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# PAPER

# Switching between spatial stimulus–response mappings: a developmental study of cognitive flexibility

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## Abstract

*Four different age groups (8–9-year-olds, 11–12-year-olds, 13–15-year-olds and young adults) performed a spatial rule-switch task in which the sorting rule had to be detected on the basis of feedback or on the basis of switch cues. Performance errors were examined on the basis of a recently introduced method of error scoring for the Wisconsin Card Sorting Task (WCST; Barcelo & Knight, 2002). This method allowed us to differentiate between errors due to failure-to-maintain-set (distraction errors) and errors due to failure-to-switch-set (perseverative errors). The anticipated age differences in performance errors were most pronounced for perseverative errors between 8–9 years and 11–12 years, but for distraction errors adult levels were not reached until 13–15 years. These findings were interpreted to support the notion that set switching and set maintenance follow distinct developmental trajectories.*

## Introduction

As children develop, they learn to interpret a wide range of inputs from the world that can help them monitor their actions, and adjust them as needed. This aspect of behaviour has been referred to as 'cognitive flexibility' or 'executive control', referring to those cognitive functions that are concerned with selection, scheduling and coordination of computational processes that are responsible for perception, memory and action (Norman & Shallice, 1986; Miller & Cohen, 2001). Cognitive flexibility has proven to be particularly sensitive to age-related change (Diamond, 2002; Nelson, 1995; Pennington, 1994; Welsh, 2002). That is, age-related improvement has been observed on for example, the Wisconsin Card Sorting Task (Baker, Segalowitz & Ferlisi, 2001; Chelune & Baer, 1986), inhibition/interference tasks (Diamond, Kirkham & Amso, 2002; Ridderinkhof & Van der Molen, 1995) and task-switch tests (Cepeda, Kramer & Gonzalez de Sather, 2001; Zelazo, Frye & Rapus, 1996).

The Wisconsin Card Sorting Task (WCST) is probably one of the most widely used tests of cognitive flexibility in clinical and research contexts. This task requires participants to sort cards according to colour, shape or number on the basis of feedback, and after a number of correct consecutive sorts, sorting rules are shifted without warning. Performance on the WCST, particularly on measures of perseverative errors, has been found to be associated with frontal-lobe lesions in human patients, especially the dorsolateral prefrontal regions. More specifically, these patients experience difficulties in switching to another sorting principle on this task, because they perseverate on the previous correct task set (Barcelo & Knight, 2002; Milner, 1963; Stuss & Levine, 2002). Developmental studies converged on the conclusion that errors observed in the performance of younger children on the WCST resemble those of adults with prefrontal damage (Chelune & Baer, 1986; Kirk & Kelly, 1986). That is, young children tend to perseverate in the previous sorting rule, which is no longer appropriate after the sorting rule has shifted. This finding has been interpreted to suggest that children fail to inhibit the previous response set (Chelune & Thompson, 1987; Diamond, 2002; Paniak, Miller, Murphy, Patterson & Keizer, 1996; Riccio, Hall, Morgan, Hynd, Gonzalez & Marshall, 1994; Rossellini & Ardila, 1993; Welsh, Pennington & Groisser, 1991; Welsh, 2002).

Although the results obtained with the WCST have provided important insights into age-related changes in executive control, the alleged specificity of the test has

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received some criticism (Anderson, Damasio, Jones & Tranel, 1991; Barcelo & Knight, 2002; Cepeda *et al.*, 2001). One of the most important criticisms is that the WCST is a complex task that requires not only problem-solving and efficient working memory to discover the new rule after a change (Osman, Zigun, Suchy & Blint, 1996; Snitz, Curtis, Zald, Katsanis & Iacono, 1999), but also the ability to inhibit inappropriate responses (Pantelis, Barber, Barnes, Nelson, Owen & Robbins, 1999; Stuss & Levine, 2002). This distinction is important from a developmental perspective, given that theories on development of executive function have emphasized the functional distinction between the development of working memory and inhibitory control (Diamond, 2002; Pennington, 1994; Welsh, 2002). These reports have received support from recent developmental neuroimaging studies, showing involvement of the dorsolateral prefrontal cortex in spatial working memory capacity (Thomas, King, Franzen, Welsh, Berkowitz, Noll, Birmaher & Casey, 1999) and the ventral prefrontal cortex in inhibitory control and interference suppression (Bunge, Dudukovic, Thomason, Vaidya & Gabrieli, 2002; Casey, Giedd & Thomas, 2000).

Attempts to achieve a better understanding of the cognitive nature of impairments in WCST performance have often involved the use of WCST-analogue versions to pinpoint distinct cognitive processes in card sorting. For example, Nelson (1976) reported using a modified WCST in which the ability to identify a rule change was brought under control, while leaving set-switching requirements intact. Whenever a sorting rule was changed, participants (frontal, non-frontal, and extra-cerebral lesion patients) were informed that the rule had changed and that they now had to determine and apply another rule. Through this cueing procedure, the patients were confronted explicitly with the need to apply rule-switch operations. Even though the explicit cues helped the patients to recognize that the previous categorization rule was no longer correct and that a new rule was to be introduced and applied (as inferred from exit interviews), the frontal patients perseverated longer than the other patient groups in no-longer correct categorization rules. Thus, the perseverative behaviour in frontal-lobe patients in the cued WCST appeared to be due to deficient set-switching abilities as opposed to deficits in noticing a rule change (see also deZubicaray & Ashton, 1996; Nagahama, Sadato, Yamauchi, Katsumi, Hayashi, Fukuyama, Kimura, Shibasaki & Yonekura, 1998; Ridderinkhof, Span & Van der Molen, 2002; Van Gorp, Kalechstein, Moore, Hinkin, Mahler, Foti & Mendez, 1997). Other authors have used WCST versions to address errors specifically linked to deficits in the ability to apply rules, rather than the ability to identify a rule change (Greve, Williams, Haas, Littell & Reinoso, 1996).

