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# Age Related Changes in Executive Control

Models, Methods and Developmental Trends



*Mark M. Span*

1. Executieve functies zijn gevoeliger voor veroudering dan perceptuele en motorische functies (this thesis).
2. Aging is not reversed development (this thesis).
3. Het taakswitch paradigma kan worden gebruikt als een maat voor flexibiliteit en inhibitie, en daarmee als een experimenteel gecontroleerde versie van de WCST (this thesis).
4. Het patroon dat ouderen vaak trager zijn *en* minder fouten maken dan jongeren kan worden doorbroken door taken te construeren waarin fouten niet te vermijden zijn (this thesis).
5. De rol van dopamine in het inhibatoire systeem zou een verklaring kunnen zijn voor de verschillen in leeftijdsgerelateerde effecten op executieve controletaken tussen kinderen en ouderen.
6. Gezien de effecten van veroudering op complexe cognitieve vaardigheden zouden ouderen nog slechts eenvoudig, repetitief werk mogen doen (en ze zouden zeker geen auto meer moeten besturen).
7. Psychology will never become exact science as long as figures and tables in manuscripts are inserted 'about here'.
8. Promotoren komen van Mars, Promovendi komen van Venus (this thesis).

The research presented in this thesis was supported by grant no. 575-25-005 from the Netherlands Organization for Scientific Research (NWO).

Printed by Print Partners Ipkamp, Enschede, The Netherlands  
Layout Mark M. Span  
Typesetting L<sup>A</sup>T<sub>E</sub>X  
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# **Age Related Changes in Executive Control**

**Models, Methods and Developmental Trends**

## **ACADEMISCH PROEFSCHRIFT**

ter verkrijging van de graad van doctor  
aan de Universiteit van Amsterdam  
op gezag van de Rector Magnificus

Prof. mr P.F. van der Heijden

ten overstaan van een door het college voor promoties ingestelde  
commissie, in het openbaar te verdedigen in de Aula der Universiteit  
op woensdag 22 mei 2002, te 12:00 uur

door

**Marcus Martinus Span**

geboren te Utrecht

**Promotiecommissie:**

Promotor: Prof. dr M.W. van der Molen

Co-promotor: Dr K.R. Ridderinkhof

Overige Leden: Prof. dr P.C.M. Molenaar  
Prof. dr A. Kok  
Prof. dr R. de Jong  
Dr H.L.J. van der Maas  
Dr U. Mayr

Faculteit: Maatschappij en Gedragswetenschappen  
Afdeling Psychologie  
Programmagroep Ontwikkelingspsychologie

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# GENERAL INTRODUCTION

One of the easiest replicable response time (RT) effects is that speed of responding increases during childhood, which reaches a peak in young adulthood, and gradually decreases in later adulthood. This consistent pattern is observed for a variety of RT tasks, ranging from the easiest two-choice RT tasks to tasks that require complicated mental acts, such as mental rotation. This pattern implies that one global mechanism underlies all age related changes, and that there are no subprocesses (cf. stages) in information processing that deviate from the generalized change in speed by developing faster or slower than others. Kail and Salthouse (1994) proposed a clock-speed metaphor, as a model of a global mechanism that changes with age, and that affects the speed of all subprocesses to the same extent. As the clock speed varies with age, the duration of task performance becomes shorter or longer. However, the relative speed differences between age groups remain the same, because the same subprocesses underlie the performance of all groups.

## 1.1 Age-Related Changes In The Efficiency Of Cognitive Processes

This view on cognitive development and aging is contrasted by the specific loss hypothesis. In the past two decades, evidence has accumulated to suggest a selective, age-related change of performance on neuropsychological measures diagnostic of frontal lobe dysfunction (e.g., Rosselli and Ardila, 1993; West, 1996; Zelazo et al., 1996). These findings have, in turn, given rise to a renewed interest in the origin of age-related changes in the efficiency of cognitive processes. The global speed hypothesis and the specific loss hypothesis are the dominant theoretical frameworks in the recent literature on cognitive development and aging. The main prediction of the global speed hypothesis is that a global speed factor accounts for all age-related variance in the efficiency of processing in a wide array of cognitive tasks. The specific loss hypothesis predicts multiple factors, related to brain development and aging, to account for age-related variance in the efficiency of cognition. Both the global speed hypothesis and the specific loss hypothesis are described in more detail below.

**The Global Speed Hypothesis** ■ The global speed hypothesis does not focus on the neural underpinnings of cognitive development and aging. Age-related changes in information-processing speed at both ends of the life span are considered to be global and generalized, in the sense that these changes are manifest to the same proportional extent in a wide array of cognitive operations. It has been observed that performance in many different speeded and non-speeded tasks is affected by age to the same proportional degree, irrespective of the nature and extent of processing required for successful task performance (Cerella, 1990; Hale, 1990; Kail and Salthouse, 1994; Myerson et al., 1990; Salthouse, 1996b; Salthouse et al., 1998a); for a review see, e.g., Bashore and Smulders (1995). The global speed hypothesis has been shown to hold in a variety of empirical and meta-analytical studies. Salthouse (2000) provides a review of recent ideas and procedures to partition age-related variance between tasks. Salthouse emphasizes the large number of variables that appear to be related to age, and suggests that these relations could be *shared* relations. Analyzing two major datasets, Salthouse concludes that 'relatively little of the effects on individual speed variables are independent of the effects on other speed variables' (Salthouse, 2000, page 48). He goes on to stress the importance of a biological plausible model of the origins of age-related speed changes.

