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Huizinga, M.; van der Molen, M.W.

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Age-Group Differences in Set-Switching and Set-Maintenance on the Wisconsin Card Sorting Task

Mariëtte Huizinga and Maurits W. van der Molen
Department of Psychology
University of Amsterdam, The Netherlands

This study examined developmental change in set-switching and set-maintenance on the Wisconsin Card Sorting Task (WCST), and sought to determine how executive function (EF) components (i.e., Working Memory, Shifting and Inhibition) may contribute to the observed changes on WCST performance. To this end, performance in four age groups (7-year-olds, 11-year-olds, 15-year-olds, and 21-year-olds) was measured on the WCST, and on three EF tasks assumed to tap Working Memory, Shifting, and Inhibition. The results showed that adult levels of performance were reached in 11-year-olds for set-switching, and in 15-year-olds for set-maintenance. A subsequent principal component analysis revealed that set-switching and set-maintenance loaded on two factors for 7-year-olds, but a single factor in the other age groups. Finally, regression analyses yielded a complex pattern of results concerning the prediction of set-switching and set-maintenance by the performance on tasks used to assess the EF components. The results were interpreted to suggest distinct developmental trends in set-switching and set-maintenance abilities required by the WCST.

Executive function (EF) refers to a range of cognitive processes that subserve goal-directed behavior (E. K. Miller & Cohen, 2001; see also Luria, 1966; Shallice, 1982). Intact executive functioning is indispensable in novel or demanding situations that require the ability to control thoughts and actions (Stuss, 1992). Thus, EF underlies the ability to adjust behavior rapidly and flexibly to the varying demands of the environment (Zelazo, Müller, Frye, & Marcovitch, 2003). In the course of development, EF becomes increasingly more efficient. Developmental theories interpret this increase as an important manifestation of

Correspondence should be addressed to Mariëtte Huizinga, Department of Psychology, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, The Netherlands. E-mail: m.huizinga@uva.nl

cognitive and emotional development (for reviews see: Diamond, 2002; Welsh, 2002).

Probably the most frequently used experimental task to assess EF is the Wisconsin Card Sorting Task (WCST; Grant & Berg, 1948; Heaton, Chelune, Talley, Kay, & Curtis, 1993). The WCST requires participants to infer, by trial and error with feedback, a relevant sorting rule out of three possible sorting rules (i.e., the color, shape, or number of the stimulus). After ten correct sorts, the sorting rule changes without warning, requiring participants to find the newly relevant sorting rule. A commonly used indicator of WCST performance is perseveration, which is defined as the persistence in responding to a previous, but currently no longer relevant, sorting principle (Heaton et al., p. 8).

The WCST was devised originally to assess deficits in EF in patients with brain damage (Berg, 1948), and the current consensus is that WCST performance relates to the integrity of the prefrontal cortex (PFC) of the brain (e.g., Demakis, 2003; Heaton et al., 1993; Lezak, Howieson, Loring, Hannay, & Fischer, 2004; Stuss & Knight, 2002). Neuroimaging studies report activation of dorsolateral PFC structures in successful WCST performance (e.g., Demakis, 2003; Monchi, Petrides, Petre, Worsley, & Dagher, 2001; Stuss & Levine, 2002). In addition, patients with PFC damage show an increased level of perseveration errors compared to normal controls (Anderson, Damasio, Jones, & Tranel, 1991; Barceló & Knight, 2002; Milner, 1963; Nagahama, Okina, Suzuki, Nabatame, & Matsuda, 2005; Stuss & Levine; Stuss et al., 2000).

Superficially, children's behavior on the WCST resembles the performance of PFC patients. More specifically, children are seen to also perseverate (Chelune & Baer, 1986; Chelune & Thompson, 1987; Heaton et al., 1993; Huizinga, Dolan, & Van der Molen, 2006; Kirk & Kelly, 1986; Paniak, Miller, Murphy, Patterson, & Keizer, 1996; Welsh, Pennington, & Groisser, 1991). Developmental studies, including the WCST, have established that adult level of performance is reached between late childhood and adolescence (Chelune & Baer; Chelune & Thompson; Huizinga et al.; Levin et al., 1991; Welsh et al.). The slow development of EF has been related to the relatively slow maturation of PFC (e.g., Casey, Tottenham, Liston, & Durston, 2005; Diamond, 2002).

DECOMPOSITION OF EXECUTIVE FUNCTION

One major difficulty in interpreting results from complex neuropsychological tasks such as the WCST concerns the lack of insight into the exact abilities that are necessary for successful performance (e.g., Miyake et al., 2000; Stuss & Levine, 2002), i.e., various EF component processes may contribute to task performance. Using structural equation modeling (SEM), Miyake et al. showed that EF can be divided into three distinct components: Working Memory, Shifting, and Inhibition (see also Fisk & Sharp, 2004; for a developmental study using SEM: Huizinga et al., 2006). Moreover, specific EF components were found to explain a significant proportion of variance related to performance on specific complex neuropsychological tasks. That is, Shifting predicted WCST performance, whereas Inhibition predicted Tower of Hanoi performance, a test used to assess planning abilities.

Recent neuro-imaging studies confirmed that EF is not unitary by showing that subcomponents of EF rely on distinct regions of PFC. For example, lateral PFC is implicated in Working Memory (Narayanan et al., 2005; Smith & Jonides, 1999), whereas medial PFC is involved in flexible switching between tasks, and in overriding a previously relevant stimulus-response association (Crone, Wendelken, Donohue, & Bunge, 2006; Ridderinkhof, Ullsperger, Crone, & Nieuwenhuis, 2004; Rushworth, Walton, Kennerley, & Bannerman, 2004). Finally, the ability to inhibit responses was found to rely on the orbitofrontal cortex (e.g., Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003; Roberts & Wallis, 2000).