Barcelo and Knight (2002) argued that these analogue versions may provide insight into the component processes underlying WCST performance, but continued to ignore the poor validity of traditional test scores (see also Barcelo, 1999; Freedman, Black, Ebert & Binns, 1998). Thus, although perseverative errors are regarded as the main signs of frontal lobe dysfunction (Stuss & Levine, 2002), the number of categories achieved is often used as an equivalent indicator (Heaton, Chelune, Talley, Kay & Curtis, 1993; Kimberg, D'Esposito & Farah, 1997). However, the errors that reduce the number of categories achieved (non-perseverative errors) may involve different brain mechanisms than perseverative errors (Barcelo, Sanz, Molina & Rubia, 1997). Indeed, using a topographical analysis of event-related potentials (ERPs), Barcelo (1999) showed that errors due to distraction and perseverative errors result from sub-optimal activation in two different prefrontal neural networks, the first referring to a frontal-central locus and the second to a frontal-extrastriate network. The differential involvement of distinct neural mechanisms in WCST performance led Barcelo and Knight (2002) to conclude that successful WCST performance requires at least two processes, the ability to maintain set (errors due to distraction) and the ability to switch set (perseverative errors).

Interestingly, a post-hoc analysis of performance errors in different age groups using traditional scoring methods (Heaton *et al.*, 1993) suggests that set switching and set maintenance are sensitive to different developmental trajectories (Chelune & Baer, 1986). More specifically, while by the age of 10 children's task competence was similar to that of young adults on all performance measures, at earlier ages performance differed between dependent measures. The increase of categories achieved and reduction in perseverative errors began at age 6, whereas failure-to-maintain-set showed little change until age 9. The functional distinction between development of set switching and set maintenance may be related to maturation of different frontal neural networks (Barcelo, 1999). This assumption is supported by recent findings emerging from brain imaging studies, which show that spatial working-memory demands (Thomas *et al.*, 1999) and the need to inhibit a prepotent response (Durston, Thomas, Yang, Ulug, Zimmerman & Casey, 2002) activate similar brain regions in adults and children (respectively, the dorsal and ventral prefrontal cortices); however, the magnitude of this activity was greater and the pattern more diffuse for children compared to adults (Casey *et al.*, 2000).

## Current study

This study set out to examine whether developmental changes in errors made on WCST-like tasks reflect separate neurocognitive developments (set switching versus set maintenance) or are related to maturation of the same cognitive process (general 'attention' skills). Four age groups performed developmentally appropriate switching tasks that were based on the principles of the WCST. A potential confound in the scoring system of the WCST is that the task requires two types of switching; the first entails switching the focus of attention, establishing which stimulus is relevant for responding, and the second entails shifting the link between the target stimulus and the selected response process (see also Bischoff-Grethe, Ivry & Grafton, 2002). This difference is important, since different neural processes may underlie differences in switching between stimulus-type and rule-type. For example, functional neuroimaging studies have recently reported different neural bases for switching attention between and across stimulus dimensions (e.g. Pollmann, 2001; Toni, Rushworth & Passingham, 2001). To dissociate the possible confound of two types of switching, we eliminated the influence of attention shifts due to dimensional change (Heaton *et al.*, 1993), but focused on the component processes that are specifically linked to switching response-mappings (Bischoff-Grethe *et al.*, 2002). This was achieved by selecting sorting rules based on the same dimension (location). Additionally, sorting rules and order of sorting stimuli within the series were determined on a semi-random basis so as to eliminate ambiguous trials (trials that could be correctly sorted on the basis of both the previously correct and the currently correct dimension) and thereby improve the 'pureness' of the perseverative error measure (Barcelo, 1999).

Our scoring method further benefited from a scoring procedure introduced by Barcelo and Knight (2002). This scoring method differentiates three types of errors that are purportedly controlled by different systems in the brain (Barcelo, 1999). A *perseverative error* is defined as a failure to switch category after receiving negative feedback from the previous trial. Errors that are traditionally scored as non-perseverative errors (Heaton *et al.*, 1993) are subdivided into two categories. An *efficient error* is defined as a switch to the wrong sorting rule on the second trial of an otherwise clear series, and is used to identify the currently correct sorting rule. In contrast, a *distraction error* is defined as a switch to a wrong category different from the one chosen in the previous trial. Distraction errors indicate that the subject has not kept track of all previously discarded categories.

A methodological problem with regard to distraction errors is that these could reflect difficulties in filtering out present distracting stimulus information, that is, a deficit in keeping relevant information on-line (Barcelo & Knight, 2002), but these errors could also reflect interference from previous sets, i.e. an inhibitory deficit (Allport, Styles & Hsieh, 1994; Swainson, Rogers, Sahakian, Summers, Polkey & Robbins, 2000). Employing a symbolic task-cueing procedure should provide conclusive evidence for the assumption that distraction errors reflect failure to keep relevant information on-line, i.e. a working memory deficit (Lehto, 1996), rather than failure to inhibit responses based on the previous sorting rule. Two versions of the task were constructed. In one version, subjects had to deduce the correct sorting rule on the basis of positive and negative feedback. In the case of a rule switch, negative feedback came unannounced and after the response was given, alerting the subject that the sorting rule that had been correct was no longer correct. In the other version, a stimulus cue was associated with a certain stimulus–response rule. In the case of a rule switch, the change of colour showed that the sorting rule had switched to another stimulus–response rule.

It was anticipated that (a) children's set-switching capabilities would reach adult levels of performance faster than children's set-maintenance capabilities, indexed by an earlier age at which error scores would approach those of adults for perseverative errors in comparison to distraction errors (Chelune & Baer, 1986) and (b) children's set switching, indexed by perseverative errors, would not be enhanced by specific task cues whereas children's set maintenance, indexed by distraction errors, would benefit from cueing sorting rules (cf. Greve *et al.*, 1996; Ridderinkhof *et al.*, 2002).

