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SYNCHRONIZATION, ANTICIPATION, AND CONSISTENCY IN MOTOR TIMING OF CHILDREN WITH DIMENSIONALLY DEFINED ATTENTION DEFICIT HYPERACTIVITY BEHAVIOUR[1]

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Summary.—We tested the hypothesis that children with hyperactive behaviour are impaired in the temporal organization of their motor output. The performance of 11 boys, scoring above a cut-off on standard scales of overactivity and inattention, was compared to that of controls in progressively more complex Motor-timing tasks. The tasks administered required self-paced and externally paced Sensorimotor Synchronization and Sensorimotor Anticipation. Deficits at a perceptual level were investigated with a Time-discrimination task. As hypothesized, we found that hyperactive children had no deficits in their *perception* of time but were impaired in *timing* their motor output. Hyperactive children were more *inconsistent* than controls in maintaining a freely chosen tapping rhythm, in synchronizing and in anticipating their motor response to external visual stimulation.

Impulsive, inattentive, and overactive behaviours in children can put their later psychological development at risk (Taylor, Chadwick, Heptinstall, & Danckaerts, 1996). When these behaviours are marked and developmentally inappropriate, they are a major part of the diagnostic definition of Attention Deficit Hyperactivity Disorder (ADHD). Neuropsychological evidence suggests that children with these behavioural features show impairments in executive and self-monitoring functions (Pennington & Ozonoff, 1996; Barkley, 1997). These functions are supposed to be mediated by the frontal lobes; structural and functional neuroimaging point towards a dysfunction in frontal circuitries as the basis of the disorder (Zametkin, Liebenauer, Fitzgerald, King, Minkunas, Herscovitch, Yamada, & Cohen, 1993; Castellanos, Giedd, Marsh, Hamburger, Vaituzis, Dickstein, Sarfatti, Vauss, Snell, Lange, Kaysen, Krain, Ritchie, Rajapakse, & Rapoport, 1996; Brandeis, van Leeuwen, Rubia, Vitacco, Steger, Borntraeger, & Steinhausen, 1998; Rubia, Overmeyer, Taylor, Brammer, Williams, Simmons, & Bullmore, 1999).

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The frontal lobe is primarily dedicated to the control of motor behaviour, with prefrontal areas providing the cognitive support necessary for the behavioural "output" (Fuster, 1985). One of the executive functions believed to be mediated by the prefrontal lobes is the temporal organization of behaviour. This includes the abilities of preplanning the acts that constitute purposeful behaviour, deciding their temporal onset, and monitoring their time course once they have been initiated (Fuster, 1985). Modern functional imaging confirms the suggestion derived from studies of brain lesions that prefrontal structures are involved in motor timing (Rubia, Overmeyer, Taylor, Brammer, Williams, Simmons, Andrew, & Bullmore, 1998b; Rubia, Overmeyer, Taylor, Brammer, Williams, Simmons, & Bullmore, 1999, 2000). The aim of this study was to test the hypothesis that hyperactive children are impaired in timing their motor output.

Intertemporal Competence

To plan behaviour in the future, the consequences of one's acts have to be foreseen. Behavioural and neuropsychological evidence suggests that hyperactive children show poor intertemporal competence, i.e., poor ability to associate events, which are separated by time. They live more in the present (Barkley, 1994) and display greater risk-taking behaviour than healthy subjects (Douglas, 1988; Barkley, 1994). Insufficient foresight also results in alterations in reward-mediated behaviour: unlike normal children, hyperactive children prefer small and immediate rewards to large but delayed ones (Douglas & Peters, 1979; Douglas, 1983; Schweitzer & Sulzer-Azaroff, 1995). They are less tolerant of delays of reward (Gordon, 1979; Campbell, Szumowski, Ewing, Gluck, & Breaux, 1982; Rapport, Tucker, DuPaul, Merlo, & Stoner, 1986; Sonuga-Barke, Taylor, Sembi, & Smith, 1991) and less reactive to punishment if it is delayed in time (Quay, 1988a, 1988b; Milich, Hartung, Martin, & Haigler, 1995). Poor anticipation by hyperactive children gives poor performance on planning tasks, in which future events have to be foreseen (Hayes, 1989; Shue & Douglas, 1992; Pennington & Ozonoff, 1996).

