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Executive Functions in Children Aged 6 to 13: A Dimensional and Developmental Study

Karin C. Brocki and Gunilla Bohlin

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A cross-sectional study using 92 children aged 6 to 13 years investigated the dimensionality and the development of executive functioning. The measures were drawn from developmentally relevant conceptualizations of executive functioning and included a go/no-go task, a verbal fluency task, a continuous performance task, a Stroop-like task, a hand movements task, and a digit span task. Analyses revealed 3 dimensions interpreted as Disinhibition, Speed/arousal, and Working memory/Fluency. Age and sex differences were analyzed for the delineated functions, which means that the results may be taken to represent age effects at the level of specific processes within the executive domain rather than on single tests. Age-dependent changes in children's performance on all 3 dimensions were demonstrated, with 3 particularly active stages of maturation: early childhood (6–8 years of age), middle childhood (9–12 years of age), and during early adolescence. Sex differences were only found for the speed/arousal dimension. The results are discussed in terms of 2 developmental executive function frameworks (Barkley, 1997b; Roberts & Pennington, 1996), where inhibition and the interaction between inhibition and working memory, respectively, are seen as key in the development of executive functioning.

Extended research within developmental psychopathology points to the importance of executive dysfunction in developmental disorders such as conduct disorder, autism, Tourette's syndrome and attention deficit hyperactivity disorder (ADHD; Chelune, Ferguson, Koon, & Dickey, 1986; Milich, Hartung, Martin, & Haigler, 1994; Ozonoff & Jensen, 1999; Pennington & Ozonoff, 1996; Shue &

Douglas, 1992). These efforts have also brought into focus the need for a better understanding of the normal development of executive functioning.

Despite the growing interest, there is little consensus on the exact definition of executive functions in adults as well as in children, and the construct has been, and still is, open to lively debate in psychology and neuropsychology (Welsh, 2002). Neuropsychologically, executive functions have been linked to the prefrontal cortex of the brain and supporting subcortical loops (Stuss & Alexander, 2000), and encompass abilities needed for goal-directed behavior such as inhibition, planning, strategy development, persistence, and flexibility of action. Research examining executive functions in children has been a relatively late-developing phenomena and most of the research is characterized by two methodological drawbacks: low construct validity of executive function tasks and a failure to base the research on theories within developmentally relevant frameworks.

The first issue of low construct validity refers to the possibility of executive tasks mapping onto a multitude of cognitive processes, executive as well as non-executive, which makes understanding of development on individual element processes hard to identify. In addition, because there is not an agreed-on task or set of tasks to assess each executive domain, it is likely that the developmental change based on specific tasks represents different aspects of certain executive domains (Welsh, 2002). This means that previous evidence on developmental change in executive functions based on single tests runs the risk of being task dependent. Therefore, developmental studies of executive functions should use multiple tests in each executive domain, enabling a dimensional analysis and thus investigation of developmental trends within the defined domains. This, in turn, facilitates understanding of the typical and atypical development of executive functions (Welsh, 2002; Wu, Anderson, & Castiello, 2002).

The second issue concerns the fact that developmental research on executive functioning has been guided by principles about frontal-lobe functioning in adults, rather than being based on theories within a developmental framework. As Welsh and Pennington (1988) pointed out, by using adultlike performance as an indicator for executive functioning, one fails to capture the actual process of development in this domain. It may be that executive skills are involved in certain behaviors in childhood that are no longer evident in adulthood. Consequently, by focusing on the criterion of adultlike performance one may mask the development of executive functions of particular importance in childhood. However, helpful models of executive function in children are now beginning to come forth. One of these models that has recently been the center of attention for developmental psychologists, especially those interested in psychopathology, is the theoretical model of Barkley (1997b) suggesting that inhibitory functions are central to effective executive functioning in general.

Barkley (1997a, 1997b) posited that behavioral inhibition, which comprises inhibition of prepotent responses, stopping of ongoing responses, and interference control, fundamentally contributes to the functioning of several other executive functions, such as working memory (verbal and nonverbal); self-regulation of affect, motivation, and arousal; and reconstitution (analysis and synthesis of information). Working memory particularly refers to the capacity of maintaining information in mind and using that information to guide immediate behavior in the absence of informative external cues (Goldman-Rakic, 1995). Although Barkley fractionated working memory into two primary components—verbal working memory (internalization of speech) and nonverbal working memory—he also pointed out that there may be as many forms of working memory as there are forms of human sensorimotor behavior that can be self-regulatory and covert (Barkley, 1997a).

In the self-regulation of affect, motivation, and arousal component, a self-regulatory part of the executive system is emphasized in that emotions are presumed to be regulated by self-directed, executive actions. This component also includes the self-generation of drive or motivational and arousal states, necessary for the maintenance and completion of goal-directed behavior. Thus, the ability to self-regulate and bring about emotional states as a support for goal-directed behavior also incorporates the intelligence to adjust and induce motivation and arousal in maintenance of behavior.

The reconstitution component of Barkley's model represents two interrelated activities—analysis and synthesis—and can be explained as the ability to separate units of behavioral sequences (analysis) and recombine them in creative ways into new sequences of behavior (verbal or nonverbal). To sum up, the four executive functions are taken to free behavior from being controlled by the immediate environment, to provide a sense of time, and to provide for behavior that is intentional and purposive.

This theory was formulated with the aim of understanding the complex cognitive and behavioral problems characterizing children with ADHD, but Barkley's formulation is also of relevance for understanding normal development. It is assumed that there is no distinction between the processes underlying normal and abnormal executive functioning; children with ADHD are assumed to be developmentally delayed with regard to inhibitory function (Barkley, 1997a).

Concerning normal development Barkley (1997a) speculated that there is a progressive development of inhibitory functioning in parallel with the development of the prefrontal regions of the brain, and that the development of the executive functions is dependent on the development of the processes labeled behavioral inhibition. Consequently, younger normal children should be, according to Barkley, less efficient in behavioral inhibition and, in turn in all four executive functions depending on it, compared to older normal children.