To establish whether results emerging from the current set-switch task are in line with the findings documented in the literature for the WCST, initial analyses will focus on the conventional scoring methods outlined in the Heaton manual (Heaton *et al.*, 1993).

## Method

### *Participants*

Four age groups participated in the study, 16 children between 8 and 9 years of age ($M = 9.2$, SD = .40, 5 female), 16 children between 11 and 12 years of age ($M = 12.2$, SD = .30, 8 female), 18 adolescents between 13 and 15 years of age ($M = 14.3$, SD = .80, 9 female) and 18 university students aged between 18 and 25 years ($M = 22.4$, SD = 2.32, 8 female).

Children and adolescents were recruited by contacting schools. These participants were selected with the help of their teacher. A primary caregiver signed a consent letter for participation. The students were recruited through flyers and received credit points for their participation.

**Table 1** *Age comparisons on Heaton scores*

| Variable | | | 8–9 years | 11–12 years | 13–15 years | 18–25 years | *F*-value df (3, 68) |
|---|---|---|---|---|---|---|---|
| *N* | | | 16 | 16 | 18 | 18 | |
| Age | | *M* | 9.2 | 12.2 | 14.3 | 22.4 | |
| | | SD | .40 | .30 | .80 | 2.32 | |
| IQ | RAVEN percentile scores | *M* | 54.71° | 48.53° | 43.75° | 81.67 | 6.54** |
| | | SD | 6.23 | 6.23 | 5.74 | 6.05 | |
| WCST | | | | | | | |
| | % Correct responses | *M* | 80.8° | 82.9 | 83.0 | 86.5 | 5.23** |
| | | SD | 4.5 | 4.0 | 4.4 | 3.8 | |
| | Number of categories achieved | *M* | 12.2° | 13.0° | 13.6 | 15.0 | 7.78** |
| | | SD | 2.5 | 1.8 | 1.4 | 0.9 | |
| | % Perseverative responses | *M* | 3.1° | 2.4 | 2.1 | 1.1 | 3.72** |
| | | SD | 2.2 | 2.0 | 1.5 | 1.2 | |
| | % Non-perseverative responses | *M* | 16.2° | 14.7 | 14.9 | 12.3 | 4.02** |
| | | SD | 3.7 | 3.0 | 3.5 | 3.0 | |
| | % Conceptual-level responses | *M* | 78.0° | 79.9° | 81.6 | 85.2 | 4.74** |
| | | SD | 7.2 | 6.2 | 5.4 | 4.1 | |
| | Failure to maintain set | *M* | 2.4° | 1.5 | 1.4 | 0.4 | 8.12** |
| | | SD | 1.7 | 1.3 | 0.9 | 0.7 | |

*Note*: ** $p < .01$; ° indicates that performance was distinguishable from adults' performance on the basis of Tukey post-hoc comparisons.

All participants reported to be healthy and took a computerized version of the Raven Standard Progressive Matrices task (Raven SPM) in order to obtain an estimate of their intelligence quotient (IQ).

Chi-square analyses indicated that gender did not differ significantly between age groups. A one-way analysis of variance (ANOVA) performed on the IQ percentile scores (Table 1) revealed a significant difference between age groups, $F(3, 68) = 6.54$, $p < .001$. Partial correlation analyses (controlling for age group) were performed to examine the possible relation between IQ and number of perseverative errors, or between IQ and number of distraction errors, but both analyses resulted in non-significant interactions ($r = -.17$, $p = .18$, and $r = .04$, $p = .77$, respectively). Additionally, for all analyses reported below, significant age-group differences in performance were re-evaluated by ANCOVA using IQ score as covariate, but IQ failed to alter any of the interactions including group. Therefore, the effects of IQ were not further investigated.

## *Task format*

### Displays

Participants were seated in front of a 17-inch computer monitor at a viewing distance of approximately 70 cm. Two displays were presented on each trial, a stimulus display and an outcome display. An example of a stimulus and outcome display is presented in Figure 1. The stimulus display consisted of four doors (3 × 5 cm) presented in two separate 'houses' on a horizontal row, A, B, C and D, followed by 1000-ms delay, followed by a cat (2 × 4.5 cm) that was presented in front of the doors. Participants were told to assist the cat in finding its way home by pressing one of four keys corresponding to the doors. The left middle, left index, right index and right middle fingers were assigned to the 'Z, X < and >' keys of the computer keyboard. The 'Z, X < and >' keys were mapped onto the doors from left to right. Upon pressing one of the keys, the stimulus display was replaced by the outcome display showing a '+' sign indicating positive feedback or a '–' sign indicating negative feedback at the location of the selected door. The stimulus associated with the next trial was presented 1500 ms after feedback onset.

### Task blocks

The task consisted of three rule-application blocks, one rule-change block and one rule-induction block. The rule-application blocks were administered to examine if there were age differences in the ability to apply different stimulus–response (S–R) rules separately. In the first rule-application block, stimuli that appeared in one of four locations designated a response with the finger compatible to the location. Thus, spatially compatible button-presses were required in response to the location