In addition, recent developmental studies reported distinct developmental trajectories of EF component processes (for reviews, see Diamond, 2002; Welsh, 2002). Several studies revealed that the achievement of adult levels of Working Memory capacity is the outcome of development that proceeds well into adolescence (e.g., Beveridge, Jarrold, & Pettit, 2002; Brocki & Bohlin, 2004; DeLuca et al., 2003; Gathercole, Pickering, Ambridge, & Wearing, 2004; Luciana, Conklin, Hooper, & Yarger, 2005; Luna, Garver, Urban, Lazar, & Sweeney, 2004). In addition, adult levels of task-shifting performance were found to be attained around the age of 12 (Cepeda, Kramer, & Gonzalez de Sather, 2001; Crone, Bunge, Van der Molen, & Ridderinkhof, 2006; Huizinga & Van der Molen, 2007; Kray, Eber, & Lindenberger, 2004). Finally, adult-levels of inhibitory control were observed to be reached around the age of 12 (Bédard et al., 2002; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Durston et al., 2002; Ridderinkhof & Van der Molen, 1995; Van den Wildenberg & Van der Molen, 2004), or early adolescence (Williams, Ponesse, Schachar, Logan, & Tannock, 1999).

SET-SWITCHING AND SET-MAINTENANCE ON THE WCST

The requirements for successful performance on the WCST include:

1. Efficient switching to the new sorting rule on the basis of feedback (i.e., set-switching; Barcelo & Knight, 2002; Heaton et al., 1993).
2. Retaining the current sorting rule in mind through varying stimulus conditions, while ignoring irrelevant aspects of the stimuli (i.e., set-maintenance; Barceló & Knight, 2002; Heaton et al., 1993).

In a recent patient study, Barceló and Knight used an analogue of the WCST to examine the nature of impairments in WCST performance. They put forward an error-scoring method that distinguished between set-switching and set-maintenance processes, which are active during the process of finding a (new) valid sorting principle. The set-switching process was indexed by two types of errors: (1) perseverative errors, which occur when a participant fails to switch to another sorting rule after receiving negative feedback on the previous trial (see also Heaton et al., 1993), and (2) efficient errors, which are related to the efficient testing of hypotheses during switching to a new sorting rule. Efficient errors occur when a participant switches to the wrong sorting rule in the second trial of an otherwise clear series requiring the new sorting rule (i.e., series with no errors other than the first error indicating that the sorting principle changed; Barceló & Knight). The set-maintenance process was indexed by distraction errors, involving random failures to maintain set. Distraction errors occur when the sorting rule is missed continuously, or when there is only one isolated error in an otherwise clear series requiring the correct sorting rule (Barceló & Knight).

Earlier, Barceló (1999) reported data from an event-related-potential (ERP) study in normal adults, indicating that perseverative errors and distraction errors are associated with distinct networks in the PFC. Errors reflecting set-switching abilities were associated with the activation of a frontal-extrastriatal network, whereas set-maintenance abilities were associated with a frontal-central activation. Aside from the finding of increased perseveration during WCST performance in the PFC patients participating in their study, Barceló and Knight (2002) suggested that the observed decrease in the ability to maintain set contributed to the set-switching deficits shown by these patients. That is, these patients had difficulties in keeping their attention focused on the new correct sorting rule (in the presence of distracting stimulus features; see also Milner, 1963).

Recently, Crone, Ridderinkhof, Worm, Somsen, and Van der Molen (2004) obtained evidence suggesting the separability of set-switching and set-maintenance processes during WCST performance. They tested four age groups (8–9-year-olds, 11–12-year-olds, 13–15-year-olds, and young adults) using an experimental analogue of the WCST, which involved spatially compatible and incompatible S-R mapping rules. This task requires the deduction of a correct sorting rule on the basis of feedback or a switch cue. Task performance was scored following Barceló and Knight (2002). Crone and colleagues observed distinct developmental trajectories for set-switching and set-maintenance abilities. More specifically, set-switching abilities developed during childhood and reached adult levels of performance at age 12, whereas set-maintenance abilities continued to develop into adolescence.

PRESENT STUDY

The question of whether children use the same abilities as adults on the traditional WCST remains unanswered to date. The WCST is a complex task, on which adequate performance draws on multiple higher cognitive processes (Miyake et al., 2000). In addition, participants may adopt different learning strategies when searching for a correct sorting rule (e.g., Schmittmann, Visser, & Raijmakers, 2006). In the present study, we examined the development of WCST performance by integrating the approaches advanced by Barceló and Knight (2002) and by Miyake et al. Barceló and Knight conceptualized WCST performance in terms of two processes—set-switching and set-maintenance—that were found to rely on distinct areas in the frontal cortex. In the current study, we adopted the conceptualization advanced by Barceló and Knight (2002) and scored WCST performance in terms of set-switching and set-maintenance abilities. Subsequently, we examined the relative contributions to these abilities of the three EF components, distinguished by Miyake et al., i.e., Working Memory, Shifting, and Inhibition. We tested children in three age groups (7-year-olds, 11-year-olds, 15-year-olds), and one group of young adults (21-year-olds). All participants were tested using a computerized version of the standard WCST, and using three tasks assumed to tap the EF components Working Memory, Shifting, and Inhibition (see also Huizinga et al., 2006)

Working Memory was defined as the collection of cognitive processes that temporarily retain information in an accessible state, suitable for carrying out any mental task (Cowan, 1998). The essence of this component is the monitoring and coding of incoming information with respect to relevance, and the replacement of information that is no longer relevant by newly relevant information. *Shifting* was interpreted as shifting back and forth between multiple tasks (Allport, Styles, & Hsieh, 1994; Monsell, 1996, 2003). When different tasks (usually choice RT tasks) are mixed within blocks, shifting between tasks typically results in an increase in RT, and a decrease in accuracy (i.e., shift costs). *Inhibition* was conceptualized as the ability to deliberately inhibit dominant, automatic, or pre-potent responses (Logan & Cowan, 1984).

