the total score of F3IQ. The effect size d appeared to be small: .19. Analyses of the posttreatment scores on the 3 subtests revealed only a significant higher score on the subtest Coding, with a small to moderate effect size d of .31 (see Table 1 for means, standard deviations, and the Wilcoxon signed rank test). After a treatment-free period of 6 weeks, the observed higher scores on F3IQ and Coding had disappeared (see Table 1).

Bourdon-Vos. Data-analyses revealed that the time during which the Bourdon-Vos was performed was significantly shorter after the treatment period, compared to the performance before the treatment period. The effect size d was small to moderate: .28. Not only did the duration of the performance of the test decrease, but also the number of omissions decreased significantly, with a moderate effect size d of .49. After the period without

treatment, data analyses showed no further significant decline in the duration of task performance and the number of omissions.

Stroop. The Wilcoxon signed rank test showed that the interference score (card 3 minus card 2) decreased significantly after the treatment period. The effect size d was moderate: .48. No further significant decrease in the interference score was observed during the treatment-free period (see Table 1 for means, standard deviations, and the Wilcoxon signed rank test).

Behavior

The Revised Conners Parent and Teacher Rating Scales, Parent version. Data-analyses by means of the Wilcoxon signed ranked test showed that, according to the parents, the child's overall behavior significantly improved after the treatment period. The effect size d was large: .81 (see Table 2 for means, standard deviations, and the Wilcoxon signed rank test). More specifically, according to the parents, the children improved significantly on all subscales, with moderate to large effect sizes d ranging from .25 (subscale Anxiety) to 1.14 (subscale Impulsive/Hyperactive). After the treatment-free period of 6 weeks, the observed improvements remained level. For means, standard deviations, and the Wilcoxon signed rank test, see Table 2.

The Revised Conners Parent and Teacher Rating Scales, Teacher version. Similar to the parents' ver-

Table 2. Means, Standard Deviations, and the Wilcoxon Signed Rank Tests (*Z* Scores, *P* Values) with Respect to the Scores on the Revised Conners Parents & Teacher Rating Scale (Conners), Administered to the Parents and the Teachers, before and after the Treatment Period of 6 Weeks and after a Treatment-Free Period of 6 Weeks

Conners	Pre		Post		Delay		Wilcoxon Pre-Post		Wilcoxon Post-Delayed	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>Z</i>	<i>P</i>	<i>Z</i>	<i>P</i>
Parents' version										
Total score	52.52	18.44	39.10	17.63	38.74	16.25	3.22	0.0005	0.15	0.88
Conduct problems I	11.76	4.89	9.20	4.69	8.79	5.13	2.46	0.007	0.06	0.95
Learning problems	7.38	1.80	6.05	2.24	6.37	2.50	2.14	0.02	0.09	0.93
Psychosomatic problems	1.71	1.59	1.05	1.32	0.84	1.07	2.16	0.02	0.70	0.48
Impulsive/hyperactive	7.33	2.01	4.90	2.49	4.84	1.83	3.07	0.001	0.11	0.91
Conduct problems II	2.52	1.94	1.90	1.68	1.79	1.47	2.28	0.01	0.32	0.75
Anxiety	3.10	2.57	2.50	2.24	2.47	1.95	1.82	0.03	0.66	0.51
Other items	19.19	8.95	13.60	8.36	13.11	7.28	3.30	0.0005	0.04	0.97
Teachers' version										
Total score	42.40	18.84	35.75	14.83	26.62	7.90	1.92	0.03	2.29	0.01
Conduct problems I	11.15	5.50	9.00	4.49	6.85	3.69	1.54	0.06	1.96	0.03
Learning problems	6.40	2.78	5.94	2.68	4.62	1.80	1.38	0.08	1.63	0.10
Psychosomatic problems	0.88	1.36	0.47	0.64	0.46	1.21	0.94	0.18	0.58	0.56
Impulsive/hyperactive	6.50	3.15	5.18	2.74	4.08	1.44	1.32	0.09	0.53	0.59
Conduct problems II	1.85	1.35	1.35	1.50	1.46	1.27	1.78	0.04	0.81	0.42
Anxiety	2.20	1.85	2.76	2.80	1.38	1.66	0.24	0.41	0.11	0.92
Other items	13.50	7.49	12.35	7.32	7.85	3.87	1.08	0.28	2.19	0.01

Table 3. Means, Standard Deviations, and the Wilcoxon Signed Rank Tests (*Z* Scores, *P* Values) with Respect to the Actigraphy-Variables, Obtained before and after the Treatment Period of 6 Weeks and after a Treatment-Free Period of 6 Weeks

Actigraphy	Pre		Post		Delay		Wilcoxon Pre-Post		Wilcoxon Post-Delayed	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>Z</i>	<i>P</i>	<i>Z</i>	<i>P</i>
Interdaily stability	0.69	0.09	0.62	0.13	0.61	0.15	1.29	0.20	0.47	0.64
Intradaily variability	0.62	0.16	0.70	0.25	0.64	0.14	1.29	0.47	0.91	0.36
Relative amplitude	0.96	0.01	0.97	0.01	0.95	0.04	0.40	0.35	1.41	0.08
L5	801	277	595	303	1354	1751	2.07	0.02	1.66	0.05
M10	45810	15473	37967	21187	44478	20639	1.45	0.07	0.73	0.47

L5 = 5 least active hours; M10 = 10 most active hours.

sion, the teachers also found that the overall behavior of the children improved significantly after the treatment period. However, the effect size *d* was moderate: .37. It is noteworthy that after the stimulation was ended the children's overall behavior further improved during the treatment-free period, with a somewhat larger effect size *d* of .51. With respect to the various subscales, significant improvements were observed for the subscales Learning Problems, Impulsive/Hyperactive, and Conduct Problems II, with small to moderate effect sizes *d* of .23, .52, and .28, respectively. The scores on these 3 subscales did not change significantly after the treatment-free period (for means, stan-

dard deviations, and the Wilcoxon signed rank test, see Table 2).