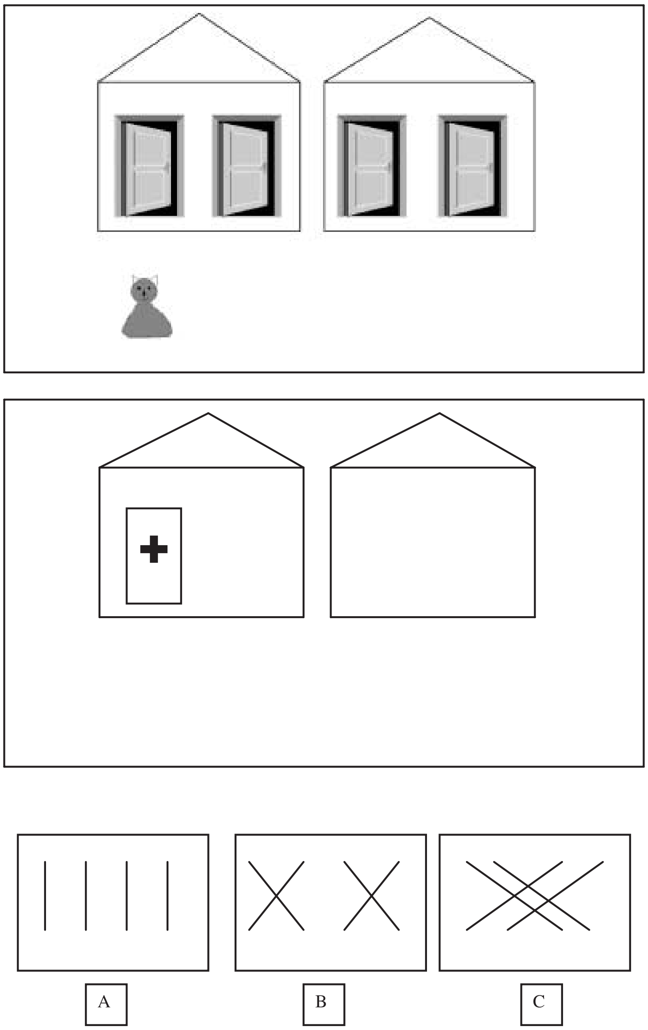


**Figure 1** *Example of stimulus display (top panel), outcome display (middle panel) and response-rules (bottom panel). See text for further clarification.*

of the stimulus (see Figure 1, bottom panel A). In the second rule-application block, stimuli that appeared at any of the four possible stimulus positions designated a response with the opposite finger of the same hand (see Figure 1, bottom panel B). In the third rule-application block, stimuli that appeared at any of the four possible stimulus positions designated a response with the finger that was assigned to the location two locations from the stimulus location (see Figure 1, bottom panel C). Stimuli in the rule-application task were presented in yellow, blue or red. Colour assignments were counterbalanced across participants and kept fixed across the experiment. The rule-application blocks consisted of 100 trials.

In the rule-change block, the subject's task was to sort stimuli using one of the three location rules. When the subject had correctly applied the relevant sorting rule for eight consecutive trials, the sorting dimension was shifted to another. The colour of the stimulus represented the dimension according to which the stimulus should be sorted. The rule-change task consisted of 150 trials or 18 correctly applied sorting rules. This condition will be referred to as the 'cued' condition.

In the rule-induction block subjects also sorted stimuli according to one of the three location rules, but now the stimulus was presented in white. The critical sorting rule was initially unknown to the subject and had to be inferred using trial-by-trial feedback. Participants were told that the relevant sorting rule could change from time to time, and that in that case they had to use trial-by-trial feedback to infer a new sorting rule. When the subject had correctly applied the relevant sorting rule for eight consecutive trials, the sorting rule was shifted to another dimension without notice. The rule-induction task consisted of 150 trials or 18 correctly applied sorting rules. This condition will be referred to as the 'non-cued' condition.

### *Design and procedure*

To familiarize the participants with the stimuli and procedure, they received three blocks of 15 practice trials of each rule-application block, in which the relation between the location rule and colour of the stimulus was explained. In case participants made more than 15% errors during a practice block, that specific practice block was repeated. There were no shifts required during practice blocks. The participants were instructed to assist the cat in finding its way home, and that the colour of the cat revealed where its house was. Before the rule-induction (i.e. non-cued) task, the participants were informed that the cat had lost its colour, and that they were to use trial-by-trial feedback to find its way home. They were also told that the cat's house could change from time to time, and that in those cases they had to use the trial-by-trial feedback again to find its new location. Care was taken that participants understood the instructions.

All participants were tested individually in a quiet laboratory or classroom. They performed the five task blocks in counterbalanced order. The rule-application blocks lasted approximately 5 minutes each. The rule-induction and rule-change conditions lasted approximately 8 minutes each. The Raven SPM was administered following the completion of the task and took approximately 20 minutes to complete. Participants were then thanked for participation and students were given credit points. Including instructions and breaks, participants spent approximately one hour in the laboratory or classroom.

*Scoring methods*

In the non-cued rule-induction task, six WCST variables were examined that have been found sensitive to development (Chelune & Baer, 1986; Chelune & Thompson, 1987) using the scoring criteria outlined in the Heaton manual (Heaton *et al.*, 1993). The variables that were examined were: (a) total percentage of correct responses, (b) number of categories achieved, (c) percentage of total responses that were perseverative, (d) percentage non-perseverative errors, (e) percentage conceptual-level responses (sequences of three correct consecutive sorts) and (f) failure to maintain set (failure to complete set after five correct consecutive sorts).

Our scoring method benefited from a recent study by Barcelo and Knight (2002), in which errors were scored as a function of past contextual information. An 'efficient' error was defined as switch to the wrong category on the second trial on an otherwise clear series (series with no other errors than the first warning error). Efficient errors were incompatible with any other type of error that could occur in the series. A 'perseverative' error was defined as a failure to switch category after the first warning error. A 'distraction' error' was defined as a switch to the wrong category different from the one chosen in the previous trial. Distraction errors were compatible with other errors that could occur earlier or later in the series. In the rule-application task (cued condition), only perseverative and distraction errors were scored (note that the rule-application task also required changing between rules, but contrary to the rule-induction task, the sorting dimension did not have to be inferred on the basis of feedback but could be applied according to the cued dimension). The scoring method was similar to the rule-induction task, with the exception that perseverative errors were defined as a failure to switch category when seeing a stimulus of a colour different from that on the previous trial.