We expected WCST performance to change during development. That is, we expected set-switching and set-maintenance processes becoming more efficient when children grow older. In addition, we examined the relative contribution of different EF components during development. More specifically, in common with previous studies (e.g., Miyake et al., 2000; Nagahama et al., 2005), we expected that, with advancing age, Shifting plays a significant role in set-switching during WCST performance. Our prediction was based on studies of PFC patients, who show deficient set-maintenance abilities on the WCST. This deficit has been ascribed to the patients' sensitivity to distraction and to the interference of irrelevant information (e.g., Barceló & Knight, 2002; Demakis, 2003; Stuss et al., 2000; see also Konishi, Chikazoe, Jimura, Asari, & Miyashita, 2005).

Previous research revealed that immature inhibitory abilities in young children contribute to deficits in executing efficient strategic behavior (Björklund & Harnishfeger, 1990; Harnishfeger, 1995; P. H. Miller, 1994). That is, as children mature, inhibitory processes become more efficient, and thus, less irrelevant information enters working memory (see also Kipp, 2005; Van der Molen, 2000). Here, we hypothesized that Inhibition will contribute most in predicting set-maintenance abilities in the youngest children.

METHOD

Participants

The present study included four normal age groups: 51 7-year-olds [30 female, *M* age = 7.2 (age range = 6–8), 67 11-year-olds [40 female, *M* age = 11.1 (age range = 10–12)], 63 15-year-olds [31 female, *M* age = 15.4 (age range = 14–16)], and 56 young adults [40 female, *M* age = 21.0 (age range 18–26)]. Statistical tests indicated that gender distribution did not differ significantly between age groups, χ^2 (3) = 6.09, $p = .107$.

Children were recruited by contacting regular public local schools located in Amsterdam, The Netherlands; the 21-year-olds were students at the University of Amsterdam, The Netherlands, and were recruited through flyers. All children of a particular age-group and all students who responded to the flyer were invited to participate in the study. Teachers assisted in the selection process in order to exclude children with learning disabilities, any health problems, neurological damage, or psychiatric problems (as listed in the *Diagnostic and Statistical Manual of Mental Disorders*, 4 [DSM-IV-TR]; American Psychological Association, 2000). Teachers received this type of information from a school psychologist affiliated to the school. Similar information was derived from a self-report of the 21-year-olds, they were asked (through a questionnaire) if they were diagnosed at any time with any of the listed disorders. Informed consent was obtained from parents (for the children) and from adolescents and students. All participants had normal, or corrected-to-normal, vision. The 7- and 11-year-olds received a small present for their participation, the 15-year-olds received € 10, and the young adults received course credit.

In order to assess their intelligence, participants were administered the Raven Standard Progressive Matrices (SPM; Raven, Court, & Raven, 1985). However, in three 7-year-olds, one 11-year-old, one 15-year-old, and seven 21-year-olds IQ data are missing because these participants were not present during the administration of the SPM. Scores were converted to quartile scores, given the norms of each age group. The Raven quartiles for the 7-, 11-, 15-, and 21-year-olds were 3.7 (*SD* = 0.44), 3.6 (*SD* = 0.50), 3.4 (*SD* = 0.49), and 3.7 (*SD* = 0.47), respectively. Statistical tests indicated that there was a significant difference between age groups on Raven SPM quartile, $F(3, 221) = 5.29$, $p = .002$. Post-hoc Bonferroni tests indicated significant differences between the young adults vs. the 15-year-olds. Given the significant difference between age groups in Raven SPM quartile scores, we re-ran the analyses reported below with Raven SPM quartile score as a covariate, and we found no relationship between IQ and the different EF measures (both within-groups and between-groups). The effects of gender and Raven scores on task performance were not further investigated.

Tasks

All participants completed the WCST and the three tasks designed to measure Working Memory, Shifting, and Inhibition. The tasks were taken from a task battery designed to assess EF from childhood through young adulthood (Huizinga et al., 2006). Task administration was computerized (Toshiba Satellite 1600 laptop; Intel Celeron 800 mHz processor; 15 inch 60 Hz monitor). All tasks required left- and right-hand responses. The response button for the right hand was the "?" key on the computer keyboard, the "z" key served for the left-hand response. The WCST was a computerized version of the standard neuropsychological test. The three tasks used to tap EF component processes were all speeded choice reaction time (RT) tasks. With the exception of the WCST, participants were coached to balance speed and accuracy when responding. Care was taken to ensure that participants understood the instructions, verified by verbal report, response accuracy, and stability of the RTs.

Wisconsin Card Sorting Task. We used a computerized version of the WCST (Somsen, Van der Molen, Jennings, & Van Beek, 2000). Against a light gray background, four key cards, numbered 1 to 4, were presented at the top of the screen. The response cards were taken from the original version of the WCST (Grant & Berg, 1948), and were presented one at a time at the bottom of the screen. The task required participants to match the series of response cards with any of four key cards by pressing the number corresponding to that key card. The display remained visible, until a choice was given. Feedback consisted of a displayed "+" sign, following a correct response, and a "–"sign, following an incorrect response.