Barkley's theoretical formulation bears similarities to the formulation by Roberts and Pennington (1996) proposing that the interaction between working memory and inhibitory function may be sufficient to characterize the cognitive and behavioral development within the executive domain. This model follows the assumption that working memory and inhibition mechanisms make use of the same limited-capacity pool of resources. Thus, a task that involves strong incorrect prepotencies requires higher and more consistent working memory activation to avoid falling prey to the prepotency. Like Barkley, these authors argued that there is no distinction between the processes underlying normal and abnormal executive functioning. Rather, these processes are taken to lie on a continuum, with success or failure of executive control depending on the interactions between inhibition and working memory. According to this formulation, normal development of executive functioning should be described in terms of the development of the two fundamental cognitive processes: inhibition and working memory.

THE DIMENSIONALITY OF EXECUTIVE FUNCTIONS IN CHILDREN

The dimensionality of executive functions in children has been explored in several studies, which often have included complex measures, most likely involving several basic components, thus making interpretations in terms of basic structure of executive functioning difficult. Welsh, Pennington, and Groisser (1991) as well as Levin et al. (1991) performed component analyses on normal participants ranging in age from 3 to 12 years and 7 to 12 years, respectively. It is interesting that the two studies obtained a very similar factor-analytic pattern consisting of three different factors. The first factor in both studies could be considered primarily as a fluency dimension, as the factor received major loadings from a number of fluency measures, both in verbal fluency and design fluency. The second factor clearly reflected a dimension of hypothesis testing and impulse control, comprising measures such as the Matching Familiar Figures Test (MFFT; Kagan, Rosman, Day, Albert, & Phillips, 1964), the Wisconsin Card Sorting Test (WCST; Grant & Berg, 1948), and commissions (false alarms) on the go/no-go test. The third factor was interpreted as planning in both studies, and included variables on the Tower of Hanoi and Tower of London tests.

In recent years Barkley and colleagues have reported two factor-analytic studies, one on preschool boys with ADHD (Mariani & Barkley, 1997) and one on adolescents with ADHD and Obsessive Defiant Disorder (Barkley, Edwards, Laneri, & Fletcher, 2001). In the former study four factors were obtained and were interpreted as Motor control, Verbal learning-memory, Picture recognition-factual knowledge, and Working memory-persistence. The data most relevant for Barkley's theoretical model is that provided in the latter factor-analytic study (Barkley et al., 2001), therefore these are described in more detail. This study re-

vealed a three-factor solution. Factor 1, Inattention, comprised various measures derived from the Continuous Performance Task (CPT), namely errors of omission, hit rate (RT) and variability of hit rate (RT). Factor 2, Working memory, included Digit Span Backward, Verbal Fluency, Simon Form Fluency (nonverbal working memory), and Object Uses task (reconstitution). Factor 3, Inhibition, comprised the errors of commission and hit rate scores on the CPT task. The first factor, although named Inattention, could be taken to reflect the executive function in Barkley's model, which is responsible for regulating motivation and arousal. A dimension that would fit the description of the function called reconstitution was not identified, nor were the verbal and nonverbal aspects of working memory separated in either of the studies reviewed.

In interpreting results from various studies it is noteworthy that in exploratory factor analysis, the obtained dimensions are highly influenced by the makeup of the sample and the variables included. This is important to keep in mind when considering the results of the studies just described, as they differ not only with regard to the variables, but also with regard to the makeup and the age range of the samples tested.

EXECUTIVE FUNCTIONING AND DEVELOPMENT

The empirical evidence available to evaluate Barkley's theoretical model, suggesting inhibition as being the fundamental core in effective executive functioning, and the account proposed by Roberts and Pennington (1996), suggesting that inhibition and working memory may be sufficient to characterize the entire executive domain for normal development, is scarce for the aforementioned reasons. However, a preliminary picture may be obtained by looking at previous studies on the sequencing of executive skills in normal development, which have included measures that fit in with the executive functions included in Barkley's model as well as the account proposed by Roberts and Pennington.

For example, Levin et al. (1991) found an increased ability to inhibit responses with increasing age on the go/no-go test in a normal sample. To be more precise, the greatest improvement in impulsive errors (commissions) and missed responses (omissions) was found between the youngest (7–8 years) and the middle (9–12 years) age groups, with little or no further improvement in the oldest age group (13–15 years). Levin et al.'s findings are consistent with the results of Williams, Ponesse, Schachar, Logan, and Tannock (1999), who used the stop-signal procedure to examine the development of inhibitory control across the life span. They reported marked development in speed of inhibiting a prepotent response between the early childhood group (6–8 years) and the mid-childhood group (9–12 years), with no additional advancement in young adults (18–29 years) and seniors (60–81 years).

The developmental trajectory of verbal fluency that probably reflects the concept of reconstitution in Barkley's model has been shown to continue development with age into adolescence (Becker, Isaac, & Hynd, 1987; Levin et al., 1991; Welsh et al., 1991; Weyandt & Willis, 1994). With regard to the development of working memory, Hale, Bronik, and Fry (1997) examined the development of both the efficiency and independence of the verbal and visuospatial components of working memory in two different age groups of children (8-year-olds and 10-year-olds) and one group of adolescents (19-year-olds). The verbal task consisted of recalling a series of visually presented digits, whereas the visuospatial task consisted of recalling the location of X's in a series of matrices. While performing the primary task, the children also had to perform a secondary task consisting of a verbal and a spatial component. There was a linear relation between age and working memory span, with the 19-year-olds performing significantly better than the 10-year-olds, who in turn performed better than the 8-year-olds. With respect to independence, all age groups showed a domain-specific interference from the secondary task, but only the 8-year-olds also showed a nonspecific interference. As Hale et al. (1997) pointed out, these results are in line with Dempster's (1992) hypothesis that the comparatively late development of the frontal lobes is central to the slow emergence of certain key cognitive abilities, such as resistance and interference.