## Results

To examine if there were a priori differences between the age groups in applying the three different stimulus–response (S–R) rules, a 4 (Age) × 3 (S–R Rule) ANOVA for error percentages in pure rule-application blocks was performed. The analysis revealed main effects of Age, $F(3, 64) = 3.26$, $p < .05$, and S–R Rule, $F(2, 128) = 4.46$, $p < .05$. Post-hoc paired comparisons revealed that 18–25-year-olds made fewer errors ($M = .98$, SD = .95) than 8–9-year-olds ($M = 4.98$, SD = 1.0), $F(1, 64) = 8.27$, $p < .005$. For 11–12-year-olds ($M = 2.38$, SD = 1.0) and 13–15-year-olds ($M = 1.40$, SD = .99), performance was not distinguishable from adult level. The effect of the S–R rule indicated that participants made more errors when applying an incompatible one-location difference block ($M = 2.7$, SD = .50) than when applying a compatible S–R block ($M = 1.5$, SD = .29), $F(1, 64) = 9.67$, $p < .005$. Likewise, participants made more errors when applying an incompatible two-locations difference block ($M = 3.1$, SD = .82) than when applying the compatible S–R rule, $F(1, 64) = 5.85$, $p < .05$, but the number of errors for incompatible one-location difference and incompatible two-location difference did not differ from each other, $F(1, 64) = .47$, $p = .48$. There was no interaction between Age and S–R Rule, $F(6, 128) = 1.04$, $p = .40$, showing that there were no age-related differences in the ability to apply the S–R rules separately.

### *Scores based on Heaton* et al. *(1993)*

For reasons of comparability between the current task and WCST tasks reported in the literature, scores based on Heaton *et al.* (1993) were computed for the non-cued task, because this task, like the original WCST, required participants to infer and apply rules on the basis of positive and negative performance feedback. The means and standard deviations for the four age groups in the non-cued rule induction task are presented in Table 1 for age in years, IQ estimate and each of the six WCST variables based on the Heaton *et al.* (1993) scoring system. The Heaton-related scores on the non-cued rule-induction task closely replicated the expected pattern of WCST scores observed in previous developmental studies. As can be seen in the last column of Table 1, there were significant age differences for all Heaton scores. Post-hoc Tukey comparisons revealed that percentage correct was lowest, and percentage perseverative responses, percentage non-perseverative error responses and failure-to-maintain-set were highest for 8–9-year-old children. Starting from age 11–12 years, performance was not distinguishable from adult levels. Percentages of conceptual-level responses and categories achieved were lowest for 8–9-year-olds and 11–12-year-olds. Starting from age 13–15 years, performance was not distinguishable from adult levels.

### *Error types based on Barcelo and Knight (2002)*

First, to examine if perseverative errors and distraction errors could be dissociated during the rule search process, we examined the occurrence of both types of errors on the first eight trials following a first warning error in the non-cued condition and following a symbolic cue change in the cued condition. As can be seen in Figure 2, perseverative errors occurred in the beginning of the

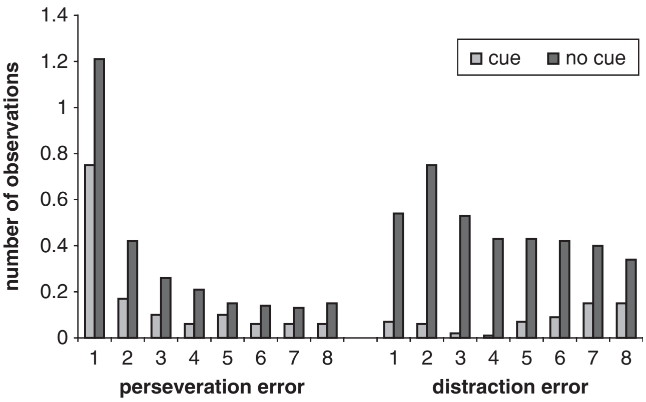


**Figure 2** *Number of perseverative errors and distraction errors over eight trials for both the no-cue and the cue condition following the first-warning error (no-cue condition) or symbolic cue change (cue condition).*

rule search process, and were only affected by a task cue on the first trial. In contrast, distraction errors occurred during all eight trials of rule searching and the symbolic task cue reduced the number of distraction errors over the whole range. These visual impressions were statistically verified by a three-way interaction between Trial Length (8 trials), Error Type (perseveration versus distraction error) and Task Cue (cue, no cue), $F(7, 497) = 3.79$, $p < .005$. A separate post-hoc ANOVA for perseverative errors resulted in a main effect of Trial Length, $F(7, 497) = 32.17$, $p < .001$, and an interaction between Task Cue and Trial Length, $F(7, 497) = 2.83$, $p < .05$. This latter interaction revealed that perseverative errors were reduced by the presentation of a task cue, but only on the first trial. That is, separate *t*-tests indicated a significant effect of task cue on the first trial following a rule shift, $F(1, 71) = 7.95$, $p < .05$, and the cue effect was not significant for trials 2 to 8 ($p$'s $> .05$). The absence of an effect of task cue after Trial 1 is probably associated with the fact that perseverative errors were already greatly reduced after the first trial and therefore had little room to fall.

A similar ANOVA for distraction errors resulted in main effects of Task Cue, $F(1, 71) = 8.09$, $p < .001$, and Trial Length, $F(7, 497) = 5.24$, $p < .001$. Separate *t*-tests for each trial revealed that distraction errors were more pronounced in the non-cued condition compared to the cued condition for each of the eight trials following a rule shift (all $p$'s $< .01$). This pattern was interpreted to suggest that the task cue helped the subjects to keep track of the current sorting rule. Further evidence for the assumption that distraction errors are related to the ability to keep relevant information on-line comes from the significant positive correlation between distraction errors and Heaton's failure-to-maintain-set ($r = .44$, $p < .001$, partial correlation controlled for age group). This pattern of findings provides the context for the interpretation of developmental changes in the number of perseveration errors and distraction errors as an index of the ability to switch set and the ability to keep information on-line, respectively.

Two analyses were conducted to evaluate developmental change in error patterns in the cued and non-cued task. The first analysis was adopted from Barcelo and Knight (2002) and examined age-related differences in error types in the non-cued task. Efficient errors, perseveration errors and distraction errors were computed as the total number of each error type divided by the number of sorting-rule shifts (i.e. categories achieved). These scores were submitted to analysis of variance with the between-subjects factor Age Group (8–9 years, 11–12 years, 13–15 years, 18–25 years) and the within-subjects factor Error Type (efficient, perseverative, distraction).