**The Specific Loss Hypothesis** ■ Within the specific loss framework, it is assumed that age-related differences in the speed of information processing are related to age-related structural and functional changes in the brain. The specific loss hypothesis predicts that age-related changes in tasks involving executive control, supported in large measure by the frontal lobes, should be more pronounced than age differences in tasks with lesser executive control demands. Proponents of the specific loss (or neurocognitive change) hypothesis (e.g., Ardila and Rosselli, 1989; Dempster, 1992, 1993; Dempster and Brainerd, 1995; Diamond, 1990; Pennington, 1994; Stuss, 1992; Welsh et al., 1991; West, 1996; Whelihan and Lesher, 1985) have proposed that age related changes in cognitive function can be attributed to age-related changes in brain structure and function.

## 1.2 Life-Span Development Of Executive Functions

**Executive Functions** ■ Executive functions are those functions that are responsible for the organization and management of more specialized cognitive processes. These functions are involved in error monitoring, interference control, task-set reconfiguration and context updating (e.g., Meyer and Kieras, 1997; Norman and Shallice, 1986; Shallice, 1994). Executive functions, or cognitive control functions refer to the ability of the cognitive system to monitor the environment and modify behavior accordingly. Executive control functions are defined operationally and should not necessarily be considered as basic mental functions, supported by specific, dedicated neural circuits in the brain. Executive functions can be conceived of as emergent features of a cognitive system, being established by interactions between existing subordinate processes in a way that generates 'executive' cognitive properties (Nieuwenhuis, 2001). For instance, interference control might be implemented

using mechanisms of selective attention, combined with the active maintenance of memory representations (Braver et al., *in press*), and endogenous task-set reconfiguration might be an emergent property of instruction-driven activation and automatic decay of task sets in working memory (Altmann and Gray, *in press*).

The existence of control processes that are distinguishable from lower level cognitive processes is inferred from neurocognitive studies focusing on the pathological failures of control in frontal lobe injured patients. Patients suffering from lesions in the frontal part of the brain often lack the ability to prevent inappropriate actions, particularly when the task requires the suppression of an overlearned, habitual response. In the Wisconsin Card Sorting Test, once frontally impaired subjects have classified cards according to one stimulus dimension (e.g., color) for a while, they experience difficulty in shifting to another sorting principle (e.g., classifying the same cards according to shape, see Milner, 1963). Other behavioral deficits that are typical of frontal lobe patients, besides the tendency to persevere, are: Failure to voluntary initiate an appropriate action, distractibility, an impairment of the control of attention, and failure to engage in specific action, despite of repeated verbal and nonverbal acknowledgement of the intention to act (see also Monsell, 1996). These behavioral deficits indicate that frontal lesions result in selective impairments in organization and monitoring of an array of different cognitive skills, rather than impairments in a specific cognitive domain (Duncan, 1986).

**Brain Structures Mediating Executive Functions** ■ Extending the literature on clinical neuropsychology, neuroimaging experiments have localized several cortical areas that mediate different executive control functions. Many investigators reported that a lesion in frontal cortex severely impairs a patient's performance in tasks that require complex cognitive processing and response inhibition (e.g., Duncan et al., 1995). Further, activation in the prefrontal region has been observed in experiments that require attention switching between two tasks, or response inhibition (e.g., d'Esposito et al., 1995). In an experiment designed to study supervisory attention, Badgaiyan and Posner (1998) observed activation of both prefrontal and cingulate cortex. Prefrontal activation appeared about 200 ms after stimulus presentation, whereas the cingulate cortex was not active until 300 ms after stimulus presentation. Since the tasks included in the experiment were known to involve executive control, it appears that both prefrontal and cingulate cortices are essential components of the system. Moreover, because the cingulate was active 100 ms after prefrontal cortex, it is probably dependent on the input from other frontal areas. It has been observed that the prefrontal cortex has regional specificity for different types of stimuli. Experiments suggest that the tasks involving storage of spatial information activate prefrontal cells in the dorsolateral part, whereas those involving object storage (e.g., face recognition) activate cells located more ventrally in the prefrontal cortex of the monkey brain (Goldman-Rakic, 1996). Imaging studies have reported this regional specificity in human subjects (e.g., Owen et al., 1996). These studies indicate that prefrontal activation is domain specific; the ventrolateral area mediates object-specific information, whereas dorsal areas support spatial information (Goldman-Rakic, 1996; Smith and Jonides, 1999; Ungerleider and Miskin,

1982). There is, however, an alternative view that suggests that prefrontal areas are organized according to processing specificity (Petrides, 1994). This view holds that ventrolateral prefrontal regions are concerned with the organization of sequences of behavioral responses and dorsolateral regions are recruited only when the task requires active manipulation and monitoring of information.

### **1.2.1 Neurocognitive Development And Aging**

During the development of the brain, some areas mature faster than others. The prefrontal cortex is one of the areas that matures the slowest. The myelinization in this area, which supports the speed of information transmission, continues until adolescence. Three important functions are ascribed to the prefrontal cortex. First of all, the prefrontal cortex provides a representation of the strategies and input to a task in working memory. But in order to keep up the efficiency of the working memory, two other functions are required. Relevant information needs to be recruited as part of the preparatory set, and irrelevant information needs to be removed or suppressed in order to prevent interference.