SEX DIFFERENCES AND EXECUTIVE FUNCTIONING

Previous studies on the development of executive functioning do not provide any consistent data on sex effects. Welsh et al. (1991) found no main effects of sex on any of the executive measures and no interactions between age and sex in their developmental study. Reader, Harris, Schuerholz, and Denckla (1994) found girls with ADHD to perform at a significantly higher level on measures of verbal fluency than boys did. Levin et al. (1991) reported an increasing disparity in word fluency between girls and boys after age 12, with girls performing at a higher level. This is consistent with the general finding that females have better verbal abilities than males (Halpern, 2000). Moreover, in a study on response inhibition and hyperactivity conducted on preschoolers, Berlin and Bohlin (2002) found boys to show a lower level of inhibitory control than girls. Comparable results were obtained by Carlson and Moses (2001), who found 3- and 4-year-old girls to significantly outperform boys on measures of inhibitory control.

THIS STUDY

The aim of this study was to expand our knowledge on the development of basic executive functions by addressing specific problems that have limited interpretation of findings in past research. As mentioned earlier, most previous studies are

guided by the construct of executive function derived from the adult neuropsychological literature, rather than on functions relevant to theories within a developmental framework. Therefore, measures based on developmentally relevant conceptualizations of executive functioning such as those provided by Barkley (1997a, 1997b) and Roberts and Pennington (1996) were used. These measures were then subjected to factor analysis to allow developmental analysis to be made on basic executive functions. Thus, age effects and sex differences were investigated for the cognitive functions identified through factor analysis of results on tasks that represent current conceptualizations of executive functioning in children.

Method

Participants

This investigation involved 92 participants who ranged in age from 6 to 13.1 years. The sample was divided according to age into four age groups (6–7.5 years, 7.6–9.5 years, 9.6–11.5 years, and 11.6–13.1 years). The mean chronological ages and number of boys and girls for each group are presented in Table 1. The participants were recruited from preschools and compulsory schools located in different parts of the country. The sample was recruited by mail, and the response rate was 66%. Written parental consent was obtained from the participating children prior to the assessment session. The parents were asked if their children had any medical or psychological problems. No children showed any history of medical or psychological problems of significance to the study. Parental occupational levels were derived using a scale based on the Swedish educational system. Only 5% of the mothers and 3% of the fathers had a 9-year compulsory school as their only schooling,

TABLE 1
Age Range in Months, Number of Participants,
Mean Age in Months, and Standard Deviation
in Months for Each Age Group

<i>Age Range</i>	<i>n</i>	<i>M</i>	<i>SD</i>
Girls	45	112.22	24.25
72–91	14	83.57	8.55
92–115	11	107.18	5.38
116–138	11	126.54	5.53
139–158	9	145.44	6.87
Boys	47	117.23	23.49
72–91	11	84.36	3.74
92–115	12	108.00	6.63
116–138	10	126.00	5.43
139–158	14	144.71	4.44

28% of the mothers and 30% of the fathers had vocational training, 15% of the mothers and 7% of the fathers had completed secondary school (12 years of schooling), and 43% of the mothers and 49% of the fathers held a university degree. In addition, 9% of the mothers and 11% of the fathers had a postgraduate university degree. A minority of the children, about 4%, did not have any siblings, 36% had one sibling, and the remaining 60% had two or more siblings.

Measures and Procedures

All children were tested individually in a quiet room at their respective school. The tasks were administered during a 1- to 1.5-hr session in the following standardized order: A go/no-go task (based on the go/no-go paradigm), a verbal fluency task (Controlled Oral Word Association Test [COWAT]; Gaddes & Crocket, 1975), a CPT, a time reproduction task, a Stroop-like task, the Kaufman Assessment Battery for Children (K-ABC) Hand Movements test (Kaufman & Kaufman, 1983), and the Wechsler Intelligence Scale for Children—III (WISC—III) Digit Span subtest (Wechsler, 1992/1994). The children received a toy worth approximately \$5 for their participation.

Nonverbal working memory. The Hand Movements test from the K-ABC (Kaufman & Kaufman, 1983) is a nonverbal working memory task that requires the child to hold information in mind by imitating sequences of hand movements produced by the experimenter. To include children somewhat older than 12 years, this test was expanded according to a procedure by Nyberg, Bohlin, Berlin, and Janols (2003), and consisted of a total of 20 trials (sequences). The trials involved series of three different hand movements (side, fist, and palm) that became progressively extended (ranging from two to six movements) and thus more complex. The Hand Movements test is presumed to tap working memory because of the requirement to hold lengthy sequences of information in mind in the absence of an external cue and utilize that information to direct an immediate response. Scoring is based on mean number of correct sequences across the 20 trials. This score was used as a measure of nonverbal working memory.

The time reproduction task (Cappella, Gentile, & Juliano, 1977; Zakay, 1992) is a task that measures one's subjective sense of time and requires the child to reproduce time. The children were presented with time intervals of 2×12 , 24, and 36 seconds in a mixed order, by the experimenter shining a flashlight, but were not told the duration. The children were then asked to reproduce the time duration, one at a time, by shining the flashlight for the same amount of time that the experimenter had shone it previously. Scoring was based on the mean deviation score, consisting of the absolute discrepancy score between the child's actual production time and the time presented by the experimenter across the six trials. This was used as a measure of nonverbal working memory.

Verbal working memory. The Digit Span subtest of the WISC-III (Wechsler, 1992/1994) is a memory task in which the experimenter reads a series of “blocks” of digits (ranging from two to nine digits) with a speed of 1 sec per digit to the child. The child is then asked to repeat every block of digits in exactly the same order as it was read (Digit Span Forward) or in the opposite order (Digit Span Backward). Both subtasks require verbal material to be held in mind across delay intervals and the latter subtask imposes a demand for organizing the material in some way to more easily restate the material when called on to do so. These abilities are typically defined as being involved in working memory. The child is allowed two attempts on each of the eight trials (independently of the success in the first attempt) and the test is terminated when the child fails both attempts on any of the trials. If both of the attempts on one trial are repeated correctly the child is given 2 points, and 1 point is given if only one of the two attempts on one trial is correct. Two scores considered as verbal working memory were obtained, which consisted of the average points across the trials on Digit Span Forward and Digit Span Backward.