Consistent with the response pattern of healthy adults reported by Barcelo and Knight (2002), young adults significantly differed in the number of perseverative, efficient and distraction errors, $F(2, 34) = 4.61$, $p < .05$. Post-hoc comparisons revealed that young adults made more efficient errors ($M = .16$, SD = .12) than perseverative errors ($M = .09$, SD = .11), $F(1, 17) = 6.60$, $p < .05$, and more distraction errors ($M = .19$, SD = .17) than perseverative errors, $F(1, 17) = 7.04$, $p < .05$, whereas the number of efficient and distraction errors did not differ from each other, $F(1, 17) = 1.23$, $p = .28$. Interestingly, an interaction between Age Group and Error Type, $F(6, 126) = 4.41$, $p < .001$, showed that younger participants were more prone to perseverative errors, $F(3, 64) = 4.23$, $p < .01$, and distraction errors, $F(3, 64) = 4.80$, $p < .01$, than young adults, whereas there was no significant difference in the number of efficient errors across age groups, $F(3, 63) = 1.29$, $p = .29$ (see Figure 3). A separate post-hoc analysis showed that the age-related decrease in the number of distraction errors was larger than the age-related decrease in number of perseverative errors, shown by a significant interaction between Age Group and Error Type (perseverative vs. distraction), $F(3, 64) = 3.20$, $p < .05$. This effect may be associated with the fact that there was more room for reduction of distraction errors than for perseverative errors.

The second analysis examined whether age-related differences in the number of distraction and perseverative errors could be reduced by the presentation of a stimulus cue. Perseveration and distraction scores were submitted to analysis of variance with the between-subjects factor Age Group (8–9 years, 11–12 years, 13–15 years, 18–25 years) and within-subjects factors Cue Type (cued, non-cued) and Error Type (distraction, perseverative). The

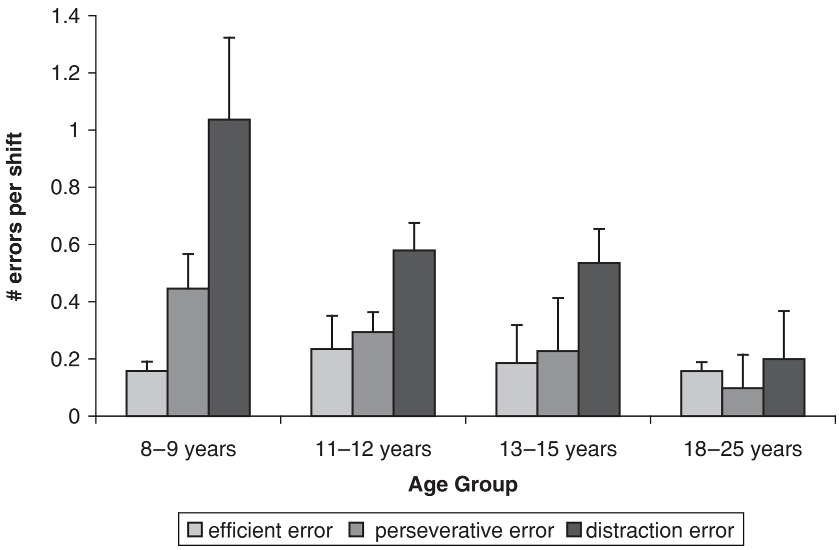


**Figure 3** *Mean number of efficient errors, perseverative errors (referring to failure-to-switch-set) and distraction errors (referring to failure-to-maintain-set) in the no-cue condition scored by the number of response shifts for each age group separately.*

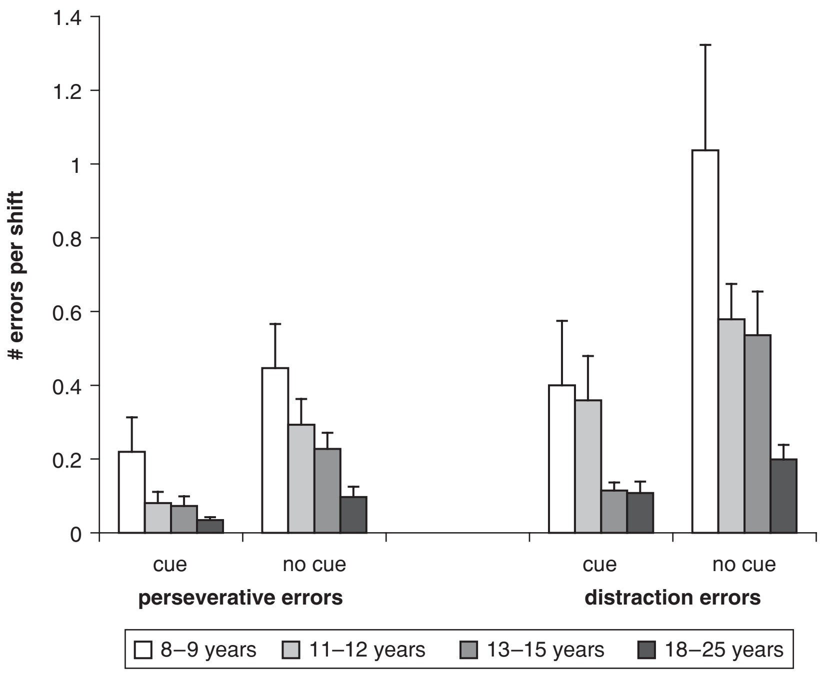


**Figure 4** *Mean number of perseverative (referring to failure-to-switch-set) and distraction errors (referring to failure-to-maintain-set) for each age group scored by the number of response shifts for task blocks with and without stimulus cue.*