Temporal Initiation and Monitoring of Motor Output

Deficient temporal monitoring affects both the planning of motor output and its actual execution. Two peculiarities characterize the motor output of hyperactive children, poor temporal control and a relatively fast response style. Hyperactive children are impaired in sensorimotor (Werry, Minde, Guzman, Weiss, Dogan, & Hoy, 1972), timed sensorimotor (Stevens, Boydstun, Dykman, Peters, & Sinton, 1967; Stevens, Stover, & Backus, 1970; Roth, Gebelt, & Gebelt, 1983), and speeded motor tasks (Denckla & Rudel, 1978; Denckla, Rudel, Chapman, & Krieger, 1985; Carte, Nigg, & Hinshaw, 1996). Impulsiveness may be related to poor motor control. Impulsiveness can be defined as a premature responding style, in which motor acts are executed prior to the appropriate time. For example, in free tapping tasks, hyperactive children tap faster than controls (Stevens, *et al.*, 1967). Premature responding is also seen in cognitive tasks, such as the Matching Familiar Figures Test (Campbell, Endmann, & Bernfeld, 1977; Rosenbaum & Baker, 1984; DeHaas, 1986). In uncertain situations, hyperactive children respond too rapidly (Sergeant & van der Meere, 1988), and they respond prematurely and therefore more inaccurately on delay (Gordon, 1979; Sonuga-Barke & Taylor, 1992) and on time-estimation tasks (Barrat, 1981; Walker, 1982). Altered motor timing may also underlie the finding that the event rate has a differing effect on the performance of hyperactive children compared to that of controls. Cognitive performance in the hyperactive child has either benefited from a fast event rate (Kappauf & Powe, 1959; Dalby, Kinsbourne, Swanson, & Sobel, 1977; Dalby, Kinsbourne, & Swanson, 1989; van der Meere, Vreeling, & Sergeant, 1992), not been optimized by a slow event rate (Sykes, Douglas, Weiss, & Minde, 1971; Conte, Kinsbourne, Swanson, Zirk, & Samuels, 1986) or even declined with a slow presentation rate (Swanson, Kinsbourne, Roberts, & Zucker, 1978; Chee, Logan, Schachar, Lindsay, & Wachsmuth, 1989; Tomporowski, Tinsley, & Hager, 1994; van der Meere, Shalev, Borger, & Gross-Tsur, 1995). Hyperactive children also prefer shorter stimulus presentation rates than do controls in memory tasks (Sonuga-Barke, Taylor, & Heptinstall, 1992); however, the speed preference or speed benefit for a hyperactive child is task- and situation-dependent. When speed is required, hyperactive children are less able to adjust their speed to the externally demanded pace, as observed on both motor (Stevens, *et al.*, 1967, 1970; Denckla, *et al.*, 1985; Carte, *et al.*, 1996) and cognitive tasks (Sergeant & Scholten, 1985; Robins, 1992; Carte, *et al.*, 1996). Both slow and fast rates impair the performance of hyperactive children on an attention task when compared to a medium event rate (van der Meere, *et al.*, 1995). A premature response style in hyperactive children does not mean that they are necessarily faster in *absolute* terms; slow reaction times are common for these children using a wide range of tasks (Pennington & Ozonoff, 1996). The output style of hyperactive children can therefore be described as poor in control and adaptation to external requirements. They have slower reaction times on structured task situations wherein the response speed has to be adapted to external requirements; when they can choose their own speed, however, they are relatively and inappropriately fast.

In this study we wanted to investigate the hypothesis that the timing functions of poor intertemporal competence, fast and premature responding in unstructured response conditions, and poor motor output adjustment in structured response situations are impaired in hyperactive children.

A possible explanatory model for the timing deficits is the hypothesis of a fast internal clock. It has been suggested, based on timing experiments, that impulsive subjects have a fast internal clock (Siegman, 1961; Rubia, Schuri, von Cramon, & Poeppel, 1997). An accelerated internal pacemaker could explain both the fast response style and the benefit from certain event rates, if they were the most suitable for the "internal" speed of the clock.

We designed a series of computer tasks to test our hypotheses of poor intertemporal competence, fast and premature response, and poor motor adjustment. A time-Anticipation task was used to control for possible deficits at a time perception level.

The hypothesis of poor intertemporal competence was tested using an Anticipation Task, whereon the appearance of an intermittently flashing visual stimulus had to be anticipated by a motor response. A free Tapping Task should test the hypothesis of a fast response style in unstructured task conditions: the hyperactive boys were expected to tap faster than controls; fast tapping would support the explanatory model of a fast "internal clock". Temporal adjustment of motor output was tested by a Sensorimotor Synchronization task whereon the motor response had to be timed to a visual stimulus which appeared repetitively on the screen at five different event rates. The use of five different event rates should test for a possible preference or benefit of the shorter event rates in the hyperactive boys, which would be further support for the fast internal clock hypothesis. The variability of performance on all tasks provides an additional measure of temporal accuracy and persistence of motor output. To control for possible deficits in the *perception* of time intervals, a duration Discrimination task was administered on which two different temporal durations of 3 sec. and 5 sec. had to be discriminated from each other.

We used an empirical and quantitative approach to assess attention deficit hyperactive behaviour as the extreme of a continuum rather than using its diagnostic assessment. The coexistence of dimensional and categorical systems reflects the fact that neither fully satisfies all questions of assessment and diagnosis in childhood psychopathology (Kasius, Ferdinand, van den Berg, & Verhulst, 1997). Both approaches can be useful. Rating scale cutoffs are relevant for understanding the diagnostic category: for example, high overlap has been found between the DSM-III–R diagnosis for ADHD derived from the parent Diagnostic Interview Schedule for Children (Version 2,3; National Institute of Mental Health, 1992) and the Child Behavior Check List (Achenbach & Edelbrock, 1983; Biederman, Faraone, Doyle, Lehman, Kraus, Perrin, & Tsuang, 1993; Jensen, Salzberg, Richters, & Watanabe, 1993; Kasius, *et al.*, 1997). Our main concern was to examine temporal organisation in children who were selected systematically from the population of children encountering educational problems because they showed high hyperactive behaviour.