Response cards could be matched on color (red, green, blue, yellow), shape (triangle, star, cross, circle), or number (1, 2, 3, 4). Once the participant made 10 consecutive correct sorts, the sorting principle was altered. The task was terminated either after the participant completed 6 categories (e.g., shape, color, form, color, form, shape), or after the maximum of 128 trials was reached. The order of the sorting principles was randomized, with the constraint that the same sorting principles did not occur consecutively. The test was administered according to the procedure outlined in the Heaton manual (Heaton et al., 1993). Three following variables of interest were selected. Perseverative error responses were defined as errors resulting from persistence in responding to a stimulus characteristic that is no longer correct (Barceló & Knight, 2002; Heaton et al.). Efficient error responses refer to a switch to the wrong category on the second trial on an otherwise clear series (i.e., series with no further errors other than the first warning error). Efficient errors were scored only in the second trial of the series and were incompatible with any other error in the remaining trials of that series (Barceló & Knight). Distraction errors were defined as a switch to the wrong category different from the one chosen in the previous trial (Barceló & Knight). The proportions of the respective error types were calculated by computing the number of a particular error type relative to the number of trials administered, multiplied by 100. In addition, we examined the number of correct responses (i.e., the number of responses that match the correct sorting principle in effect at the time the response is made) and the number of categories achieved (i.e., the number of sequences of 10 consecutive correct matches to the criterion sorting strategy). The proportion of correct responses was indexed by computing the number of correct responses relative to the number of trials needed to complete the test, multiplied by 100.

Working Memory. In the Tic Tac Toe task (adapted from Milner, 1971), participants were required to retain visual information about the orientation of a pattern of figures active in their working memory. Working memory load was varied by using patterns consisting of three vs. four letters (i.e., low memory load vs. high memory load). The task consisted of a memorization phase and a recognition phase. A pattern consisting of *X*s and *O*s was presented within a 3 × 3 grid during the memorization phase. Working memory load was varied by using patterns consisting of three vs. four letters (i.e., low memory load vs. high memory load). The recognition phase was initiated by pressing the space bar. During this phase, the *X*s and *O*s were presented one after another at different positions in the grid, each for a period of 600 msec, in series that varied from four to seven presentations for the low memory load, and from four to nine presentations for the high memory load. As soon as the pattern of *X*s and *O*s included the pre-specified pattern indicated in the memorization phase, participants were required to press a button. Participants first received a practice block of 3 trials, followed by one block including 15 trials for low memory load and one block including 15 trials for high memory load. The low and high memory load blocks were counterbalanced across participants to control for order effects. Participants had 3,500 msec to respond; the time interval between trials varied randomly between 900 and 1,100 msec (drawn from a uniform distribution). The main dependent variables were the accuracy proportions and median RTs on the low and high memory load blocks.

Shifting. In the Local-Global task (adapted from Miyake et al., 2000) participants responded to randomly presented rectangles or squares by pressing a left or right response button, respectively. Larger (global) rectangles/squares consist of smaller (local) rectangles or squares. In one block participants responded to the local figure, in a second block they responded to the global figure (blocks 1 and 2, in randomized order; 30 practice trials and 50 experimental trials per block), and in the third block they alternated between a series of four "local" trials and a series of four "global" trials (block 3; 90 practice trials, 150 experimental trials). A cue indicated to which dimension (global or local) the participants should respond. Cues relating the global (local) dimension consisted of a big (small) square, which was presented on one side of the target stimulus, and a big (small) rectangle, which was presented on the other side of the target stimulus. The color of cues and target was red. They remained on the screen until a response was given. Participants had 3,500 msec to respond. The time interval between presentation of the cue and of the target stimulus was 500 msec. The interval between the response and the presentation of the cue was fixed at 1,000 msec. The main dependent variables were the accuracy proportions, and median RTs on task repetition and task alternation trials.

Inhibition. In the present version of the Stop-signal task (adapted from Van Boxtel, Van der Molen, Jennings, & Brunia, 2001), participants had to respond as fast as possible to a left or right pointing arrow by a left or right button press. On 25% of the trials, the color of the arrow changed unpredictably from green to red, indicating that the response to the arrow stimulus should be inhibited. The time interval between arrow onset and arrow color varied depending on the participant's performance. A dynamic tracking algorithm was used to ensure that stopping approximated 50% correct inhibited responses. The stimulus remained on the screen until a response was given. Participants had 1,250 msec to respond. The time interval between the response and the arrow onset on the subsequent trial varied randomly between 1,650 and 2,150 msec (drawn from a uniform distribution). There were 50 practice trials and two blocks of 100 experimental trials. The main dependent variables were the proportion of correctly inhibited trials and the median stop stimulus reaction time (SSRT), reflecting the latency of the internal response to the stop signal (see Logan, 1994).

Procedure

The order of tasks was counterbalanced across participants. The WCST, however, was always administered last, in view of the inter-individual variation in total time needed to complete the task. Both at the schools and the university, the tasks were administered in a dimly lit quiet room. There were 3-minute breaks between tasks, and a 10-minute break after three tasks. Each test session lasted approximately 1.5 hours. At the end of the test-session, the 15-year-olds and 21-year-olds completed a paper-and-pencil version of the Raven SPM (Raven et al., 1985); the children completed this task individually in the classroom (with all participants present).

Exclusion Criteria

A participant was excluded if one of the following criteria was met: failure to complete at least one category at the WCST; mean accuracy percentage at the low memory load of less than 55% (Tic Tac Toe task); less then 55% correct on the first two blocks (Local-Global task); proportion correct inhibits lower than 20% or higher than 80% (Stop Signal task). Sixteen 7-year-olds, six 11-year-olds, and two 21-year-olds were excluded (this exclusion did not result in a significant change in gender distribution and Raven score per age group).[1]

RESULTS

The goal of the present study was to examine the development of WCST performance by integrating the approaches advanced by Barceló and Knight (2002) and by Miyake et al. (2000). We scored WCST performance in terms of set-switching and set-maintenance abilities (see Barceló & Knight. Subsequently, we examined the relative contributions to these abilities of three EF components: Working Memory, Shifting, and Inhibition, as distinguished by Miyake et al.. The results are presented in three sections. The first section focuses on the performance on the WCST and the three EF components tasks. This allows for the comparison of results obtained in the present sample to those reported in the literature. The second section focuses on the correlations between the measures reflecting set-switching and set-maintenance processes on the WCST. The third section focuses on the extent, to which EF components Working Memory, Shifting, and Inhibition tasks predict WCST set-switching and set-maintenance. In the analyses reported below, Age Group (7-year-olds, 11-year-olds, 15-year-olds, 21-year-olds) was included as a between-subjects factor.