analysis resulted in a three-way interaction between Age Group, Cue Type and Error Type, $F(3, 64) = 3.00$, $p < .05$. As can be seen in Figure 4, the cued condition served to decrease the age-related difference in both distraction errors and perseverative errors. These visual impressions were verified statistically by a significant interaction between Age Group and Cue Type for distraction errors, $F(3, 64) = 3.69$, $p < .05$, showing that difference scores between cued versus non-cued distraction errors were higher for 8–9-year-olds (.64) than for young adults (.09), whereas for 11–12-year-olds (.22) and for 13–15-year-olds (.42) performance was not distinguishable from young adults (Tukey post-hoc comparisons). The trend towards a similar reduction for perseverative errors just failed to reach significance, $F(3, 64) = 2.07$, $p = .07$ (difference scores between cued versus non-cued perseverative errors reduced from .07 for young adults to .16, .21 and .22 for 13–15-year-olds, 10–12-year-olds and 8–9-year-olds, respectively). However, the non-significant age-effect on reduction in perseverative errors following the presentation of a task cue may have resulted from insufficient power. When the two youngest age groups were taken together and compared with young adults, the age effect (cue–no cue) was now significant, $F(1, 47) = 7.09$, $p = .01$.

Separate planned between-age ANOVAs were performed for distraction and perseveration errors in non-cued and cued tasks separately. These comparisons revealed a significant age effect for distraction errors in the *non-cued* task, $F(3, 64) = 4.80$, $p < .05$, for which post-hoc Tukey comparisons revealed that distraction error scores differed between 8–9-year-olds and young adults, but failed to discriminate between 11–12-year-olds, 13–15-year-olds, and young adults. In the *cued* task, the age difference between distraction error scores was almost statistically significant, $F(3, 64) = 2.34$, $p = .08$. When age groups 8–9-year-olds and 11–12-year-olds were taken together and compared with the 13–15-year-olds and young adults, distraction errors discriminated between age groups significantly, $F(2, 68) = 3.53$, $p < .05$, and post-hoc Tukey comparisons confirmed that adult levels were not reached until 13–15 years.

Furthermore, in both the cued and non-cued tasks, number of perseverative errors were significantly affected by Age Group, $F(3, 64) = 2.74$, $p < .05$ (cued task), $F(3, 64) = 4.23$, $p < .05$ (non-cued). Tukey comparisons revealed that perseverative error scores of 8–9-year-olds exceeded those of young adults, but did not discriminate between 11–12-year-olds, 13–15-year-olds and young adults, for both the cued and the non-cued task.

## Discussion

This study examined to what extent developmental changes in set switching and set maintenance should be interpreted in terms of distinct developmental trajectories (Chelune & Baer, 1986), or reflect development of a single underlying cognitive process. This question was addressed by adopting two analytic procedures from the neuropsychological literature that allowed us to chart developmental patterns of failures-to-maintain-set versus failures-to-switch-set on a stimulus–response rule-switch task. Before turning to a discussion of the results that are most pertinent to this question, we first evaluate the current results relative to those of the WCST using the more conventional analyses of the WCST.

### *Conventional analyses*

The current rule-switch task differed from the original WCST in that only switching of rules was required, rather than switching focus to both rules and stimulus dimensions (i.e. extra-dimensional switches to a different stimulus dimension). The reason for this reduction in switch requirements was to provide a purer index of errors due to switching response mappings without the potential influence of distraction due to changes in stimulus dimension. Interestingly, the analysis of scores based on the traditional Heaton *et al.* (1993) scoring system yielded a pattern of findings that is largely comparable to age-related changes in WCST performance previously reported in the literature (Chelune & Baer, 1986; Paniak *et al.*, 1996; Rossellini & Ardila, 1993). Comparison of the mean differences revealed that young children performed more poorly than adults on all six Heaton *et al.* (1993) parameters. Several studies have reported that improvement in WCST performance, which occurs with increasing age, continues until children are around 10 years old (Chelune & Baer, 1986; Welsh *et al.*, 1991). The present results were consistent with those reports on almost all measures. Except for the number of categories-achieved and the percentage conceptual-level responses, performance of children older than 8–9 years paralleled adult levels of performance. Thus, for most WCST measures adult level was reached before the age of 11–12 years, suggesting accelerated maturation in middle childhood, but for some measures adult level was not reached until age 13–15 years, suggesting additional maturation during late childhood and adolescence (see also Anderson, Anderson, Northan, Jacobs & Catroppa, 2001; Welsh *et al.*, 1991).

A second difference with regard to the original WCST is that sorting rules were based on spatial locations, which required the integration of both information about the identity and the spatial location of the stimulus. Analyses of the rule-application blocks revealed that applying incompatible S–R mappings was more difficult than applying compatible mappings but this effect did not differ across age groups. A similar difference in difficulty of response rules is seen in the original WCST as individuals perform less accurately using 'number' than 'colour' rules (Heaton *et al.*, 1993). More important, there were no age differences in the ability to apply these separate stimulus–response mappings. This result is consistent with the literature showing that performance on spatial tasks has reached maturity relatively early in development (Passler, Isaac & Hynd, 1985; Welsh *et al.*, 1991; see also Van den Wildenberg & Van der Molen, 2003).

Taken together, the results summarized above suggest that the current rule-switch task yielded a pattern of findings that is similar to the results reported by previous studies using the original version of the WCST. The pattern of findings provides the context for a discussion of developmental changes in set maintenance and set switching on the present rule-switch task.

### *Failure to maintain set versus failure to switch set*

The primary goal of this study was to examine if effects of age on set switching and set maintenance capabilities reflect a unitary trend or separate developmental trajectories. This issue was addressed by using an error scoring method and context of interpretation reported by Barcelo and Knight (2002). The current results show error patterns that are, most likely, sensitive to three separate age trends. The first type of error is an efficient error that results from unsuccessful use of contextual information. The incidence of this error type did not differ across age groups, suggesting that children are already capable of utilizing contextual cues at the age of 8–9.