Method

Subjects and Selection Procedure

Since hyperactive behaviour is commoner among males and may have a different basis among girls (James & Taylor, 1990), only boys were included in this study. The boys were selected from special educational services on the basis of questionnaires administered to parents (Child Behavior Checklist; Verhulst, 1985; Achenbach, 1994) and teachers using the Teacher Rating Form (Verhulst, 1985; Achenbach, 1994). All boys were right-handed, based on two questions (writing and eating) of the Annett's handedness questionnaire (Annett, 1970) and on the observation of the hand used for writing their own names.

Eleven hyperactive boys in the age range of 6–12 years ($M_{age} = 9.4$ yr.), rated at or above the 94th percentile on the "attention problems" scales on both questionnaires, were tested. Subjects who scored above cut-off for any other scale (except conduct disorder) were excluded from the study. Also excluded were boys with reading, language, or learning disorders. Children who met criteria for both attention problems and conduct disorder were included because we considered the latter to be a compilation of the disorder rather than a comorbidity (Fergusson, Horwood, & Lloyd, 1991; Taylor, *et al.*, 1996). Three of the boys met criteria for both conduct disorder and attention problems.

The 11 boys in the control group in the age range of 6 to 12 years ($M_{age} = 9.0$ yr.) were recruited from normal public schools, and all rated below the 75th percentile on all syndrome scales of the Child Behavior Checklist and the Teacher Rating Form.

Intelligence quotient was assessed by using four subtests of the Wechsler Intelligence Scale for Children–Revised (Vocabulary, Arithmetic, Block Design, and Picture Arrangement). These subtests correlate .93 to .95 with the full administration of the WISC–R (Groth-Marnat, 1990). Children were included if they had a prorated Full Scale IQ greater than 80. All subjects were unmedicated.

Experimental Tasks

Sensorimotor Anticipation Task.—A visual stimulus (an airplane) appeared 40 times on a computer screen with a fixed interstimulus-interval of 6 sec. The child was instructed to monitor the intertemporal gap between the appearances of the first three airplanes and to press a response button with the right index finger in anticipation of the appearance of the fourth and subsequent airplanes. The children had thus to estimate the time interval and press the button shortly before in their estimation the stimulus would appear on the screen. The children were advised to estimate the interstimulus-interval by either counting or intuition. The task involves several cognitive functions of time estimation, sustained attention (to time), and sensorimotor timing. The continuity of stimulus appearance (no breaks between trials) imposes a high processing load on the subject by requiring mental resetting on every stimulus to monitor the next temporal interval. Implicit feedback was given by the perception of the synchrony or asynchrony of their own button-press in relation to the appearance of the stimulus. Dependent measures were the "Anticipation" Time and its variability. The Anticipation Time is the "response" time in anticipation of the stimulus appearance. The Anticipation Time reflects the accuracy of time estimation, while its variability reflects the consistency of the time estimation. This task is a variant of a delayed response task whereon a motor response has to be made in response to a stimulus appearing after a fixed interval. The delayed response task has been widely used to test motor preparation and motor timing, eliciting the well-known motor expectancy wave in electrophysiological studies, reflecting motor preparation, motor timing, and expectancy (Deecke, Kornhuber, Lang, & Schreiber, 1985; Brunia & Damen, 1988). By instructing subjects to anticipate their response to the stimulus instead of reacting to it, we intended to impose a higher load on time-estimation and motor-timing functions compared to the "classical" delayed response task. Our task variant has been shown to activate plausible brain regions for motor-output timing functions in healthy subjects (Rubia, *et al.*, 1998b, 2000) but not in subjects with ADHD (Rubia, *et al.*, 1999).

Free tapping.—Free tapping is a validated experimental paradigm to investigate the speed and consistency of self-produced finger tapping and has been used with adults and children (Mates, 1990; Kooistra, Snijders, Schellekens, Kalverboer, & Geuze, 1997; Kumai & Sugai, 1997) as well as in ADHD (Stevens, *et al.*, 1967, 1970). The subjects were required to tap a response button with the right finger 80 times as regularly as possible at a freely chosen rhythm. The reaction times reflect the preferred speed, while the consistency and regularity of the motor production is reflected by the variability of response.

Sensorimotor synchronization task (timed tapping).—Subjects were required to synchronize their motor response via a right-handed button-press to a visual stimulus (airplane) which appeared at a fixed event rate on a computer screen. Synchronization of finger tapping using repetitive stimuli is a validated experimental paradigm to study sensorimotor timing mechanisms, widely used in adults, children, and groups of patients (Fraisse, 1978; Najenson, Ron, & Behroozi, 1989; Mates, Radil, & Poeppel, 1992; Kumai & Sugai, 1997; Piek & Skinner, 1999; Rubia, *et al.*, 1999). Good perceptual-motor integration is required to achieve sensorimotor coincidence. Five blocks of 60 trials were administered. Interstimulus intervals were 400 msec., 500 msec., 700 msec., 1200 msec., and 1800 msec. The most relevant independent measure is the variability of responses, reflecting consistency of sensorimotor co-ordination.