Verbal fluency. The COWAT (Gaddes & Crockett, 1975) is a verbal fluency task that measures the ability to generate an appropriate strategy without any external stimulus. The task is divided into two parts, semantic and phonemic fluency. In the semantic fluency task the child is asked to generate as many animals and things to eat as possible within a time constraint of 1 min for each category. In the phonemic fluency task the child is asked to generate as many words as possible beginning with the letters F, A, and S with a time constraint of 1 min per letter. In addition to tapping strategy employment and the generation of ideas, the latter task also demands phonological awareness. The words must be selected according to the following rules: No words must begin with a capital letter, and each word must be used only once. Scoring was based on the total number of animals generated, total number of things to eat generated, and total number of words generated across the three letter trials. A mean score was calculated across the semantic and phonemic parts and used as a measure of Verbal fluency.

Inhibition. A computerized go/no-go task based on the go/no-go paradigm (e.g., Iaboni, Douglas, & Baker, 1995; Shue & Douglas, 1992), designed to tap the child’s ability to inhibit a prepotent response was used. It measures the child’s ability to rapidly differentiate between go and no-go stimuli. The child was instructed to respond as quickly as possible by pressing the spacebar on the computer keypad each time a go stimuli (a square with an X, a square with a short vertical line in the middle, a square with a diagonal to the right, and a square with a diagonal to the left) appeared on the screen, and to inhibit the response when a no-go stimulus was presented (a square with a long vertical line in the middle). The stimulus duration was 460 msec, with a random interstimulus interval (ISI) ranging from 2,550 msec

to 2,783 msec. The task consisted of a total of 100 trials, and to develop a prepotent response (a response habit) the majority of the trials (75%) consisted of go targets. Scoring was based on the number of commission errors (incorrectly responding to a no-go stimulus) and omission errors (failing to respond to a go stimulus). Commission errors were considered a direct measure of inhibitory control, whereas omission errors were considered a measure of inattention. Reaction time (RT) was measured to go stimulus (correct responses) and formed the variable go/no-go RT.

A computerized Stroop-like task (Gerstadt, Hong, & Diamond, 1994) was used in this study. The Stroop task is a popular measure of interference control, producing a conflict between processes of automatic (overlearned) responses and novel responses. The classic Stroop task (Stroop, 1935) requires individuals to name the color of the ink a word is printed in while inhibiting reading the word (e.g., the word *green* might be printed in blue ink). Stroop interference (the Stroop effect) occurs when automatic word reading interferes with the processing of ink color when the word and ink color are incongruent. It has been suggested that the Stroop effect is dependent on and may even be confounded by reading skill (MacLeod, 1991); thus the Stroop effect may not tap inhibitory control in those who are not fluent readers (e.g., young children). Therefore, the Stroop task employed in this study did not require reading skills and was a modified version of Gerstadt's "Day-Night" Stroop (Gerstadt et al., 1994). To avoid the ceiling effect that has emerged on this task by the age of 6 years (Passler, Isaac, & Hynd, 1985) and to make it more challenging across a wider span of ages, the task was modified according to a procedure described by Berlin and Bohlin (2002). This version consisted of four different picture pairs, where the picture in each pair was each other's opposite (day-night, boy-girl, large-small, and up-down). The children were presented with the pictures one at a time on the computer screen and were instructed to say the opposite to what they saw on the screen as quickly as possible. For example, if a picture of a girl was shown on the screen the child was required to say "boy." The task consisted of two conditions differing in terms of the ISI. In the first condition each picture was presented for a time period of 1200 msec with an ISI of 2700 msec, and in the second part each picture was presented for a time period of 800 msec with an ISI of 2300 msec. There were 16 pictures presented in random order in each condition, with a total of 32 pictures across the two conditions. Initially, three summary scores were registered: not corrected errors (naming the picture that was presented on the screen instead of the opposite), corrected errors (initially naming the picture presented on the screen but correcting oneself to say the opposite), and no answer errors (failing to give an answer at all). However, nearly none of the children made any not corrected or no answer errors, thus the primary index of interference control was the corrected errors, which was used as a summary score of interference control. The number of corrected errors for each condition was totaled to provide a summary score: total number of corrected errors.

A computerized version of the CPT (Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956) was used in this study. The CPT paradigm requires the maintenance of vigilance to simple stimuli and the inhibition of responses to competing stimuli over a prolonged period of time. In the current version, five different stimuli were included: a square with an X, a square with a short vertical line in the middle, a square with a long vertical line in the middle, a square with a diagonal to the right, and a square with a diagonal to the left. The child was instructed to press a response key as quickly as possible every time a cue stimulus (a square with an X) was immediately followed by a target stimulus (a square with a vertical line), while inhibiting responses to any of the other stimuli. The figures were presented randomly with a show time of 460 msec and a random ISI ranging from 2550 msec to 2783 msec. The task consisted of a total of 100 trials with a target rate of 25%. Scoring was based on the number of commission errors (incorrectly responding to a nontarget) and omission errors (failing to respond to a target). Similar to the go/no-go task, omission errors were considered a direct measure of inattention. In addition, in line with the method developed by Halperin et al. (1988), commission errors were analyzed and divided into different types of impulsivity and inattention based on the sequence of stimuli immediately preceding the erroneous response. The following types of commissions were registered:

1. A response to a nontarget stimulus following the cue was considered as reflecting a failure of the child to interrupt an ongoing response and use that delay to reflect on whether or not it was appropriate to respond. Consequently this type of commission was labeled CPT disinhibition.
2. A response to the cue stimulus before the onset of the target stimulus was considered to reflect the inability of the child to wait for the next stimulus and was therefore considered to reflect impulsivity. Consequently this response pattern was given the name CPT impulsivity.
3. A response to the target stimulus not preceded by a cue stimulus was considered as a failure to delay responding to allow a memory search for the previous stimulus. Thus this type of commission was interpreted as CPT inattentive impulsivity. RT was measured for correct responses and formed the variable CPT RT.