The second type of error refers to perseveration (similar to Heaton's perseverative errors). Similar to previous reports (Chelune & Thompson, 1987; Welsh *et al.*, 1991), perseverative errors decreased with age. As anticipated, this decrease was largest between ages 8–9 and 11–12 years. Although the steep decrease between ages 8–9 and 11–12 was observed for both the cued and the non-cued task, switch cues attenuated perseverative behaviour for the youngest age group. This latter result was unexpected, given that previous studies including prefrontal patients and elderly subjects showed that switch cues failed to attenuate perseverative behaviour (Nelson, 1976; Ridderinkhof *et al.*, 2002; Van Gorp *et al.*, 1997). The typical interpretation of these studies is that prefrontal patients and older subjects fail to switch responses while noticing the rule change. In contrast, perseverative behaviour in young children may be associated with children's failure to monitor performance feedback when switches are not explicitly cued (see also Crone, Jennings, van Beek & Van der Molen, 2003). It should be noted that different results may be obtained for younger children. For example, Zelazo *et al.* (1996) observed that perseverative behaviour of 3-year-olds was not attenuated by the presentation of explicit task cues. Thus, perseverative behaviour may be associated with different mechanisms dependent on age.

Finally, the third type of error refers to errors due to distraction (similar to Heaton's failure-to-maintain-set). These errors are presumed to reflect inability to maintain set across a sequence of trials. Errors of distraction were reduced by task cues for all age groups. The age reduction, however, was different for the cued and non-cued task. That is, although the ability to maintain set was sensitive to developmental change for both conditions, in the non-cued task, changes were most pronounced between ages 8–9 and 11–12, but for the cued task changes were most pronounced between ages 11–12 and 13–15.

The findings are largely consistent with those reported by Chelune and Baer (1986), pointing towards earlier maturation of rule switching than rule maintenance. That is, in the cued task, adult levels were reached earlier for perseveration errors than for distraction errors. For perseveration errors adult levels were reached by 11–12 years, but for distraction errors adult levels were not reached until 13–15 years. Thus, the difference between 8–9-year-olds and 11–12-year-olds was most obvious for perseverative errors in both the cued and the non-cued task whereas the difference between 11–12-year-olds and 13–15-year-olds appeared only for distraction errors. Together these results suggest that set maintenance and set switching reflect differential developmental trajectories.

Recent progress in the field of developmental neuroscience has implied that children gain control over their behaviour concurrent with prefrontal cortex maturation (Casey *et al.*, 2000; Posner & DiGirolamo, 2000). Importantly, subdivisions of the prefrontal cortex may have different functions, although the distinctions are not yet fully understood. That is, the ability to maintain a rule on-line and inhibit interference has been associated with activity in both the dorsal and ventral lateral prefrontal cortex (Bunge, Kahn, Wallis, Miller & Wagner, 2003; Miller & Cohen, 2001), whereas the ability to perform a task switch is specifically associated with the dorsal lateral prefrontal cortex (Dreher & Berman, 2002; Sylvester, Wager, Lacey, Hernandez, Nichols, Smith & Jonides, 2003). Monchi, Petrides, Petre, Worsley and Dagher (2001) implicated involvement of dorsolateral and ventrolateral prefrontal cortex during different stages of the WCST; dorsolateral prefrontal cortex being involved when information had to be updated, and ventrolateral prefrontal cortex being involved when subjects received negative feedback, indicating a mental shift. Thus, although the specific neural circuits underlying set maintenance and set switching are not yet fully understood, developmental trajectories for rule maintenance and rule switching may be associated with maturation of different subregions of the prefrontal cortex.

From a theoretical perspective, set maintenance and set switching have previously been interpreted in terms of activity of the contention scheduling system and the supervisory attentional system, respectively, on the basis of the Norman-Shallice model (Norman & Shallice, 1986; Shallice & Burgess, 1993; see also Somsen, Van der Molen, Jennings & Van Beek, 2000; Van der Molen, 2001). Contention scheduling involves routine selection between potentially demanding competing schemas, which are themselves well learned, and can be related to set maintenance. Coping with novelty, as demanded during set switching, involves a separate mechanism – the supervisory attentional system – that modulates the operation of contention scheduling by providing additional activation or inhibition of schemas competing in the lower-level mechanism. The present observation that young children made more distraction as well as perseverative errors in the non-cued WCST suggests that contention scheduling as well as the supervisory system become more efficient with age. The additional cues that were presented in the cued spatial rule-shift task most likely aided the contention scheduling system, because interference of competing schemas was reduced, helping subjects to keep track of the to-be-applied schema. Likewise, the additional cues alerted the supervisory system of novelty, resulting in a general decrease in number of perseveration errors. Thus, the additional cues may have aided both the supervisory and the contention scheduling system, and therefore served to reduce age-related differences in distraction errors and perseverative behaviour (Norman & Shallice, 1986). It should be noted that perseverative errors were already fairly low at the youngest ages in this study. Reduction in perseverative errors has been found to be particularly accelerated during early and middle childhood (e.g. Zelazo *et al.*, 1996).

## Concluding comments

In conclusion, this study reported a WCST analogue task in which we replicated the general two-factor structure of the original WCST that has been reported in several previous papers. This structure separates (1) set-switching processes and (2) set maintenance. Further, using a recent error-scoring method, this study has demonstrated that these dissociable processes are independently sensitive to development. The error pattern of young children was very similar to errors typically made by prefrontal patients (Barcelo & Knight, 2002), suggesting an important functional relation between switching and maintaining set and prefrontal maturation (Stuss, 1992; Van der Molen, 2001). The development of these separate functions may be associated with maturation of different areas of the prefrontal cortex. The current results also have important implications for clinical groups that have been associated with impairment in set-switching ability, such as children with Attention-Deficit-Hyperactivity-Disorder (e.g. Cepeda, Cepeda & Kramer, 2000; Seidman, Biederman, Faraone, Wever & Ouelette, 1997). Examining distraction versus perseverative errors in these groups may clarify how these separate factors can assist in the diagnosis of various forms of developmental neuropathology.

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