Time discrimination task.—Time discrimination in the seconds' range is one of the four major methods in time-estimation research (Bindra & Waksberg, 1956; Zakay, 1990). Pairs of airplanes were presented on the screen, separated by an interval of 1 sec. The first airplane's presentation had a duration of 5 sec., while the second airplane's presentation was of either 5 sec. or 3 sec. duration. The children were instructed to judge whether the length of both time intervals was identical or different by pressing the right or left response button, respectively. Decision time was 3 sec.; 10 trials were administered. The children were advised to estimate the durations by either counting or intuition.

Data Analysis

Group means were compared using t tests with adjustment for heterogeneity of variance as appropriate. Repeated-measures analyses of variance were made, with tests of over-all group differences based on Wilks Lambda criterion (Girden, 1992; Norušis, 1993), with block comparisons made using polynomial contrasts. For each repeated-measures analysis a further multivariate analysis of variance was carried out which tested group differences for each measure separately by block using univariate F tests to give further information on the specific nature of the group differences. All results for the repeated-measures models of analysis of variance are given in the text while the univariate tests are given, with descriptive statistics, in Table 1 below. To control for Type I errors in the univariate F tests, joint multivariate confidence intervals were estimated as well as the unadjusted tests which are described in the text. Only for the variance of one subtest did results differ. Estimates of effect size based on η^2, which gives an assessment of the total variance explained by the study groups, were investigated for differences which fell short of significance to examine the possibility that marked group differences were present but not statistically significant due to low power. All analyses were carried out using SPSS Version 6.1 (SPSS, Inc., 1994).

Results

Mean prorated Full Scale IQ differed significantly between the groups (Controls $M = 114.0$, $SD = 13.3$; ADHD $M = 96.5$, $SD = 15.0$; $t_{20} = 2.91$, $p < .009$). The difference was due to a higher mean prorated Verbal IQ for the Control group (Control $M = 118.5$, $SD = 14.3$; ADHD $M = 93.3$, $SD = 16.5$; $t_{20} = 3.84$, $p < .001$), whereas groups did not differ in mean prorated Performance IQ (Control $M = 106.1$, $SD = 12.2$; ADHD $M = 101.0$, $SD = 12.2$; $t_{20} = .98$, ns).

None of the dependent variables was significantly correlated with prorated Full Scale IQs. In view of the differences between groups on prorated Verbal IQ, even though no correlations between Verbal IQ and the dependent variables were found, each analysis was repeated with prorated Verbal IQ as a covariate. The effect of prorated Verbal IQ was not significant in any of these subsidiary analyses.

Sensorimotor Anticipation Task

Data were divided into two blocks to investigate effects of learning. Response times of 300–700 msec. were considered impulsive, reflexive responses triggered by onset of the stimulus. Since all the children were told never to press the button after seeing the stimulus but always in anticipation of it, these are impulsive errors of commission (Impulsive Errors). Groups were compared in the number of these erroneous Impulsive Errors using multivariate comparisons with block as the within-subject factor and group as the between-subject factor. Response times ranging between 700 and 6300 msec. were considered Anticipated Responses. The time of anticipation and its variability were compared between the groups using multivariate comparisons.

There were no over-all group differences in the Anticipation Time ($F_{1,20} = 2.65$, ns); there was no significant effect of block ($F_{1,20} = 3.89$, $p = .06$) and no interaction of group by block ($F_{1,20} = 1.35$, ns), indicating that there was no differential learning effect over the groups; cf. Table 1.

There was, however, a statistically significant effect for group for the variability of Anticipation Time ($F_{1,20} = 10.19$, $p = .005$) and for block ($F_{1,20} = 5.62$, $p = .03$), with a decrease of variance in both groups in the second block, but no interaction of group by block ($F_{1,20} = .53$, ns). In other words, no differential learning was observed (cf. Table 1 and Fig. 1).

Impulsive Errors were defined as all responses in the temporal range of 300–700 msec. after stimulus onset. Repeated-measures analysis of variance showed a significant effect for group ($F_{1,20} = 8.7$, $p = .008$) but not for block ($F_{1,20} = 0.2$, ns) or group by block ($F_{1,20} = .57$, ns). The Hyperactive boys thus made more Impulsive Errors, reacting to the stimulus onset instead of fulfilling the instruction of anticipating onset (Table 1). A significant negative correlation was observed between age and the variability of the Anticipation Time ($r = -.62$, $p = .002$) and the number of Impulsive Errors ($r = -.47$, $p = .03$).

There was also a significant ($p < .01$) correlation between the number of Impulsive Errors with scores on the attention scales of the Teacher Rating Form ($r = .55$) and the Child Behavior Checklist ($r = .51$) and for the vari-