Results

Dimensional Analysis

Principal factor analysis with age as a covariate was conducted with the entire sample using SAS (version 8.2). Age groups were combined and it was examined that the Measure of Sampling Adequacy value for each variable did not fall below .50. Both orthogonal and oblique rotations were performed. A

three-factor solution obtained factors with eigenvalues greater than 1, with Cattell's scree test favoring a three-factor solution as well. Orthogonal and oblique rotations yielded the same factors, but size of the interfactor correlation ($r = -.12$ to $-.15$) favored an orthogonal rotation. In interpreting the factors, loadings greater than .30 were considered salient. The results are shown in Table 2. The first factor, Disinhibition, was clearly a dimension reflecting problems with inhibition as it was composed entirely of four measures tapping impulsivity and inattention, those being two types of CPT impulsivity, CPT inattentive impulsivity, and go/no-go impulsive errors (commissions). The second factor, Speed/Arousal, included CPT RT, go/no-go RT, and inattentive errors (omissions) on both the CPT and go/no-go tasks. The third factor, Working Memory/Fluency (WM/Fluency) comprised verbal fluency (semantic and phonemic), hand movements, Digit Span (Backward and Forward), Stroop-like task, and time reproduction.

Developmental Trends

The means and standard deviations of the variables for the four age groups on all executive tasks are presented in Table 3. To assess the impact of age and gender on executive function, a multivariate analysis of variance (MANOVA) was per-

TABLE 2
Principal Components Factor Structure of Executive Function Measures
Based on the Total Sample, With Age as a Covariate

<i>Measures</i>	<i>I: Disinhibition</i>	<i>II: Speed/Arousal</i>	<i>III: WM/Fluency</i>
CPT disinhibition	.87	.07	-.18
CPT impulsivity	.80	.05	.12
CPT inattentive impulsivity	.63	-.12	.01
Go/no-go commissions	.38	-.07	-.27
Go/no-go RT	-.17	.80	-.18
CPT RT	-.12	.73	-.01
CPT omissions	.11	.39	.04
Go/no-go omissions	-.01	.38	-.22
Digit span forward	-.03	-.01	.49
Verbal fluency (COWAT)	-.00	-.10	.48
Digit span backward	-.13	-.09	.40
Hand movements	-.20	-.16	.40
Stroop	.20	-.23	-.41
Time reproduction	-.02	-.10	-.43
Factor eigenvalues	2.12	1.72	1.39

Note. $N = 92$. CPT = Continuous Performance Test; RT = reaction time; COWAT = controlled oral word association test. The salient loadings for each factor are shown in italics. Negative loadings on Factor 3 reflect that a lower score indexed a better performance, in contrast to the other measures loading on this factor.

TABLE 3
Mean Performance Scores and Standard Deviations for Boys and Girls on All Executive Measures as a Function of Age

<i>Measures</i>	<i>6–7.5 Years Old</i>						<i>7.6–9.5 Years Old</i>						<i>9.6–11.5 Years Old</i>						<i>11.6–13 Years Old</i>					
	<i>Boys</i>			<i>Girls</i>			<i>Boys</i>			<i>Girls</i>			<i>Boys</i>			<i>Girls</i>			<i>Boys</i>			<i>Girls</i>		
	<i>M</i>	<i>SD</i>		<i>M</i>	<i>SD</i>		<i>M</i>	<i>SD</i>		<i>M</i>	<i>SD</i>		<i>M</i>	<i>SD</i>		<i>M</i>	<i>SD</i>		<i>M</i>	<i>SD</i>		<i>M</i>	<i>SD</i>	
CPT disinhibition	4.36	2.65		2.42	2.92		4.16	3.24		3.72	3.37		3.60	2.95		2.00	2.68		2.92	2.46		2.44	1.42	
CPT impulsivity	4.09	4.22		3.85	7.27		5.91	9.60		5.81	10.15		4.80	9.78		2.45	2.94		1.42	2.02		1.44	0.72	
CPT inattentive	5.27	4.29		5.85	5.17		5.25	5.32		3.27	3.77		2.70	2.00		4.02	4.04		2.42	4.01		0.77	1.09	
impulsivity																								
CPT omissions	2.45	2.84		3.50	3.52		1.16	1.33		2.18	2.92		1.10	1.10		1.81	1.88		0.50	0.75		0.55	1.01	
CPT reaction time	0.80	0.19		0.99	0.24		0.66	0.12		0.71	0.11		0.62	0.08		0.81	0.18		0.62	0.17		0.68	0.09	
Go/no-go commissions	11.81	3.81		9.57	6.32		13.25	5.01		14.72	4.31		10.40	3.47		9.36	4.29		12.07	5.99		9.11	2.93	
Go/no-go omissions	4.54	6.26		7.14	7.18		5.08	9.89		3.91	3.53		2.20	2.25		5.90	7.55		2.71	6.00		4.11	3.01	
Go/no-go RT	0.74	0.10		0.87	0.17		0.66	0.12		0.71	0.11		0.61	0.04		0.73	0.12		0.60	0.13		0.62	0.04	
Verbal fluency	7.63	3.27		8.90	4.62		13.97	3.58		15.84	5.95		15.93	4.62		16.63	3.84		17.04	5.45		19.25	5.74	
(semantic and phonemic)																								
Hand movements	0.39	0.13		0.45	0.17		0.46	0.14		0.60	0.40		0.57	0.11		0.57	0.15		0.69	0.14		0.64	0.12	
Digit Span Forward	5.41	0.80		5.75	1.25		7.08	1.56		7.28	1.95		7.30	2.16		7.20	1.16		8.64	2.05		7.22	1.48	
Digit Span Backward	3.28	0.90		2.86	0.77		3.58	0.66		4.45	1.57		3.90	1.59		4.37	1.02		6.88	1.44		5.66	1.73	
Stroop	7.18	4.40		6.14	8.03		5.91	2.06		4.27	2.83		3.10	1.96		4.00	2.48		4.35	3.17		2.22	1.39	
Time reproduction	9.66	6.31		5.13	2.18		5.20	4.46		4.19	5.27		2.05	1.29		2.57	1.52		2.08	1.37		1.37	0.73	