Developmental Trends on the WCST and EF Component Tasks

WCST. The means and standard deviations of the four age groups are reported in the left panel of Table 1. A MANOVA performed on the proportions of correct responses, the number of categories achieved, and the proportions of perseveration and distraction errors revealed significant main effects for Age Group [$F(3, 217) = 13.62, p < .0001, \eta_p^2 = .16, F(3, 217) = 11.30, p < .0001, \eta_p^2 = .14, F(3, 217) = 8.00, p < .0001, \eta_p^2 = .10$ and $F(3, 217) = 9.31, p < .0001$ $\eta_p^2 = .11$, respectively]. A trend was observed for the main effect of Age Group on the

[1]The relatively large amount of 7-year-olds excluded from the study was largely caused by failure on the Tic Tac Toe test (9 participants).

TABLE 1
WCST Dependent Variables per Age Group; SDs Between Parentheses

	Age Group				*Post-hoc (Bonferroni)*		
	1	*2*	*3*	*4*			
Dependent Variable	*7-year-olds*	*11-year-olds*	*15-year-olds*	*21-year-olds*	*1 vs. 2*	*2 vs. 3*	*3 vs. 4*
Correct responses	47.9 (17.3)	57.7 (17.6)	66.1 (14.5)	65.6 (15.1)	.014*	.026*	1.000
Categories achieved	3.1 (1.7)	3.7 (1.9)	4.7 (1.7)	4.8 (1.8)	.521	.009*	1.000
Perseverative errors	24.8 (13.0)	18.3 (11.5)	15.8 (9.7)	14.8 (9.6)	.017*	1.000	1.000
Efficient errors	.4 (.5)	.5 (.8)	.7 (.8)	.8 (1.1)	1.000	1.000	1.000
Distraction errors	22.3 (10.9)	20.5 (9.5)	14.7 (5.1)	16.5 (7.6)	1.000	.001*	1.000

*significant at $p < .05$

proportion of efficient errors, $F(3, 217) = 2.60$, $p = .052$, $\eta_p^2 = .04$. The results of post-hoc Bonferroni analyses are presented in the right panel of Table 1. The analyses showed that the proportion of correct responses was smaller in 7-year-olds than in 11-year-olds (ns.),[2] and smaller in 11-year-olds than in 15-year-olds. The 15-year-olds did not differ from 21-year-olds. The number of categories completed was smaller in 7-year-olds than in 11-year-olds, smaller in 11-year-olds than in 15-year olds, and smaller in 15-year olds than in 21-year olds. In addition, the proportion of perseveration errors was larger in 7-year-olds than in 11-year-olds. The 11-year-olds did not differ from 15-year-olds, who did not differ from 21-year-olds. The age groups did not differ from each other with respect to efficient errors. The proportion of distraction errors was larget in 7-year-olds than in 11-year-olds, larger in 11-year-olds than in 15-year-olds, and larger in 15-year-olds than in 21-year-olds.

Thus, we observed two distinct developmental trajectories for set-switching and set-maintenance processes. That is, set-switching performance (i.e., perseveration errors) improved until adolescence, whereas set-maintenance performance (i.e., distraction errors) improved until young-adulthood.

Working Memory. The first response in each block and trials with RTs shorter than 200 msec were excluded from the analysis. Separate repeated measures ANOVAs were performed, with Load (low vs. high) as a within-subjects factor. Dependent variables were response speed (median RTs on correct trials) and the square root of error proportions. ANOVAs, performed on accuracy (% correct) and RT, revealed significant main effect of Age Group on accuracy, reflecting an increase of accuracy when children grow older [70% in 7-year-olds vs. 86% in 11-year-olds vs. 90% in 15-year-olds vs. 92% in 21-year-olds; $F(3, 217) = 57.34$, $p < .0001$, $\eta_p^2 = .44$]. Moreover, we found a significant main effect of Age Group on RT, showing a decrease in response latencies between the ages of 7 and 11, and 11 and 15, and an increase (ns.) between the ages of 15 and 21 (446 msec in 7-year-olds vs. 398 msec in 11-year-olds vs. 344 msec in 15-year-olds vs. 369 msec in 21-year-olds; $F(3, 217) = 24.76$, $p < .0001$, $\eta_p^2 = .26$). In addition, there was a significant effect of Load on accuracy, showing a higher accuracy on trials with a low working memory load compared to trials with a high working memory load (92% vs. 78%; $F(3, 217) = 157.14$, $p < .0001$, $\eta_p^2 = .42$). Moreover, we found a significant effect of Load on RT, indicating shorter RTs on low-load trials than on

[2]One anonymous reviewer argued that the non-significant difference between 7- and 11-year-olds resulted from the fact that a large number of 7-year-olds was excluded due to their failure on the Tic Tac Toe task. As a result of this exclusion 7-year-olds with relatively better working memory abilities might be included in the study. Subsequent Bonferroni analysis that included the 7-year-olds that were initially excluded from the Tic Tac Toe task did however not reveal a significant difference on "categories achieved" between 7- and 11-year-olds ($p = .43$).

high-load trials (365 msec vs. 413 msec; $F(3, 217) = 131.44$, $p < .0001$, $\eta_p^2 = .38$). Finally, for both accuracy and RT, the interaction of Age Group and Load was significant, $F(3, 217) = 29.06$, $p < .0001$, $\eta_p^2 = .29$ and $F(3, 217) = 3.85$, $p = .010$, $\eta_p^2 = .05$, respectively.