TABLE 1
UNIVARIATE COMPARISONS FOR TIMING TASKS BY GROUP

Task	Measure	Comparison		ADHD		Test†	*df*	*p*
		M	*SD*	*M*	*SD*			
Free Tapping	RT	722.7	428.9	890.1	593.2	.76	20.0	ns
	*SD**	94.8	115.3	324.0	298.2	2.38	12.9	.03
Synchronization, msec.								
400	RT	411.9	31.9	377.8	17.9	9.55	1,20	.006
700	RT	590.0	93.4	641.3	58.4	2.38	1,20	ns
900	RT	792.6	91.1	811.7	96.8	0.23	1,20	ns
1200	RT	1055.9	86.1	1061.9	98.3	0.02	1,20	ns
1800	RT	1642.2	116.4	1671.6	161.1	0.24	1,20	ns
400	*SD**	88.3	27.2	81.8	15.0	0.48	1,20	ns
700	*SD*	149.7	46.6	191.6	23.2	7.10	1,20	.02
900	*SD*	128.0	49.5	221.9	42.4	22.86	1,20	.001
1200	*SD*	130.3	39.3	240.5	64.2	23.58	1,20	.001
1800	*SD*	156.5	29.2	269.3	98.5	13.27	1,20	.002
Anticipation								
Block 1	Time	4842.6	677.5	4129.8	1072.2	3.47	1,20	ns
Block 2	Time	4951.7	595.6	4551.6	1001.3	1.30	1,20	ns
Block 1	*SD*	720.0	279.5	1289.8	505.3	10.70	1,20	.004
Block 2	*SD*	626.0	265.8	1112.5	519.4	7.65	1,20	.01
Block 1	Errors	0.73	1.10	2.55	2.07	6.62	1,20	.02
Block 2	Errors	0.45	0.82	2.73	2.53	8.01	1,20	.01
Time Discrimination	Errors	2.09	1.51	2.55	1.86	0.63	20.0	ns
	RT	920.6	364.8	902.1	120.5	0.16	12.2	ns
	SD	310.3	103.6	500.8	255.7	2.54	14.0	.02

† Test for free tapping and time discrimination refer to *t* tests of group differences. Tests for synchronization and anticipation tasks refer to univariate *F* tests. * Intrasubject standard deviation.

ability of response with scores on the attention scales of the Teacher Rating Form ($r = .59$) and the Child Behavior Checklist ($r = .55$).

Free Tapping Task

No group differences were found for the mean Tapping Time ($t_{20} = -.76$, ns); however, significant group differences were found for the within-subject standard deviation ($t_{12.9} = -2.38$, $p = .03$), which was larger for the children with ADHD (see Table 1 and Fig. 1).

There was also a significant negative correlation between variability and age in all children ($r = -.62$, $p > .002$), suggesting that variability of Tapping Time of older children diminishes. A significant correlation ($p < .05$) was observed between the variability of response with the scores on the attention scales on the Teacher Rating Form ($r = .52$) and the Child Behavior Checklist ($r = .43$).

Synchronization Task (Timed Tapping)

A repeated-measures analysis of variance showed no significant group

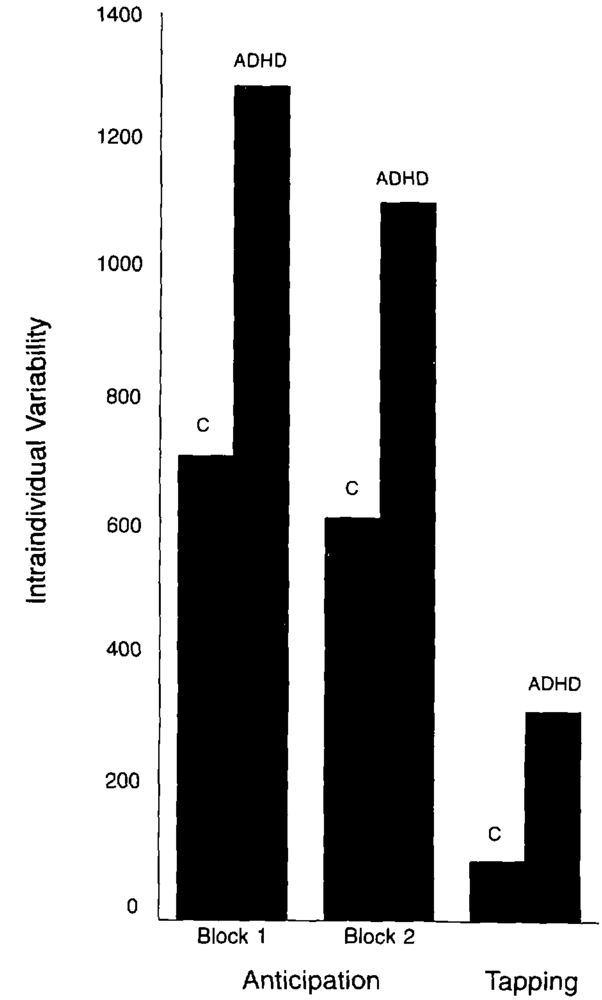

FIG. 1. Anticipation and tapping tasks: intraindividual variability of anticipation and tapping times by two groups ($ns = 11$): ADHD and Control (C)

differences for Synchronization Time ($F_{1,20} = .28$, ns). Contrary to what was expected, the Hyperactive group did not show an over-all tendency to adjust their motor response earlier than the control children. The only exception was a significant effect for group at the shortest time interval as shown by a univariate F test, indicating that the Hyperactive children showed a faster synchronization time ($F_{1,20} = 9.6$, $p = .006$); cf. Table 1. The accuracy of sensorimotor control was measured by the intra-individual variability of Synchronization Time for which a significant effect of group was found ($F_{1,20}$ = 34.5, $p<.001$). There was also a significant effect for block ($F_{4,17}=45.3$, $p<.001$) and an interaction of group by block ($F_{4,17}=9.7$, $p<.001$). Univariate tests for each time interval showed that the Hyperactive group had a higher variability of Synchronization Time at all intervals except for the first interval of 400 msec. Interestingly, the group differences in variability increased with increasing time intervals, given a relatively stable variability in the control group and an increasing variability in the Hyperactive group with increasing temporal intervals (Table 1 and Fig. 2).