The idea that cognitive control affects the speed on a variety of tasks is consistent with neuropsychological insights (e.g., Fuster, 1997; Roberts and Pennington, 1996; Welsh and Pennington, 1988). Roberts and Pennington (1996) identify several tasks that are particularly relevant for the study of inhibition and prefrontal functioning. The Stroop task, the Go/No-Go task, the WCST, the antisaccade task and the AB task are all suggested to imply inhibitory function and are all shown to be especially vulnerable to cognitive development and aging. Bjorklund and Kipp-Harnishfeger (1990) reviewed research results from cognitive development and integrated them in a larger theory about the efficiency of inhibition. They argued that the age-related changes in the efficiency of inhibition are responsible for findings concerning attentional deficiencies, because inhibition serves to keep task-irrelevant information out of the working memory. Dempster (1992) showed that there is a large similarity between children and patients with frontal-lobe lesions in the pattern of performance deficits on interference-sensitive tasks. He combined information about frontal-lobe functions with the view on resistance to interference, and argued that this synthesis is "a step toward a unitary theoretical explanation of diverse expressions of cognitive development and aging"(p. 65). Two neurobiologically oriented theories that focus on specificity of age-related changes in cognitive abilities and appear to be successful in accounting for the age trends, the frontal-lobe hypothesis and the dopamine hypothesis, deserve explicit consideration.

### 1.2.2 The Frontal Lobe Hypothesis

The frontal lobe hypothesis entails that frontal (specifically prefrontal, and more specifically dorsolateral prefrontal) brain structures and the cognitive functions that rely on these parts of the brain are most susceptible to effects of age on the speed of information processing on both ends of the life span. This *frontal lobe hypothesis* has given rise to a series of research efforts, which have indicated that frontally-supported executive control functions are more sensitive to age-related speed changes than functions supported by other parts of the brain. For instance, in the area of cognitive aging, the inhibition deficit hypothesis as proposed by Hasher and Zacks (1988) suggest that age-related impairments result from a weakening of inhibitory processes in working memory. The major premise of this work is that age-related differences in a variety of cognitive domains can be attributed to ontogenetic differences in the efficiency of inhibitory processes that are supported by the frontal cortex (e.g., Dempster, 1991; Harnishfeger and Bjorklund, 1993; West, 1996).

One of the assumptions of the frontal lobe hypothesis is that developmental differences in the ability to resist interference depend on the efficiency of the frontal lobes of the brain. Recent research suggests that the frontal lobes play an important role in the ability to effectively inhibit or suppress interference from stimuli and associations that are not relevant to the task at hand (Fuster, 1997). In addition, the frontal lobes are also the last region of the brain to develop and the first to show signs of deterioration in later life. The ‘frontal lobe model’ (Kramer et al., 1994; West, 1996) assumes that resistance to interference is a fundamental feature of the cognitive system (i.e., a psychological primitive) that cannot be explained in terms of other cognitive processes. West (1996) extended the frontal lobe hypothesis beyond the earlier work on inhibitory control to include memory processes supported by the prefrontal cortex. West proposes a synthesized model that includes four separable components of prefrontal functioning: prospective memory, retrospective memory, interference control and the inhibition of prepotent responses.

Several caveats are in order, however. First, a more sophisticated and differentiated picture of age-related change in frontal-lobe structure and function is beginning to emerge in the literature (for a review see Band et al., in press; Greenwood, 2000). Neuronal loss differs between regions within frontal cortex (with more modest change in, e.g., supplementary motor area, premotor area, Broca’s area, and primary motor cortex), between subregions within dorsolateral prefrontal cortex, and even between cortex layers within the same subregions (e.g., Uylings and de Brabander, in press). Second, age-related neurobiological changes should be considered in relation to corresponding age-related cognitive decline. Some cognitive control functions are more susceptible to the effects of aging than others (e.g., Ridderinkhof et al., in press); for instance, control functions thought to rely on orbitofrontal cortex show no marked changes with age even though this brain area is subject to considerable neurobiological deterioration (Phillips and Della Sala, 1998). Some neuroimaging evidence indicates that age-related reductions in frontal-lobe activation are equally (or even less) frequent or severe than age-related reductions in activation elsewhere in the brain (for review see Grady, 2000). These age-related increases in frontal activation

in some (mostly working-memory) tasks have been attributed to increased recruitment of executive control functions to compensate for an age-related loss of efficiency of other cognitive functions (such as memory storage; see, e.g., Reuter-Lorenz et al., 2001). Third, as argued by Rabbitt and colleagues (e.g., Rabbitt et al., 2001), a variety of methodological problems may have contributed to questionable support for the frontal-lobe hypothesis. Construct and discriminant validity of many of so-called frontal tasks is unclear (e.g., Rabbitt et al., 1997) and frontal tests are often not strongly correlated (Burgess and Shallice, 1997), thus casting some doubt on the general validity of the frontal-lobe hypothesis of cognitive development and aging.