A MANOVA performed on the difference scores (i.e., high load vs. low load) indicated that in all age groups accuracy of performance decreased with the increase in working memory load (30% in 7-year-olds; 13% in 11-year-olds; 7% in 15-year-olds; 4% in 21-year-olds). This effect was most pronounced in younger children, and decreased with age. Post-hoc Bonferroni analyses revealed that the effect on accuracy differed significantly between the 7- and 11-year-olds; 11-year-olds did not differ from 15-year-olds, who did not differ from 21-year-olds. In addition, the MANOVA did not show RT differences between 7-year-olds and 11-year-olds, 11-year-olds and 15-year-olds, and 15-year-olds and 21-year-olds.

Shifting. The first four responses in each block, trials with RTs shorter than 200 msec and trials that were preceded by error trials, were excluded from the analysis. Separate repeated measures ANOVAs were carried out with Trial Type (repetition vs. alternation) as within-subjects factor. The ANOVA performed on the square root of accuracy (% correct) and RT revealed a significant main effect of Age Group on accuracy, reflecting a decrease of errors when children grow older (89% in 7-year-olds vs. 93% in 11-year-olds vs. 94% in 15-year-olds vs. 96% in 21-year-olds; [$F(3, 217) = 13.29$, $p < .0001$, $\eta_p^2 = .16$]. In addition, a significant main effect of Age Group on RT was found, indicating shorter response latencies with advancing age (890 msec in 7-year-olds vs. 537 msec in 11-year-olds vs. 448 msec in 15-year-olds vs. 420 msec in 21-year-olds; [$F(3, 217) = 173.60$, $p < .0001$, $\eta_p^2 = .71$]. The main effect of Trial Type failed to reach significance on accuracy ($p = .09$), but the main effect of Trial Type on RT was significant, $F(3, 217) = 210.57$, $p < .0001$, $\eta_p^2 = .49$, reflecting longer RTs on alternation trials compared to repetition trials (615 msec vs. 533 ms). Importantly, for both accuracy and RT, the interaction of Age Group and Trial Type was significant, $F(3, 217) = 3.47$, $p = .017$, $\eta_p^2 = .05$ and $F(3, 217) = 16.27$, $p < .0001$, $\eta_p^2 = .18$, respectively. Accuracy on repetition trials was higher than on alternation trials, and this effect decreased in the child groups but not in the young-adult group (3% in 7-year-olds; 1% in 11-year-olds; 0% in 15-year-olds; –1% in 21-year-olds). A MANOVA performed on the shift costs difference scores (i.e., the decrease in accuracy on alternation trials compared to repetition trials within mixed-task blocks) did not show accuracy differences between 7-year-olds and 11-year-olds, 11-year-olds and 15-year-olds, and 15-year-olds and 21-year-olds.

In addition, RTs on repetition trials were faster compared to RTs on alternation trials and this effect decreased with age (74 msec in 7-year-olds; 46 msec in 11-year-olds; 40 msec in 15-year-olds; 34 msec in 21-year-olds). A MANOVA performed on the shift costs difference scores (i.e., the increase in RT on alternation trials compared to repetition trials within mixed-task blocks) showed that RT shift costs differed significantly between the 7- and 11-year-olds, whereas 11-year-olds did not differ from 15-year-olds, who did not differ from 21-year-olds.

Inhibition. The first four responses in each block were excluded from the analysis. A MANOVA was performed on response ratio (%) and SSRT. Participants were able to stop their responses on stop-signal trials in about half of the trials on which a stop signal was present ($M = 48.9\%$, $SD = 8.2$), and the MANOVA revealed no significant effect of Age Group, $F(3, 217) = 1.38$, $p = .251$, $\eta_p^2 = .02$. This finding indicates that the tracking algorithm worked well in all age groups. For SSRT, a significant main effect of Age Group was observed, $F(3, 217) = 18.58$, $p < .0001$, $\eta_p^2 = .20$, showing that SSRT decreased from 297 msec ($SD = 89$) msec in 7-year-olds, through 232 ($SD = 57$) msec in 11-year-olds and 214 ($SD = 67$) in 15-year-olds, to 203 ($SD = 55$) msec in 21-year-olds. Post-hoc Bonferroni analysis showed that the speed of response inhibition increased during childhood, as indicated by a significant difference between the 7-year-olds and the 11-year-olds, whereas 11-year-olds did not differ from 15-year-olds, who did not differ from 21-year-olds.

Correlations between Set-Switching and Set-Maintenance on the WCST

To explore the relation between set-switching and set-maintenance processes during WCST performance, principal components analyses (PCA) with orthogonal rotation were performed per age group (see Table 2). To determine factor consistency, a loading of .400 was used as a criterion. Using the criterion of Eigenvalues greater than one, two factors were extracted in the youngest children, and one factor in the three oldest age groups.

In the 7-year-olds, nature of the two factors was as follows: Factor 1 included the proportion of perseverative errors and the proportion of efficient errors (i.e., representing a set-switching factor; factor loadings .837 and –.871, respectively), whereas Factor 2 included the proportion of distraction errors (i.e., representing a set-maintenance factor; factor loading .960). This distinction could not be made in

TABLE 2
Eigenvalues and Variance (%) Accounted for by Each Component per Age Group

Age Group	*Component*	*Eigenvalue*	*Variance (%)*	*Cumulative %*
7-year-olds	1	1.467	49.90	48.90
	2	1.117	37.23	86.13
11-year-olds	1	1.745	58.18	58.18
15-year-olds	1	1.484	49.47	49.47
21-year-olds	1	1.816	60.55	60.55

the three oldest age groups, resulting in a single factor extracted by the PCA. The factor loadings of the proportions of perseverative errors, efficient errors, and distraction errors in the 11-year-olds were .747, –.838, and .698; in the 15-year-olds .763, –.477, and .822; in the 21-year-olds .776, –.786, and .772, respectively.