There was no significant correlation between age and the variability of Synchronization Time but a significant correlation ($p<.05$) between the Synchronization Time for the first interval with the attention scores on the Child Behavior Checklist ($r=-.58$) and the Teacher Rating Form ($r=-.57$) and for the variability of the next four Synchronization Times with the scores on the attention scales of the Child Behavior Checklist ($rs=.54$, .70, .67, and .69) and on the Teacher Rating Form ($rs=.45$, .71, .81, and .79).

Time Discrimination Task

No group difference was found for the number of Discrimination Errors, the errors in the correct attribution of the second interval as a longer or identical duration to the first one ($t_{20}=-.63$, ns). No group differences were observed either for Decision Time, the time needed to make the decided response ($t_{12.2}=.16$, ns). A significant group difference was, however, observed for the variability of Decision Time ($t_{14}=-2.54$, $p=.02$); cf. Table 1. The Hyperactive group did not differ from the control group in discrimination of temporal durations even though the latency of discriminating the temporal intervals was more variable. There was no significant correlation for any of the time discrimination variables with age. There was also no significant correlation between any of the dependent variables and the scores on the attention scales on the Teacher Rating Form and the Child Behavior Checklist.

It is possible that apparently negative findings are due to insufficient power. To investigate this possibility we calculated the effect size η^2 (Cohen, 1988) for those dependent values which did not differ significantly between groups. η^2 gives an estimate of the amount of variability in the dependent measures explained by group membership. The η^2 value for the RT in the Free Tapping task was .05, for the Anticipation Time .12, and for the Time Discrimination Errors and Reaction Times .02. These *post hoc* effect sizes are relatively small (Cohen, 1988). Only the effect size of the negative findings of the Anticipation Times was relatively large according to Cohen's criteria (1988) and compared to the effect sizes of η^2 of .15 in Carte, *et al.*'s

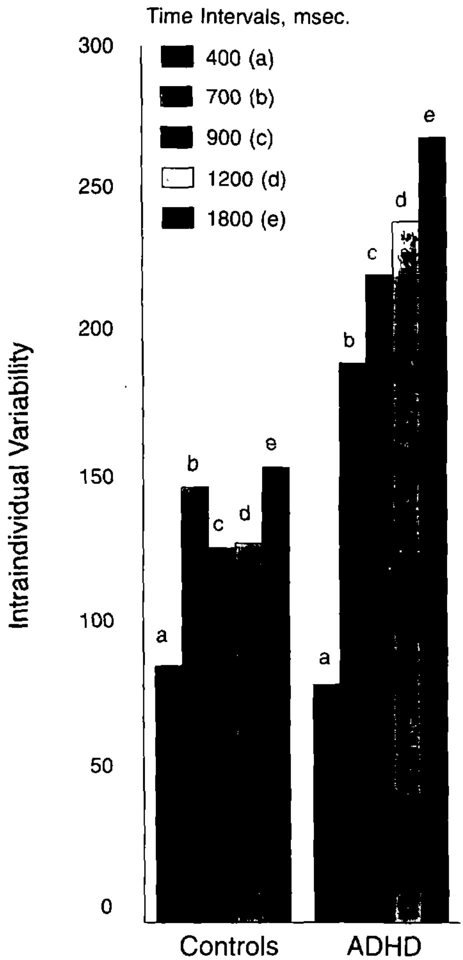

FIG. 2. Synchronization task: intraindividual variability of sensorimotor synchronization time over the different time intervals (msec.) for two groups ($ns = 11$)

study (1996), wherein a group of 43 children with ADHD and 31 controls were compared on the speeded motor tasks of Denckla (1974). A direct comparison between effect sizes of both studies is, however, limited because tasks were different.

Discussion

We investigated the hypothesis of timing deficits at the executive motor output stage of behaviour in childhood hyperactivity. As hypothesized, this group of hyperactive children showed no timing deficits at a perceptual level, suggesting normal discrimination of temporal durations in the range of seconds; however, the hyperactive boys demonstrated deficits in the temporal organization of their motor output. They were more inconsistent in anticipating, self-regulating, and synchronizing their motor execution to external visual stimulation. The boys' performance at these different stages of temporal motor regulation is discussed separately.

Time Perception

As expected, we found no group differences in ability to discriminate two different temporal intervals. Reports of deficits in time estimation in hyperactive children are controversial. Capella, Gentile, and Juliano (1977) noted that hyperactive children overestimated in a time production task, which could not be replicated by Senior, Towne, and Huessy (1979). Walker (1982), Barrat (1981), and van den Broek, Bradshaw, and Szabadi (1992) reported that impulsive children and adults underestimated temporal intervals in time reproduction tasks. Barkley, Koplowitz, Anderson, and McMurray (1997) stated differences between hyperactive children and controls in a time-reproduction task were observed: the hyperactive children underestimated short intervals and overestimated long intervals. Attentional deficits may, however, have accounted for the time-estimation deficits reported in their study, since there was a significant effect of distraction on the time estimations of the hyperactive children but not for controls. The estimation of longer temporal intervals is easily confounded by other basic dysfunctions such as deficits in sustained attention and working memory present in hyperactive subjects (Pennington & Ozonoff, 1996). Our version of a duration Discrimination task was designed to target more directly the perceptual aspect of temporal processing and to minimize the load on sustained attention and working memory compared to time-estimation tasks. Our findings of no performance deficit therefore suggest that there is no alteration in perceptual time estimation in children with hyperactive behaviour. This conclusion has, however, to be considered preliminary, since the effect size was relatively small.