**The Dopamine Model Of Cognitive Aging ■** Neurobiological changes with age include changes in a variety of neurotransmitter systems, including cholinergic, serotonergic, and most prominently dopaminergic systems. Bäckman et al. (2000) reported that statistical control of age-related deterioration of striatal dopaminergic receptor binding eliminated the age-related variation in performance of a number of cognitive tasks. This suggests that dopaminergic transmission is an important neuromodulatory factor in age-related cognitive decline. Age-related decreases in neurotransmitter concentration are evident in dopamine levels in the prefrontal cortex (e.g., Goldman-Rakic and Brown, 1981; Kaasinen et al., 2000). Thus, the age-related decline in cognitive control functions associated with prefrontal cortex may be mediated (at least in part) by reduced proficiency of dopaminergic projections to prefrontal cortex (or to brain areas that are heavily interconnected with prefrontal cortex). Li and Lindenberger (1999) have reported results of computational simulations that relate age-related deterioration of catecholaminergic systems (among which dopamine) to several benchmark phenomena of aging, such as increases in mean response time and interindividual variability of response times. The cognitive control processes of updating and active maintenance of context information are driven largely by dopaminergic reinforcement-learning signals (e.g., Braver and Cohen, 2000). Braver et al. (in press) reported that performance in older adults was impaired specifically in measures that capitalized on such context updating processes. Holroyd and Coles (2001) developed a neurobiologically based mathematical model of reinforcement learning. This model includes a parameter reflecting the strength of the dopaminergic reinforcement learning signal, which is used to select and reinforce adaptive behaviors. Nieuwenhuis et al. (2001) observed an age-related deficiency in reinforcement-learning rate, and showed that this deficiency could be modelled only by manipulation of the dopamine parameter. Given the role of dopamine and catecholamine in the frontal cortex, this model could provide an important guide at the biological level for cognitive development across the lifespan.

Although neurobiological change in some frontal areas, particularly dorsolateral prefrontal cortex, clearly plays a crucial role in task performance of older adults, the frontal-lobe hypothesis is at least in need of refinement, as all is not lost in the frontal cortex, and all is not lost in cognitive control (Band et al., in press). The dopamine hypothesis may provide complementary insights, contributing specificity to our understanding of the relation between age-related changes in cognitive control and underlying neurobiological factors.

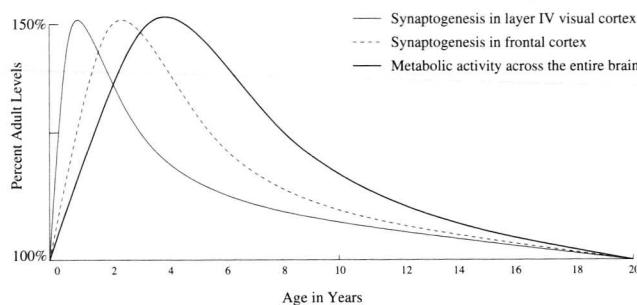


Figure 1.1: Relationship between age and various aspects of brain development (synaptogenesis in layer IV visual cortex and in frontal cortex, and metabolic activity across the entire brain). From Bates et al. (1992).

### 1.2.3 Brain Development

The age-related changes in the efficiency of cognitive operations are expressed in terms of inhibitory functioning. A strong version of this hypothesis would imply that the same brain structures and cognitive processes are involved in the increased efficiency during development, and the decreased efficiency during senescence. This 'strong frontal lobe hypothesis' therefore predicts structural and functional changes in the brain during senescence to mirror the changes during development. Studies of structural, chemical and physiological development of the human brain show a protracted and variable maturational time course, including both progressive and regressive events. The development of the brain spans at least 10–15 years (Chugani and Phelps, 1986; Conel, 1939; Huttenlocher, 1990). After the developmental stage of brain maturation, effects of aging on the brain become apparent. In the following paragraphs, a synopsis is given of effects of development and aging on structural and functional properties of the human brain. For a more elaborate review on the growing and aging brain the reader is referred to e.g., Dawson and Fischer (1994); Johnson (1997); van der Molen and Ridderinkhof (1998b); West (1996).

**Brain Mechanics** ■ Knowledge of postnatal maturation of the human brain is confounded by several issues (Stuss and Benson, 1986). These issues are related to the specific nature of the sample, and to techniques used in the quantification of changes in the brain (Uylings and de Brabander, in press). Nevertheless, some consistent findings also emerge from the literature. It is generally believed that there is a hierarchical pattern of cortical development and aging. In this view brain development completes gradually from primary motor and sensory areas to adjacent secondary areas to associative regions (including prefrontal). An example of this pattern is given in Figure 1.1

The gross anatomy of the brain is intact at birth, with identifiable major cortical gyri. The laminar structure of even the prefrontal cortex is virtually complete, and connective apparatus are largely present in the newborn infant. In contrast, tertiary sulcation appears to be sharpening throughout the full life-span. Studies reporting the degree of myelination indicate that the prefrontal cortex is among the last to develop (Yakolev, 1962). The supra-

limbic zones, which comprise the frontal, parietal, and temporal associative areas, display slow but progressive myelination during early and middle development. In contrast, the production of synapses seems to be equivalent in all areas of the cortex (Rakic et al., 1986), although Bates et al. (1992) do show evidence for differentiation for synaptogenesis (see Figure 1.1). Changes found in the aging brain are characterized by degeneration and a loss of neurons and dendritic mass, neurotransmitter function (e.g., dopamine depletion), loss of myelin (white matter), and changes in metabolic state and bloodflow (e.g., Kline and Scialfa, 1996; Scheibel, 1996). In general, the aging brain decreases in size and weight. Although this shrinkage is mainly due to loss of water, beyond the age of 75 other factors, including loss of grey matter are also involved. Possible causes for the decline in processing speed and cognitive functioning are the loss of dendritic mass in posterior and frontal areas of the brain (e.g., Bashore, 1993; Haug et al., 1983; Scheibel, 1982; Scheibel and Scheibel, 1975), reduction of the cerebral blood flow to the anterior cortex (e.g., Gur et al., 1987; Shaw et al., 1984) and decline of neurotransmitter production such as dopamine (Arnsten et al., 1994).