Prediction of WCST Performance

We examined the relative contribution of Working Memory, Shifting, and Inhibition to the factor structure that emerged from the PCA. The mean accuracy score on the Tic Tac Toe task, the median RT on alternation trials on the Local-Global task, and SSRT were the indicators of Working Memory, Shifting, and Inhibition, respectively. The factor scores obtained in the PCA reported above were the criterion variables in backward regression analyses with a probability of F-to-remove > .10.

The regression analyses revealed that in 7-year-olds Factor 1 was best predicted by the model including Shifting, $F(1, 42) = 3.05$, $p = .088$, explaining 6.9% of the variance. Factor 2 was best predicted by the model including Inhibition, $F(1, 42) = 3.58$, $p = .066$, explaining 8.0% of the variance. In 11-year-olds Factor 1 was best predicted by the model including Shifting, $F(1, 62) = 7.66$, $p = .007$, explaining 11.2% of the variance. In addition, in 15-year-olds Factor 1 was best predicted by the model including Shifting and Working Memory, $F(2, 58) = 4.63$, $p = .014$, explaining 14.2% of the variance. Finally, in 21-year-olds Factor 1 was best predicted by the model including Working Memory, $F(1, 55) = 7.58$, $p = .008$, explaining 12.3% of the variance.

DISCUSSION

The present study was designed to investigate the development of set-switching and set-maintenance processes underlying WCST performance (see also Barceló & Knight, 2002). In addition, we examined the relative contribution of the EF components Working Memory, Shifting, and Inhibition to set-switching and set-maintenance during WCST performance (see also Miyake et al., 2000).

Developmental Trends of Set-Switching and Set-Maintenance on the WCST

Barceló and Knight (2002) distinguished between set-switching and set-maintenance processes involved in WCST performance. Set-switching abilities are associated with efficiently switching to the new sorting rule on the basis of feedback, and are indexed by the proportions of perseverative and efficient errors. In this study, performance of set-switching abilities (i.e., perseverative errors) reached young-adult levels in 11-year-olds. This finding is consistent with the results of prior developmental studies (Chelune & Baer, 1986; Crone et al., 2004; Lehto, 2004; Welsh et al., 1991). It should be noted, however, that in contrast to other studies (Barceló & Knight; Crone et al.), the number of efficient errors observed here was rather low. Efficient errors occur when a participant switches to the wrong sorting rule in the second trial of an otherwise clear series comprising the new sorting rule (i.e., series with no errors other than the first error indicating that the sorting principle changed; Barceló & Knight). We hypothesize that the current finding of relatively few efficient errors is due to the absence of ambiguous trials in other studies. The current computerized implementation of the standard WCST included ambiguous trials, which reduced the chances of committing efficient errors. Set-maintenance requires the retention in mind of the current sorting rule throughout varying stimulus conditions, while ignoring irrelevant aspects of the stimuli, and is indexed by the proportion of distraction errors. In the present study, set-maintenance performance on the WCST continued to develop into adolescence. This finding is consistent with the results of other studies, reporting the improvement of set-maintenance performance into adolescence (e.g., Chelune & Baer, 1986; Crone et al., 2004). This developmental trend indicates that with advancing age children are less susceptible to random failures to maintain set during WSCT performance. The reported age-related increase in set-maintaining performance might reflect an increased ability to keep information on-line (Barceló & Knight, 2002; Case, 1992; Crone et al., 2004; Gathercole et al., 2004).

Developmental Trends on EF Component Tasks

In the present study, we observed performance relating to Working Memory to develop into adolescence, whereas Shifting and Inhibition performance reached young-adult levels in 11-year-olds. The developmental trend for Working Memory is similar to the age-group differences found in earlier studies using the Corsi blocks test (a test with a similar format as the Tic Tac Toe test). These studies showed that adult levels of performance are not reached until adolescence (Hitch, Halliday, Dodd, & Littler, 1989; Issacs & Vargha-Khadem, 1989; Kemps, De Rammelaere, & Desmet, 2000; Wilson, Scott, & Power, 1987).

Similar to other studies, Shifting abilities (as reflected by shift costs, i.e., the difference in RT and accuracy on alternation trials relative to repetition trials) reached young-adult levels of performance by the age of 12. The larger shift costs in younger children have been interpreted to reflect immature levels of EF (Cepeda et al., 2001; Zelazo, Craik, & Booth, 2004), or a delay in the retrieval of S-R links from memory (Crone, Bunge et al., 2006).

Finally, consistent with previous studies, performance on the stop-signal inhibition task reached young-adult levels of performance by the age of 12 (Van den Wildenberg & Van der Molen, 2004; Williams et al., 1999). This finding is consistent with the literature assuming that the ability to inhibit develops rapidly during childhood (e.g., Dempster, 1992; for reviews see also Kipp, 2005; Van der Molen, 2000).

Thus, performance analyses showed different developmental trends in the performance on Working Memory, Shifting, and Inhibition tasks. The performance on the Working Memory task continued to develop into young-adulthood whereas the performance on the Shifting and Inhibition tasks attained mature levels during adolescence. The finding of different developmental trends is consistent with previous studies reporting that EF becomes more efficient as children grow older, and that adult-levels of performance on various EF tasks are attained at different ages during childhood and adolescence (e.g., Cepeda et al., 2001; Huizinga et al., 2006; Luna et al., 2004; Van den Wildenberg & Van der Molen, 2004). Importantly, these findings are usually interpreted in terms of PFC maturation (e.g., Gogtay et al., 2004; Sowell et al., 2004). That is, the improvement of EF during childhood and adolescence has been interpreted to reflect gradually less diffuse and more focal PFC activation with advancing age (e.g., Amso & Casey, 2006; Casey et al., 2005).