Intertemporal Competence

Hyperactive boys were more inconsistent than control boys in anticipating a regularly appearing stimulus. We were aware of findings of premature responses of impulsive subjects on time-estimation tests or on tasks where a response has to be withheld (see introduction), and we therefore expected premature responding by these hyperactive boys. Our data, however, did not show a consistent tendency to respond prematurely by the hyperactive group. We did, however, find a higher number of Impulsive Errors in the hyperactive group. Impulsive Errors were defined as responses where the children did not anticipate the next stimulus or the previous one but did "react" to the stimulus on the screen with a button press. Such large impulsive reactions to the stimuli may reflect poor inhibitory control. Deficits in motor response inhibition have repeatedly been noted in hyperactive subjects (Schachar & Logan, 1990; Schachar, Tannock, Marriott, & Logan, 1995; Rubia, Oosterlaan, Sergeant, Brandeis, & van Leeuwen, 1998a; for overview see Quay, 1997).

In summary, we found impulsive errors and inconsistent sensorimotor anticipation by the hyperactive group. The fact that we did not find differences in the time onset of anticipation but only in the variability of temporal onset suggests that the impairment was not in time estimation or intertemporal competence but in consistency of motor adjustment. Although the small sample limits the interpretability of the negative findings, the effect size for the Anticipation Times was relatively large compared to another study with larger samples (Carte, *et al.*, 1996) and according to Cohen's criteria for effect sizes (1988). Our interpretation of the hyperactive boys' performance as a reflection of inconsistency in motor timing rather than time perception is supported by our negative findings on the Time Discrimination task. We cannot, however, rule out the possibility that the variability of response reflects deficits in sustained attention. Sustained attention to the passage of time underlies time estimation (Zakay, 1993) and a deficit in sustained motor attention could have led to inconsistent anticipatory accuracy.

Free Tapping

The hyperactive boys were more inconsistent in maintaining a self-chosen stable temporal rhythm. Variability of response time in a free-rhythm task measures the consistency of an internal timing process or the consistency of the motor system implementing this internally timed response (Wing & Kristofferson, 1973). One or both processes seem to be impaired in the hyperactive boys. Our hypothesis of a speed preference in an unstructured situation could not be confirmed by our results, since the hyperactive boys did not tap faster than control boys. This contrasts with the findings of Stevens, *et al.* (1970) of faster tapping by hyperactive children. Increased speed of tapping would have supported our "fast internal clock" hypothesis; however, the small sample and cognitive heterogeneity in this sample of hyperactive boys (some tapped faster, some slower) may have accounted for the negative findings. Replication in a larger sample is necessary to reject the hypothesis of an accelerated internal clock in children with hyperactive behaviour.

Sensorimotor Synchronization

On the paced tapping task hyperactive children showed higher variability of interstimulus response except at the shortest interval of 400 msec. The accuracy of synchronization depends on the sensory system (ability to perceive asynchrony), the motor system (ability to correct the perceived asynchrony), and the accuracy of the corresponding time-keeping mechanism in a sequence of responses (Mates, 1994). Based on our findings on the Discrimination and Anticipation tasks, we believe that the inaccuracy of synchronization is not due to limits of the sensory input system but to limits in the two later motor stages which are responsible for generating a rhythmic response pattern and for the transfer of this temporal pattern to the motor-response output.

Lack of temporal stability in sensorimotor coordination in hyperactive children has been observed previously. Denckla, *et al.* (1985) found reduced speed, rhythmicity, and precision in dyslexic children with attention deficits than for a pure dyslexic group during speeded motor tasks. Overflow movements and dysrhythmias in a battery of timed motor tasks have also been the most discriminating features of hyperactive children compared with controls (Denckla & Rudel, 1978). Minor neurological signs indicative of sensorimotor incoordination can distinguish hyperactive from normal children (Werry, *et al.*, 1972). The data presented here are in keeping with the view that deficits in motor coordination and motor timing are central to the disorder of hyperactivity.

As the hypothesis of an accelerated internal clock could not be confirmed, we assume that it is not the "internal time-keeper" or rhythm-producing mechanism that is disturbed in these children, but the transfer of this internal rhythm-generating mechanism to the motor output stage. Stimulus–response compatibility experiments (van der Meere, Baal, & Sergeant, 1989), the failure of hyperactive children to adjust motor speed after mistakes (Sergeant & van der Meere, 1988), and motor presenting studies (van der Meere, *et al.*, 1992) suggest that the last stage of executive behaviour, the motor adjustment stage, which translates a specific motor program into muscular language, is impaired in hyperactive children. Findings of variable go-processes and dysfunctional inhibitory processes in stop tasks (Rubia, *et al.*, 1998a) support the hypothesis of a dysfunction at the stage of motor adjustment. We therefore suggest that the high variability in motor and sensorimotor timing of the hyperactive boys reflects a failure in transcoding from an internally generated rhythm to motor output.