**Electroencephalography** ■ The hierarchical nature of development of cortical areas in the brain is also suggested by the results from electroencephalography measurements (EEG) (Thatcher, 1994). Electroencephalography entails the measurement of electrical activity of the brain off sensors attached to the scalp. An elaborate analysis of developmental changes in EEG has been performed by Thatcher (1994). Thatcher focused on coherence of activity between sensors (scalp locations). He observed a marked difference of coherence between hemispheres. Coherence in the EEG is an index of the functional coupling of sources of activity in the brain. Developmental changes in the left hemisphere involved a progressive lengthening of intercortical connections between sensory areas and frontal regions. In the right hemisphere, developmental change mainly involves a contraction of long-distance frontal connection to shorter sensory connections. These developmental changes appeared at the ages of 6–10 years, and coincide with transitions in behaviour as described by neo-Piagetian theories on cognitive development. The literature on EEG changes during senescence has been reviewed by Dustman et al. (1993). Dustman et al. found that EEG activity was more coherent in older adults compared to young adults. These findings led Dustman et al. to believe that a functional breakdown of the autonomy of specific cortical areas occurred in older adults. The aging brain seems to respond in a more homogeneous and global fashion. They propose that this decreased heterogeneity is due to an age-related loss of inhibitory function.

**Event Related Potentials** ■ Using averaging techniques EEG activity can be synchronized with stimulus presentation or responses, resulting in Event Related Potentials (ERP). ERP's reflect the brains electrical response to the event to which the EEG is synchronized. Several ERP studies show evidence of hierarchical development and aging of the underlying brain structures (For a review see e.g., McDowd and Shaw, 1999; Ridderinkhof and van der Stelt, 2000).

An example of a study on age-related differences in cortical activity employing ERP's is Fabiani et al. (1998). Using the relatively simple oddball paradigm, Fabiani et al. provides evidence for diminished frontal lobe function in normal aging. The presentation of an unsuspected, deviant stimulus in a series of predictable stimuli (i.e., in the oddball paradigm), elicits a complex ERP waveform characterized by a large positivity peaking over the parietal cortex with a latency of approximately 300 ms (P3 component) in adult subjects. The P3 component of the ERP elicited by target events becomes more frontally oriented in elderly subjects. This finding may index less efficient frontal lobe function in the elderly. On the basis of individual differences in the distribution of the P3 component elicited by target stimuli in an oddball paradigm the old subjects were divided into two groups. Those elderly subjects who showed frontal-maximal P3 scalp distributions had lower performance on standardized neuropsychological tests of frontal lobe function than those elderly subjects who showed posterior-maximal scalp topographies. This study is an example of studies showing differential age-related changes in the brain's cortical activity that can be linked to performance. For an overview of paradigms used in ERP research on the aging brain see e.g., Kok (1997, 1999); Kok and Zeef (1991).

An example of the use of ERP in the study of age-related differences in development can be found in Johnstone et al. (1996), who found a decrease with age in the brains cortical response (the N2 component, a negative peak with a latency of approximately 200ms) and behavioral indicators (decrease in reaction time and errors to irrelevant stimuli) of discrimination processing of task irrelevant stimuli in subjects aged 8-18 years. The P2 component (a positive peak with a latency of approximately 200ms) of the ERP and behavioral indicators of response inhibition showed a similar systematic increase with age from childhood through adolescence. Courchesne (1990) showed that visual and auditory P3s mature at different rates: The amplitude of the visual P3 increases sharply between three and four years of age followed by a gradual decrease in amplitude, duration and latency throughout childhood reaching mature values not until young adulthood. The auditory P3 follows a somewhat different trajectory. These data show that auditory P3 latencies drop by 130 ms to their adult values around the age of 12. Johnson Jr (1989) reported a similar pattern of results. Visual P3 latency undergoes a gradual and modest change compared with the larger and more abrupt change in auditory P3 latency.

**PET Studies** ■ PET (positron emission tomography) is a brain imaging technique that uses a radioactive tracer to show chemical activity of the brain. The PET scanner pinpoints the destination of radioactively tagged glucose (or oxygen) to reveal the parts of the brain involved in performing an experimental task. During early development, the ontogeny of glucose metabolic patterns is shown to proceed in phylogenetic order, with functional maturation of older anatomical structures preceding that of newer areas (Chugani and Phelps, 1986; Chugani et al., 1987). Increases in cerebral blood flow are reported as early as three months of life for parietal, temporal, and primary visual cortices, basal ganglia and cerebellar hemispheres. Glucose metabolic activity in the dorsolateral occipital cortex remains relatively low during this period. This observation is consistent with anatomical studies showing later maturation of these regions compared to calcarine cortex (Rabinowicz, 1979). Even during these early developmental stages, the frontal cortex is the last brain region to undergo a maturational rise in glucose metabolic activity. The lateral portion of the frontal cortex starts to gain activity at about 6–8 months of age, and the dorsal parts follow after 8–12 months. This functional maturation is synchronized with the appearance of higher cognitive abilities (Chugani, 1994).