Rest-Activity Rhythm

As Table 3 shows, the scores on the actigraphy variable L5 significantly declined after the treatment period of 6 weeks. Although the M10 variable also declined, it did not reach statistical significance. The effect sizes *d* were .92 (large) and .66 (moderate), respectively (for means, standard deviations, and the Wilcoxon signed rank test, see Table 3). No treatment effects were observed with respect to IS, IV, and RA. Of note is that the score

on L5 showed a significant increase after the 6-week period without treatment (moderate effect size d of .60). The increase in scores on M10 after the treatment-free period was not significant (for means, standard deviations, and the Wilcoxon signed rank test, see Table 3).

DISCUSSION

The goal of the present pilot study was to examine whether TENS, a nonpharmacological central nervous system stimulant, could have a beneficial influence on cognition, behavior, and the rest-activity rhythm of children with ADHD. The results will be discussed per domain: cognition, behavior, and the rest-activity rhythm.

Cognition

The preliminary results indicate a positive effect of TENS on cognitive functioning, though the strength of the effect varies from small to moderate ($d = .19$ to $d = .61$). By comparison, a recent study⁶¹ found minimal improvement in neuropsychological functioning following methylphenidate treatment in children with ADHD. The finding that the performance on the majority of the tests did not continue to improve significantly during the treatment-free period indicates a real treatment effect rather than a test-retest effect. The positive effect of TENS on the Stroop interference performance supports its effect on executive control functions and more specifically on the prefrontal cortex and the anterior cingulate cortex.⁶²

One explanation for these findings might be as follows. Han⁶³ showed that high-frequency bursts of electrical nerve stimulation as was applied in the present study facilitate the secretion of BDNF. BDNF is crucial for normal development and plasticity of the brain.⁶⁴

Behavior

According to the parents who filled in the Revised Conners Parent and Teacher Rating Scales, the children showed a strong improvement in all aspects of behavior after TENS treatment. The greatest improvement was observed in impulsivity and hyperactivity (subscale Impulsive/Hyperactive), whereas anxiety decreased the least. The child's behavior did not change remarkably after

cessation of treatment. Although significant, the opinion of the teacher on the overall child's behavior was less pronounced in comparison with the parents'. It is remarkable that the strongest effect was again observed with respect to hyperactivity and impulsivity (subscale Impulsive/Hyperactive), suggesting that TENS, similar to stimulant medication,⁶⁵ might restore the children's inhibitory capacity by stimulating the prefrontal cortex. Another interesting finding is that overall behavior, as evaluated by the teacher, further improved significantly during the treatment-free period, with a moderate effect-size d of .51. One possible explanation might be that a positive development in behavior may further increase or be more easily noticed only in a highly structured environment such as school.

Rest-Activity Rhythm

Although no significant changes were observed with respect to the rest-activity variables IS, IV, and RA after the treatment period of 6 weeks, both L5 and M10 showed decreases, effects with a large and moderate effect size, respectively. The finding that after the treatment-free period L5 significantly increased and M10 increased to a somewhat lesser extent supports a real treatment effect of TENS. L5 represents the 5 least active hours, which most probably represent the hours at nighttime. In contrast, M10 implies the 10 most active hours, which will probably take place during the day. Similar to the effects of TENS on cognition and behavior, the finding that both L5 and M10 decreased by TENS supports the rationale that TENS enhances inhibition mediated by the prefrontal cortex. One explanation might be that TENS has a modulatory effect on the SCN. It has been proposed that dysfunction of the SCN may be contributing to many of the symptoms seen in ADHD.⁶⁶ The neurotrophin BDNF, which is an important rhythmic output from the SCN circadian clock,⁶⁷ has been found to be involved in sleep regulation.^{22,23,68,69} It might be speculated that the effect of TENS treatment on sleeping patterns both in AD and ADHD might possibly be the result of increased BDNF, which in turn has a beneficial effect on sleep.

The positive effect of TENS on L5 and M10 in ADHD could be of particular clinical relevance in that ADHD is characterized by nightly restlessness and hyperactivity during the day. Although stimulant medication therapy has been shown to decrease awake activity rates in children with

ADHD,⁷⁰ a recent study found that stimulant medication did not seem to affect sleeping patterns in ADHD children.¹⁶

Limitations

A 1st limitation of the present study was that the investigator who administered the neuropsychological tests and the parents/teacher who filled in the Revised Conners Parents and Teacher Rating scale were not blind with respect to the study design. On the other hand, both the parents' and teachers' ratings would probably have been very critical because the extent of the parents' and teachers' burden is directly related to the effectiveness of the treatment. In other words, both parents and teachers have nothing to gain by reporting positive results that are not realistic. The only real objective measurement in the present study concerned the assessment of the rest-activity rhythm by actigraphy. A 2nd limitation of the present study is the lack of a control group. For ethical reasons, that is, the children who participate have to stop their medication, we first wanted to do a pilot study to examine whether TENS could have a positive effect in children with ADHD. A 3rd limitation is that we did not apply a Bonferroni correction to the significance level of 0.05 to control for multiple tests.

Considering the encouraging effects of TENS on cognition, behavior, and the rest-activity rhythm in children with ADHD in the present study, it is justified to do a next study with a more rigorous design, including a control group.

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