The hypothesis, that a fast event rate would benefit the hyperactive children's performance in the timed sensorimotor task, could only partly be confirmed. We did not find a graded effect of the length of the time intervals on performance (such as increasingly premature synchronization onset times for the hyperactive boys with increasing length of time intervals). We did, however, observe a qualitatively different performance pattern in the hyperactive boys during the shortest time interval of 400 msec. compared with the four longer time intervals. The hyperactive boys had a significantly faster synchronization rate at the 400-msec. interval and a low variability of synchronization. Different explanations may be advanced for this fast tapping in the shortest time interval. The fast rhythm could fit with the hypothesis of a fast internal clock and thus confirm the suggestion of an accelerated internal clock. Our findings, however, on the free-tapping task did not confirm the hypothesis of a fast internal clock. It seems more likely that the shortest interval could have induced automaticity. Difficulties with effortful behaviour as compared to automatic processing have been found in hyperactive children (Borcherding, Thompson, Kruesi, Bartko, Rapoport, & Weingartner, 1988; Robaey, Breton, Dugas, & Renault, 1992; Carte, *et al.*, 1996). Further studies are necessary to replicate and explain this phenomenon.

Good and stable sensorimotor timing should be reflected in low variability of motor responses near the temporal onset of the sensory cue. Hyperactive children showed a gradual increase in variability of motor synchronization with longer time intervals. There was no significant group difference at the shortest interval of 400 msec. but increasing group differences with increasing time intervals of 600 to 1,800 msec. due to an increase in variance for the hyperactive group at the longer time intervals. This finding of increased inconsistency in motor timing with increasing interval length meets our prediction of a graded decrement in accuracy of motor adjustment with longer premovement delays. It parallels the observed decline in the performance of hyperactive children in cognitive tasks with slow event rates (Sykes, *et al.*, 1971; Conte, *et al.*, 1986; van der Meere, *et al.*, 1995). It may also confirm our hypothesis that hyperactive children have increasing difficulty in adjusting motor speed to external requirements, the more different the event rate is from the preferred speed. In cognitive task situations, with relatively long event rates of several seconds, motivational explanatory models, such as boredom, "delay aversion" (Sonuga-Barke & Taylor, 1992), or poor ability to sustain attention (Cohen, Weiss, & Minde, 1972) may account for increasing variability in performance, but they can hardly be adduced for the motor deficits found at such short intervals. The results are more in keeping with a motor-timing deficit in hyperactive children.

To summarize, these findings of a variable response in hyperactive children in anticipating and synchronizing external visual stimulation and in free tapping support our hypothesis of a motor-timing deficit in children with hyperactivity. We could not confirm the hypothesis of a fast internal clock for the hyperactive children, but we confirmed our hypothesis of poor motor adjustment in both free and structured task situations.

Effect of Age

We found a negative correlation between age and variability of performance in the free tapping and Anticipation tasks and between age and impulsive errors in the Anticipation task. The age effect may reflect a developmental sharpening of the temporal regulation of the motor output and supports the hypothesis of a developmental lag in hyperactivity during childhood (Mattes, 1980). Functional neuroimaging data from this group confirm the hypothesis of a maturational delay in ADHD. We observed reduced mesial and dorsolateral prefrontal activation in a clinical sample of adolescents with ADHD while performing a Delay Task, a variant of the Anticipation Task applied here on which subjects had to synchronize instead of anticipate their motor response to the stimuli (Rubia, *et al.*, 1999). A linear age effect was found for this prefrontal activation during performance on the Delay task by healthy subjects in the age range from 12 to 35 years (Rubia, *et al.*, 2000). This finding of a functional frontalization with age during motor timing supports the hypothesis of frontal dysmaturation in ADHD.

Specificity and Generalizability of Findings

The main difference between subjects and control boys was in their hyperactive behaviour. The intellectual level seemed not to have accounted for the timing deficits of the hyperactive boys, since none of the measures of the timing tasks correlated with the intelligence quotients and we covaried this out. The specificity of timing problems in those with hyperactive behaviour, however, remains to be clarified by comparisons with other behaviourally defined groups. The generalizability of findings to the clinical disorder needs to be clarified. We are currently investigating the specificity and generalizability of the motor timing deficits found here by doing a follow-up study in which we compare the performance of a larger sample of children with the clinical diagnosis of ADHD and those of a psychiatric and a normal control group on the same motor timing tasks.

We are aware that the small sample in our study imposes limitations on the interpretations of the negative findings. Further studies using larger samples should show whether the present findings can be corroborated. Until then, these findings have to be considered preliminary. We are, however, more confident with the positive findings which emerged in this study despite the small sample. We found that the hyperactive boys showed highly inconsistent rhythm production, sensorimotor synchronization, and anticipation, despite having normal time discrimination. These deficits in free and externally matched motor timing suggest that children with hyperactive behaviours have dysfunctional temporal control of their motor output.

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