The most consistent finding in normal aging is a marked decrease in cortical metabolism, particularly in the frontal lobes (Loessner et al., 1995; Moeller et al., 1996). Usually, global cortical cerebral metabolic rate of glucose shows a significant decline with age (approximately 6% per decade), with exception of most of the occipital cortex and part of the cerebellum. The most significant effects are found in the association neocortex in perisylvian temporo-parietal and anterior temporal areas, the insula, the inferior and posterior-lateral frontal regions, the anterior cingulate cortex, the head of caudate nucleus, and the anterior thalamus, in a bilateral and essentially symmetrical fashion (Petit-Taboué et al., 1998).

**Magnetic Resonance Imaging** ■ Magnetic resonance imaging (MRI) is an imaging technique used primarily in medical settings to produce high quality images of the structure of the brain. MRI is based on the principles of nuclear magnetic resonance, a spectroscopic technique used to obtain microscopic chemical and physical information about molecules. Using MRI, Raz et al. (1997) found the most substantial age-related decline in the volume of the prefrontal gray matter. No significant age-related differences were observed in the parahippocampal and anterior cingulate gyri, inferior parietal lobe, pericalcarine gray matter, the precentral gray and white matter, postcentral white matter and inferior parietal white matter. Consistent righthand asymmetry was found in the whole cerebral hemispheres, superior parietal, fusiform and orbitofrontal cortices, postcentral and prefrontal white matter. The left side was physically larger than the right in the dorsolateral prefrontal, parahippocampal, inferior parietal and pericalcarine cortices, and in the parietal white matter. However, Raz et al. reported no significant differences in age trends between hemispheres.

Functional magnetic resonance imaging (fMRI) is used to visualize brain function, by visualizing changes in chemical composition of brain areas or changes in the flow of fluids that occur over time spans of seconds to minutes. In the brain, blood perfusion is presumably related to neural activity, so fMRI, like other imaging techniques such as positron emission

tomography, can be used to find out what regions of the brain are activated when subjects perform specific tasks or are exposed to specific stimuli. However, fMRI has a better temporal and spatial resolution than PET. Cabeza (2001) reviewed functional neuroimaging studies of cognitive aging in the domains of visual perception, episodic memory encoding and semantic memory retrieval, episodic memory retrieval, implicit memory, and working memory. He reported that the most consistent finding of these studies was that brain activity tends to be less lateralized in older adults than in younger adults. Casey et al. (2000) report on a number of normative pediatric fMRI studies examining prefrontal cortical activity in children during memory and attention tasks. These studies, while largely limited to the domain of prefrontal functioning and its development, are shown to support the theory of hierarchical and continued development of attention and memory throughout childhood and adolescence. Specifically, the magnitude of activity observed in the prefrontal cortex was greater and more diffuse in children than in adults.

**Summary ■** In general, the results of neurobiological and physiological studies on the effects of development and aging on the brain provide a coherent picture. The hierarchical view on development is supported by physiological studies on brain tissue, neurotransmitter function, electroencephalic measurements, functional and structural MRI and PET studies. Frontal areas of the brain are last to develop and are most vulnerable to effects of aging.

#### 1.2.4 Age-Related Changes In The Efficiency Of Executive Functions

Paradigms for investigating executive control, or frontal lobe functioning typically involve a set-shifting component. Using confirmatory factor analysis Miyake et al. (2000) established the separability of the executive functions 'mental set shifting', 'inhibition of prepotent responses' and 'information updating' in several frontal lobe tasks, including the Wisconsin Card Sorting Test (WCST), random number generation and the 'Tower of Hanoi'. Mental set shifting was found to be the underlying factor for WCST performance. Omori et al. (1999) observed activation patterns in the prefrontal cortex during a set shifting task that were similar to those observed during the performance of the WCST. They concluded that the dorsolateral prefrontal cortex including the middle and inferior frontal gyri are involved in attentional set-shifting of both perceptual and non-perceptual characteristics.

Performance in the WCST and similar tasks has been observed to change with age (cf. Heaton et al., 1993). In particular, the tendency to persevere in no-longer-correct sorting rules decreases as children grow older (e.g., Chelune and Baer, 1986; Zelazo et al., 1996), and increases during the later stages of life. Older adults display more perseverative behavior in the WCST than young adults (e.g., Arbuckle and Gold, 1993; Dywan et al., 1992; Fristoe et al., 1997; Kramer et al., 1994; Loranger and Misiak, 1960; Raz, 2000; Salthouse et al., 1996). The age-related changes in performance observed in these tasks resemble the corresponding deficits seen in frontally impaired patients (for reviews see Raz, 2000; van der Molen and Ridderinkhof, 1998b). Nagahama et al. (1997) used the WCST in a PET study and observed that, compared to a task that featured the same stimuli but that did not involve rule-induction and set-shifting abilities, WCST performance yielded

the most significant activation in dorsolateral prefrontal cortex. In older adults activation in the prefrontal areas was reduced, suggesting a relation between reduced rule-induction and set-shifting capabilities and reduced prefrontal activation in aging. A further PET study indicated that the dorsolateral prefrontal activation occurred during set shifting even when rule-induction requirements were lifted (Nagahama et al., 1998).

Keys and White (2000) examined the relationship between age, executive abilities, and basic motor speed in an aging population. Using tasks that measured two aspects of executive ability (set formation and set shifting), they found that poorer executive performance was associated with increasing age. Age accounted for a unique and significant proportion of variance in executive performance after controlling for psychomotor speed. These results suggest that age has an effect on executive abilities that cannot be explained solely in terms of general slowing.