Note. CPT = Continuous Performance Test; RT = reaction time.

formed for each of the three dimensions, that is, for the variables having salient loadings on the separate factors (Disinhibition, Speed/Arousal and WM/Fluency), using age and sex as independent variables. When the overall MANOVA was significant, a priori contrasts were performed for successive age groups. Table 4 summarizes the results of the MANOVAs and contrast procedures.

Disinhibition. A significant main effect of age was obtained on the variables comprising the Disinhibition factor (CPT disinhibition, CPT impulsivity, CPT inattentive impulsivity, and go/no-go commissions), $F(12, 214) = 2.17, p < .01$. However, no significant main effect of sex, $F(4, 81) = 1.29$, nor a significant Age \times Sex interaction was obtained, $F(12, 214) = 0.77$. A priori contrasts of age groups revealed a developmental shift between the second and the third age group, with the latter performing at a significantly higher level than the former ($p < .05$). The two youngest age groups did not differ significantly from each other, nor did the two oldest age groups (see Figure 1). The results for the separate dependent variables within the Disinhibition factor showed that performance improved with age on the CPT inattentive impulsivity and on the go/no-go commissions ($p < .05$), and that there was no significant main effect of age on the CPT disinhibition and CPT impulsivity variables.

Speed/Arousal. A highly significant main effect of age was obtained on the variables comprising the Speed/Arousal factor (go/no-go reaction time, CPT reaction time, CPT omissions and go/no-go omissions), $F(12, 215) = 2.91, p < .0001$. There was also a highly significant main effect of sex, $F(4, 81) = 3.57, p < .0001$, but no Age \times Sex interaction, $F(12, 215) = 0.41$, was obtained. A priori contrasts comparing performance across the four age groups on the Speed/Arousal factor showed that youngest age group was significantly slower in their performance compared to the second age group ($p < .01$). However, the second age

TABLE 4
Standardized Mean Factor Score by Age Group and Significance Tests
of Developmental Effects

Factor	Age Group								F	Effects
	1		2		3		4			
	M	SD	M	SD	M	SD	M	SD		
I: Disinhibition	0.07	0.51	0.20	0.69	-0.10	0.49	-0.17	0.35	2.17	1, 2 > 3, 4*
II: Speed/Arousal	0.38	0.53	-0.01	0.37	-0.07	0.38	-0.29	0.29	2.91	1 < 2, 3, 4**
III: WM/Fluency	-0.30	0.24	-0.01	0.24	0.09	0.15	0.27	0.22	6.05	1 < 2, 3, 4** 2, 3 < 4*

* $p < .05$. ** $p < .01$.

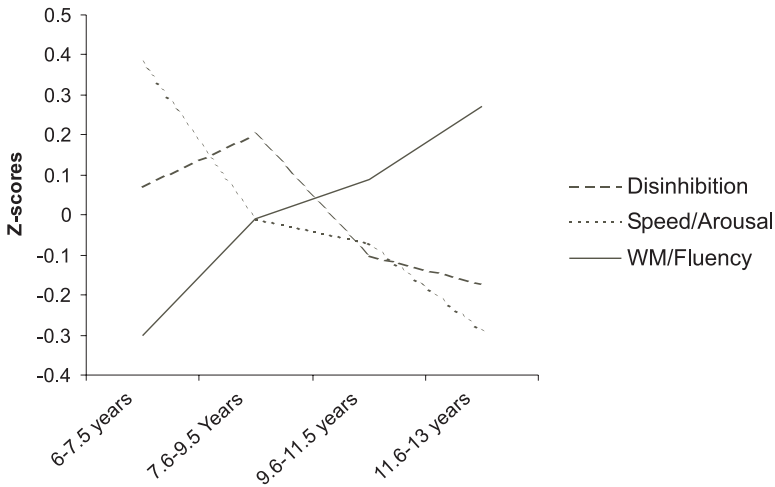


FIGURE 1 Standardized mean score on the Disinhibition, Speed/Arousal, and WM/Fluency factors as a function of age.

group did not differ in their performance compared to the third age group, nor did the third and fourth age group differ from each other (see Figure 1). With the exception of CPT omissions, the results for the separate variables comprising the Speed/Arousal factor showed a significant effect of age ($p < .05$). There was also a significant main effect of sex ($p < .01$) on both of the RT variables (CPT and go/no-go), with girls performing at a significantly slower level than boys. There was also a tendency ($p < .10$) for girls to make more omissions on the CPT and go/no-go tasks.

WM/Fluency. A significant main effect was obtained of age on the variables comprising the WM/Fluency factor (fluency, hand movements, Digit Span Forward, Digit Span Backward, Stroop-like task, and time reproduction), $F(18, 224) = 6.05, p < .0001$, whereas neither the main effect of sex, $F(6, 79) = 1.30$, nor the Age \times Sex interaction, $F(18, 224) = 1.27$, were significant. A priori contrasts comparing performance on the WM/Fluency factor again revealed that the youngest age group performed at a significantly lower level compared to the second youngest age group ($p < .001$). In addition, improved performance was seen across age on WM/Fluency, with the oldest age group performing significantly better than the second oldest age group ($p < .001$). However, the second and third age groups performed essentially alike (see Table 3). The results for the separate dependent variables within the WM/Fluency factor showed that performance improved with age on all of these variables ($p < .05$).