Contribution of EF Component Processes to WCST Performance

PCA revealed that, in 7-year-olds, set-switching and set-maintenance abilities loaded on two respective factors. This pattern of findings was taken to suggest that successful WCST performance of 7-year-olds draws upon both the genuine ability to flexibly switch to the new sorting principle and the ability to maintain set. Interestingly, in the older age groups, a separate set-maintenance factor was not observed, suggesting the development of the ability to resist distraction from irrelevant interfering information. This finding is consistent with previous literature, in which the ability to maintain set is associated with an increased ability to keep information on-line in working memory (Barceló & Knight, 2002; Case, 1992; Crone et al., 2004). The finding of WCST performance being represented by two factors in 7-year-olds and by only one single factor from late childhood on is taken to suggest the increasing efficiency of EF, most likely reflecting the increasing focal PFC activation that is observed during childhood and adolescence (e.g., Amso & Casey, 2006; Casey et al., 2005).

We regressed WCST performance (as indexed by the respective principal component scores reflecting the Barceló and Knight [2002] scoring method) on the Working Memory, Shifting, and Inhibition tasks. The regression analyses revealed that the set-switching factor observed in 7-year-olds was predicted by Shifting (as expected) and the set-maintenance factor by Inhibition (as expected). The finding that Shifting contributed to WCST performance is in accordance with previous studies showing that the ability to flexibly shift between tasks contributes to WCST performance (e.g., Miyake et al., 2000; Nagahama et al., 2005). The finding that Inhibition is a good predictor of the set-maintenance factor is in accordance with theories assuming that young children are more susceptible to interference from irrelevant information (e.g., Dempster, 1992; Ridderinkhof & Van der Molen, 1995; for reviews, see also Kipp, 2005; Van der Molen, 2000). Distraction errors can be regarded as an untimely reset of the contents of working memory due to an inadequate ability to refrain from processing interfering stimuli or to inhibit interfering responses (Barceló, 1999). The ability to deal with interference fosters the active selection of relevant task information. Specifically, as shown in the current study, young children are less likely to inhibit responses on the WCST that were previously correct, but currently incorrect. That is, response selection on the current trials is guided by a rule that was correct on previous trials but incorrect on the current trial.

The single factor found in the three oldest age groups was best predicted by Shifting (in the 11-year-olds), Shifting and Working Memory (in the 15-year-olds), and by Working Memory (in the 21-year-olds). Thus, in 11- and 15-year-olds successful WCST performance appears to draw upon the ability to flexibly switch to the new sorting rule. The finding of Working Memory involvement in WCST performance of 11- and 15-year-olds replicates earlier work with adults (e.g., Bechara, Damasio, Tranel, & Anderson, 1998; Huizinga et al., 2006; Konishi et al., 1999). Finally, it was found that from late childhood on, Inhibition does not predict WCST performance. This finding is taken to suggest to reflect the complete maturation of inhibitory processes by around age 12, as reported earlier in the literature (Bédard et al., 2002; Bunge et al., 2002; Durston et al., 2002; Ridderinkhof & Van der Molen, 1995; Van den Wildenberg & Van der Molen, 2004). The current results suggest that, with advancing age, one is increasingly able to keep different alternatives (rules) in mind, while searching for the new correct sorting rule on the basis of feedback. This notion is supported by studies reporting the emergent ability to update information in working memory with advancing age (e.g., Beveridge et al., 2002; Brocki & Bohlin, 2004; DeLuca et al., 2003; Gathercole et al., 2004; Luciana et al., 2005; Luna et al., 2004; see also Barceló & Knight, 2002; Case, 1992; Crone et al., 2004). Interestingly, this notion is supported by the developmental trend into adolescence of Working Memory observed in the current study.

Conclusion

The current study set out to assess the developmental trajectories of set-switching and set-maintenance on the WCST. In addition, the relative contribution of the EF components Working Memory, Shifting, and Inhibition was examined to the observed age-group differences in WCST performance. The major findings that emerged from this study were (a) young-adult levels of performance were reached in 11-year-olds for set-switching, and in 15-year-olds for set-maintenance, (b) set-switching and set-maintenance loaded on two factors in the 7-year-olds but on a single factor in the other age groups, and (c) regression analyses yielded differential contributions of Working Memory, Shifting, and Inhibition to set-switching and set-maintenance on the WCST during development.

The current pattern of findings is interpreted to suggest distinct developmental trends in set-switching and maintenance abilities required by the WCST. It could be argued here that these interpretations must be qualified in view of the relatively small sample of participants. It should be noted, however, that the amount of variance explained in all age groups is hardly cause for alarm (i.e., it ranged from about 55% in the 11- and 15-year-olds to 87% in the 7-year-olds). Moreover, the current findings are in accord with previous work showing developmental improvement in set-switching and set-maintenance in WCST performance (Crone et al., 2004; see also Chelune & Baer, 1986; Chelune & Thompson, 1987; Huizinga et al., 2006; Levin et al., 1991; Welsh et al., 1991). In addition, previous neuro-imaging studies showing distinct developmental trajectories of EF components support the findings reported in this study (Bunge et al., 2002; Crone, Donohue, et al., 2006; Klingberg, Forssberg, & Westerberg, 2002; Luna & Sweeney, 2004). Within a broader context, the different developmental patterns found in this study reflect differential development of PFC contributions to EF (for reviews see Casey et al., 2005 and Diamond, 2002). Future research is needed to provide further insight in the developmental pattern of PFC activation in relation to the development of processes underlying WCST performance.

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