**Task-Shifting** ■ Age-related performance differences in task shifting have been studied extensively in the aging population. Age-related differences in the speed of information processing have been found in situations where on-line selection among competing sets is required (e.g., Mayr et al., 1996). The general finding that the adverse effects of the requirement to shift between tasks increase with age, combined with the evidence from neurocognitive studies that aging affects specifically those brain areas that are involved in cognitive control processes, has inspired a number of new studies of the effects of age on shift costs (e.g., Duncan et al., 1996; Hartley et al., 1990; Kramer et al., 1999; Kray and Lindenberger, 2000; Mayr and Kliegl, 2000; Salthouse et al., 1998a; van Asselen and Ridderinkhof, 2000). All studies replicate the basic finding (Botwinick et al., 1958b; Brinley, 1965) that shift costs increase with age.

Given that the brain structures involved in adaptive control processes are especially sensitive to the effects of aging, we may ask whether shift-cost patterns for different set-shifting components differ between young and older adults. Only recently, results are starting to appear on lifespan trends (Cepeda et al., 2001) in task-shifting performance. Cepeda et al. studied changes in preparatory and interference processes which underlie switching between different tasks. Their study provides evidence of a differential time course for the development of active preparatory processes and inhibition, with preparatory processes becoming efficient during early development.

The recent interest in inhibitory ability has inspired two major models of cognitive development. Bjorklund and Kipp-Harnishfeger (1990) derived a model of inefficient inhibition based on the cognitive aging literature (Hasher and Zacks, 1988) that is basically an extension of the mental capacity notion. Hasher and Zacks proposed a model of cognition that includes at least three main functions for an inhibitory mechanism: inhibition determines which activated representations gain access to working memory, inhibition suppresses no longer relevant representation from working memory, and inhibition prevents prepotent or recently rejected candidates for response from gaining control before weaker representations are considered. Dempster (1992, 1993) proposed another framework in which the susceptibility to interference is a key factor. He adopted a neuropsychological

perspective based on the assumption that developmental change in the ability to resist distraction is related to the maturation of the frontal lobes. Both models will be described in more detail below (see also van der Molen, 2000).

**Inefficient Inhibition** ■ Bjorklund and Kipp-Harnishfeger (1990) hypothesized that inhibitory processes become more efficient during development. This increased efficiency results in less irrelevant information entering working memory and, thus, increasing its functional capacity. They conceptualized processing efficiency in terms of activation speed and inhibition in terms of a process that counteracts the spread of activation (see also Kipp-Harnishfeger, 1995). Following Case (1985), they proposed that developmental changes in cognitive processing are linked to the maturation of the nervous system; most notably, the formation of myelin.

Harnishfeger and Bjorklund (1993) pointed out that the results from a variety of experimental paradigms are consistent with their notion of age-related differences in inhibition efficiency. The evidence included findings from selective attention tasks (McDowd and Birren, 1990; Sugar and McDowd, 1992; Tipper et al., 1989), memory tasks (Bjorklund and Kipp-Harnishfeger, 1990; Craik and Salthouse, 1992), tasks requiring the ability to inhibit motor responses, including the stop-signal task (Logan and Cowan, 1984) and the Piagetian A-B task (Diamond, 1985), and procedures for assessing verbal self-regulation (Luria, 1961).

**Susceptibility To Interference** ■ Dempster (1992, 1993) presented a theoretical framework that is basically a synthesis of developmental research (suggesting that resistance to interference contributed to diverse expressions of cognitive development and aging) and neuropsychological research (indicating that the frontal lobes were critically involved in interference-sensitive tasks). He amassed considerable support for the idea that the susceptibility to interference is a critical factor in age-related differences in cognitive efficiency. Examples include various attention tasks designed to examine the ability to focus, divide or maintain attention (Davies et al., 1984). Age-related change in the susceptibility to interference is also demonstrated in studies using the Wisconsin card sorting test (WCST) (Chelune and Baer, 1986; Fristoe et al., 1997) to examine the ability to shift response set.

Dempster (1992, 1993) pointed to frontal lobe function in order to provide a unified account of the wide range of interference phenomena reported in the developmental literature. He referred to the extensive evidence suggesting that the frontal lobes are heavily involved in interference regulation (Fuster, 1997). Frontal lobe damage leads also to marked deficits on interference-sensitive tasks that are similar to those of young children. Both from an ontogenetic and a phylogenetic perspective, the frontal lobes are the last to mature, and the first to decline (see also Bjorklund and Kipp-Harnishfeger (1995)). These considerations led Dempster (1993) to conclude that the frontal lobes are heavily involved in the selection, regulation and verification of human behavior, including the ability to resist interference.

Finally, Dempster (1993) argued that inhibition is best conceptualized in terms of a family of processes. In his view, inhibition has a variety of operating characteristics that may vary on temporal (e.g. proactive, coactive, and retroactive), formal (motoric, perceptual, and linguistic), and spatial (internal and external) dimensions. Dempster speculated that

these varieties of inhibition have different developmental trajectories and so give rise to a stage-like quality to the development of a child's sensitivity to interference. Initially, the child is particularly sensitive to motoric forms of interference. This is followed by a period of increased sensitivity in perceptual forms of interference accompanied by a decline in the sensitivity to motoric interference. Eventually, children show increased sensitivity to linguistic interference associated with reduced sensitivity to perceptual interference. Inhibition is singular in that it refers to a common underlying mechanism – the frontal lobes. At a more detailed level, however, inhibition applies to a variety of mechanisms, each specialized to meet specific inhibitory demands (Dempster, 1993, p. 19).