DISCUSSION

A dimensional analysis was used to evaluate the structure of executive functions as assessed by measures based on developmentally relevant models of executive formulations (Barkley, 1997b; Roberts & Pennington, 1996). Three independent factors interpreted as Disinhibition, Speed/Arousal, and WM/Fluency were identified. Second, age and sex differences were analyzed for the delineated functions, and age-dependent changes in children's performances on all three dimensions were demonstrated, whereas sex differences were found only for the Speed/Arousal dimension.

Dimensional Analysis

Disinhibition. The first factor included CPT disinhibition, CPT impulsivity, CPT inattentive impulsivity, and errors of commission on the go/no-go task and reflected a positive correlation among the four disinhibition scores. It is noteworthy that the Stroop-like task, which presumably taps the interference aspect of disinhibition (Barkley, 1997a), did not converge with the rest of the inhibitory measures on this factor, but loaded on the factor tentatively named WM/Fluency. The inhibition tasks that loaded on the Disinhibition factor merely demand that a response be withheld, whereas the Stroop-like task requires that a response be withheld, in addition to the requirement that a shift to a new response is made. This result is in accordance with Pennington's (1997) differentiation between inhibition that demands the individual to stop and to do nothing in its place, and inhibition that demands the individual to stop and do something else.

The Disinhibition factor in this study could be interpreted to reflect the type of inhibition that Barkley (1997a) referred to as inhibition of a prepotent response, but it should be noted that the CPT task did not make the response prepotent in the same sense as did the go/no-go task, because in the former case only a minority of the stimuli required a response. Therefore, the characteristic of merely withholding a response, pointed to by Pennington (1997), may be more useful in describing the phenomenon delineated in this dimension.

Speed/Arousal. The second factor included RT on the go/no-go task and on the CPT task as well as omissions on the same tasks, reflecting that the slower RTs the children had the more errors of omission they made. Barkley et al. (2001) obtained a similar factor, which they named Inattention. However, as previously mentioned, this factor can also be interpreted to reflect a deficit in self-regulation of arousal and motivation to meet situational demands. The occurrence of such a dimension is in line with the idea of the ability to regulate arousal as an important aspect of task performance (Barkley, 1997a; Douglas, 1999).

A third interpretation is that the dimension reflects the speed–accuracy trade-off phenomenon; that is, the tendency of slowing down one’s RTs in favor of making more correct responses (Halpern, 2000), in this case fewer commission errors. In the current situation it would mean that the children who were very cautious waited so long to respond that omissions were scored.

WM/Fluency. Digit Span (Forward and Backward), verbal fluency, hand movements, the Stroop-like task, and time reproduction converged to form the third factor, WM/Fluency. At first blush the measures converging on this factor seem quite diverse; however, after closer task analysis, important similarities emerge among the tasks. The verbal fluency measure was presumed to tap reconstruction, a function distinct from working memory in Barkley’s (1997b) model. However, the findings are highly parallel to those reported by Barkley et al. (2001), who just named the factor Working Memory. The requirements of the verbal fluency task of analysis and synthesis, strategy generation without any external stimulus, the need to maintain in mind which words have already been said implicate a certain load on the working memory system. On these grounds, it is reasonable that the fluency measure does load together with Digit Span Forward and Backward, hand movements, and time reproduction, which all require abilities typically defined as working memory (i.e., fixing and holding information in mind while acting on it and using it to execute tasks).

Another measure that, somewhat unexpectedly, loaded on this dimension was the Stroop-like task, hypothesized to measure inhibition. However, as mentioned earlier, the Stroop-like task used in this study undoubtedly belongs to the type of inhibition where the child has to not only stop a response, but also switch to a more appropriate response (Pennington, 1997). In other words, the Stroop-like task used in this study measures flexibility and interference control. Indeed, prominent researchers within the field of working memory have argued that this type of inhibition may be an inherent part of working memory (Conway & Engle, 1994; Goldman-Rakic, 1995).

The association of an inhibition measure with working memory performance is in line with the findings by Kerns, McInerney, and Wilde (2001), demonstrating a significant relation between inhibition and working memory, operationalized as time reproduction. The authors interpreted this result to indicate that “the waiting component of a time reproduction task requires at least some level of behavioral inhibition” (p. 29).

Like previous factor-analytic studies, the results did not support a distinction between verbal and nonverbal working memory; the measures hypothesized to tap verbal working memory (Digit Span) along with the verbal fluency measure loaded together with the nonverbal working memory measures of hand movements and time reproduction. It is important to note here that a general problem with many types of nonverbal working memory tasks is that the material presented can

be recoded into a phonological code (Pickering, 2001). This might serve as a speculative explanation to the convergence of the verbal and nonverbal measures reflected in the results of this study. For example, it is quite reasonable to speculate that children used a verbal strategy when asked to perform the time reproduction task as well as the hand movements test. To be more specific, in the time reproduction task, when presented with a temporal duration, the most natural way to estimate the length of that duration is, of course, to count the duration in seconds, which is a phonological approach to remembering a time duration. Similarly, in the hand movements test the sequence of hand movements could be coded verbally in terms of the name of the movement, for example *flat*, *side*, or *fist*, so that the child would mentally present a sequence of “words” instead of privately reimagining the observed sequence of hand movements. Of course, this is just speculation and the need for further research is recognized.

Developmental Trends

On the Disinhibition dimension, where withholding of a response was primarily required, the most striking developmental advances occurred at ages 7.6 to 9.5 and 9.6 to 11.5, with little further improvement in the oldest age group. It is interesting to note that the obtained developmental trend is very similar to that reported by Levin et al. (1991), who utilized the go/no-go task as a measure of inhibition to a prepotent response. They found a great developmental shift, with a steep decline in both omissions and commissions between the 7- to 8-year-old age group and the 9- to 12-year-old age group, with no further improvement in the 13- to 15-year-old age group. Comparable results were obtained by Welsh et al. (1991), who found that impulsive responding matured by age 10. These researchers used the MFFT, a test quite different from the current measures of inhibitory control at a surface level. However, this task does require a delay in responding and reflection of the stimulus during the delay to correctly perform the task in the least number of trials.

The Speed/Arousal factor indicated a major gain in development between the first age group (6–7.5-year-olds) and the second age group (7.6–9.5-year-olds). If interpreted in terms of speed of processing, these results could be compared to the results by Williams, Ponesse, Schachar, Logan, and Tannock (1999), who reported impressive gains in speed of inhibiting a prepotent response between the 6- to 8-year-old and 9- to 12-year-old groups. However, if interpreted as arousal the results are in accordance with Van der Meere and Stemerink (1999), who showed a developmental course in state regulation in the early school years.

The performance on tasks included in the WM/Fluency factor appeared to improve significantly at two points in development. The first one occurred around the age of 8, with one further improvement around 12 years of age. The first developmental spurt seen in the WM/Fluency dimension could be interpreted as reflecting the developmental change in the coding of nonverbal stimuli. Across a range of

studies, it has been found that young children tend to code information in visual form. However, after the age of 8 years, children are inclined to use a more phonological approach to nonverbal stimuli (Fenner, Heathcote, & Jerrams Smith, 2000; Hitch, Halliday, Schaafstal, & Schraagen, 1988; Hitch, Woodin, & Baker, 1989; Luciana & Nelson, 1998; Palmer, 2000). Furthermore, it has been found that children who use a phonological code perform better than those who do not, suggesting that a phonological coding improves recall (Hitch et al., 1988). With regards to the current results, it could be speculated that the older children have learned to use a verbal strategy when asked to perform the various tasks primarily thought to tap nonverbal working memory and are, consequently, more effective in their performance (see discussion on dimensional analysis).

It is reasonable to conclude that the latter developmental spurt occurring between 9.6 and 13 years of age on the WM/Fluency dimension is reflecting the protracted course of development observed on verbal fluency tasks (Levin et al., 1991; Welsh & Pennington, 1988; Welsh et al., 1991). The verbal fluency measure used in this study contained both semantic and phonetic fluency. Because the youngest children are just beginning to become phonologically aware, they have difficulty coming up with words starting on a certain letter. The older children are also more likely to be more competent using strategies, which is likely to have a positive effect on their results.

Sex Effects

The main effect of sex on the Speed/Arousal factor indicated, somewhat surprisingly, that girls performed at a lower level on this dimension than boys did. The results were significant for the RT measures and there was also a tendency for girls to make more errors of omission (missed responses). This finding may be related to the Becker et al. (1987) study, which found White boys to be faster on go/no-go RT compared to White girls as well as compared to Black boys and Black girls. It is not clear that these results reflect a tendency for girls to lag behind boys in their development of self-regulation of arousal to meet situational demands. The results could perhaps be ascribed to sex differences in response style. It may be that girls tend to take a more cautious approach to selecting answers than boys and if there is not enough time such a bias would result in a less accurate response pattern. Indeed, Hagekull and Bohlin (1998) found girls to be more conscientious than boys when conducting a study on childhood temperament dispositions. Gallagher (1998) and Gallagher (1989) found strong support for the idea that cautiousness, or some other response bias, is responsible for a large portion of sex differences found in cognitive abilities. However, it is in place to point out that there are no simple or single answers to the many questions of sex differences in cognitive abilities.

In summary, the data showed different developmental trajectories depending on type of executive function. The dimension interpreted as Speed/Arousal seemed to be the first one to reach maturity, with the most active period of development occurring around the age of 8. The “withholding” dimension of inhibition revealed maturity around age 10, along with the first developmental spurt on the WM/Fluency factor. The second developmental spurt on WM/Fluency indicates protracted development into adolescence. Comparison with previous studies regarding the development of executive functions has been made to strengthen conclusions. However, comparisons are difficult because the developmental trends of this study concerned dimensions of cognitive processes rather than on separate tests. Nevertheless, it may be concluded that the developmental data obtained in this study converge with previous developmental studies of executive functions in that there appear to emerge three stages of maturation: early childhood (6–8 years of age), middle childhood (9–12 years of age), and adolescence.

Limitations

Although our developmental analysis constituted an improvement compared to previous studies in terms of avoiding single measures, the fact that the same dataset was used to identify the dimensions as well as to assess age and sex effects may be seen as a weakness. However, the dimensional analysis was performed controlling for age and thus should not reflect age differences in the sample. Replication of the dimensional structure as well as the developmental changes would of course strengthen the generalizability of the results. Finally, it is reasonable to speculate that the cross-sectional design and the small sample size within each age group may have limited the power of the study. The sample size in this study is, however, not so different from previous developmental studies on executive functioning (e.g., Levin et al., 1991; Welsh et al., 1991) and as the developmental timetable obtained converges with previous developmental data, the age effects reported on executive functioning are most likely reliable.

CONCLUSION

The study was performed using a normal sample and thus the results of the dimensional analysis represent normal executive functioning. It is interesting that the obtained dimensional structure was very similar to that obtained by Barkley et al. (2001) despite the fact that their sample was older and encompassed mainly participants diagnosed with ADHD. The results thus strongly support the view of inhibition–disinhibition and working memory as two salient aspects of executive functioning (Roberts & Pennington, 1996). The second dimension identified by this study as well as by Barkley et al. (2001) could be interpreted as reflect-

ing a speed function and as such should perhaps not be viewed as part of the executive domain but as an ability at a lower cognitive level. However, it could also be interpreted as reflecting a regulatory function, which has been viewed as a central executive component (Eslinger, 1996). Our developmental analysis was based on the dimensional structure, which means the results may be taken to represent age effects at the different processes within executive functions rather than on single measures, which should be regarded as a strength of this study. Knowledge of such developmental change in normal functioning should be important in analyzing and understanding behavior and executive functioning of various developmental disorders, particularly when asking whether clinical disorders and problems represent the extremes of dimensions that apply to everyone, or categories that are different in kind.

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