### 1.3 Methodological Issues

#### 1.3.1 Complexity Effects In Cognitive Aging And Development

Comparing effects of experimental manipulations between groups of different ages causes some specific difficulties. As age-related changes in the speed of responding are found on a wide array of tasks, a large amount of these effects are shared across domains. These speed changes are most evident as processing complexity increases. This phenomenon, known as the Age-Complexity effect, has been attributed to general changes in the speed of processing that affect all components of processing indiscriminately, both within and across tasks in a particular processing domain.

**Regression Analysis** ■ The complexity effect is usually demonstrated by means of a Brinley Plot. A Brinley plot is a scatterplot showing mean response times on a range of tasks for older adults or young children, plotted against mean response times of a control group, usually young adults. Across a wide range of conditions, response times of experimental and control groups appear to be linearly related. The function relating the two groups usually has a slope around 1.5 and a negative intercept. These functions typically explain more than 90% of the variance in the data. A slope exceeding 1.0 indicates that at each level of complexity of the tasks, the experimental group (children or older adults) is slowed proportionally. Ratcliff et al. (2000) showed that this reflects an age-related increase in variability of mean response times. Furthermore, results from Brinley analysis indicate that mean response times in the experimental group can be accurately predicted from response times of the control group. It should be noted, however, that in simulation studies accurate fits were obtained regardless of whether the data were simulated to reflect global age related changes or to reflect process-specific age-related changes in response latency (Molenaar and van der Molen, 1994).

The Age  $\times$  Complexity interaction that appears in Brinley plots has important consequences for the interpretation of age-related changes in performance on tasks designed to infer executive control functions. In executive control tasks, it is usually expected that children and older adults show larger response latencies than young adults. However, the Age  $\times$  Complexity interaction will invariably lead to larger age-related slowing in the experimental group for more complex tasks compared to simple tasks. Thus, in paradigms used to measure executive control deficits the age-related effect is consistent with the

global slowing hypothesis (cf. Spieler, 2001). The notion of such a global mechanism has been criticized on many counts, ranging from methodological issues to demonstrations of differential age changes (e.g., Cerella, 1991; Fisk and Fisher, 1994; Fisk et al., 1992; Fisk and Rogers, 1991).

**Analysis of Variance ■** The regression-analytic procedures, commonly used in the meta-analytic literature, may conceal task-dependent and process-specific age changes in processing speed that can be revealed using analysis of variance (ANOVA) techniques (for an example see van der Molen and Ridderinkhof, 1998a). To detect *disproportional* age-related effects some researchers transform the data from the experimental group according to the parameter values obtained in Brinley analysis. These parameters are taken to be estimates of global slowing effects. After transformation, any Age  $\times$  Task Type interaction is considered evidence for disproportional slowing on the tasks at hand. For review on the use of regression analysis in developmental and aging research the reader is referred to Ridderinkhof and van der Stelt (2000) and Myerson et al. (1992).

ANOVA is usually used to test the null hypothesis of zero age effects on response latency and error incidence against the alternative hypothesis that response latencies and error rates of children and older adults exceed those of young adults. ANOVA and Brinley analysis typically yield contradictory results (see, e.g., Bashore and Smulders, 1995), in the sense that ANOVA often indicates significant age effects on some tasks and not on others, whereas Brinley analysis usually indicates that the age-related variance in each of these tasks is well-described by a single global speed function. The observation that Brinley analysis has limited discriminatory value (Molenaar and van der Molen, 1994), and other objections to the Brinley analysis technique (e.g., Bashore and Smulders, 1995), have led several researchers to propose alternative methods.

**The Third Way ■** To provide a direct statistical test of the differential sensitivity of executive and non-executive functions to the effects of age one can examine the age-related variance that is *unique* to executive-function performance (that is, not shared with performance in the non-executive tasks), cf. Salthouse (1996a). The global speed hypothesis predicts that after partialing out the covariance with non-executive task performance, little variance in executive-function performance remains to be explained uniquely by age (see Figure 1.2).

According to the specific loss hypothesis, in contrast, age should affect performance in the executive-function tasks even when non-executive task performance were entered as a covariate in an analysis of covariance (ANCOVA, for an example see Nieuwenhuis et al. (2000)). A more general procedure to infer unique contribution to age-related variance is hierarchical regression. An example of this procedure is given by Williams et al. (1999), who used the stop-signal procedure to examine the development of inhibitory control. Reaction times to the stop and go signals were used to assess performance in inhibition and response execution, respectively. Hierarchical regression confirmed that the age-related change in inhibitory control could not be explained by general speeding or slowing of responses.

A less common method of analyzing response time data is by means of structural equa-

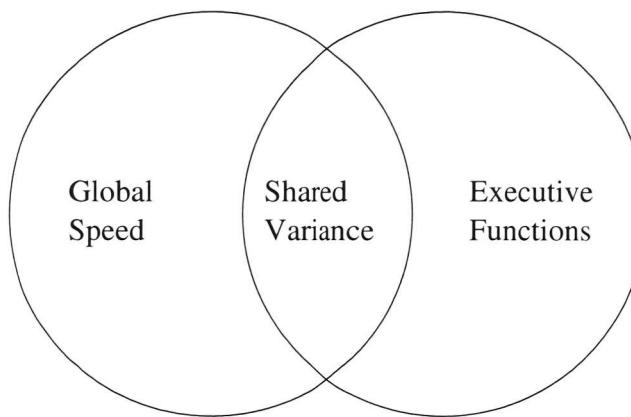


Figure 1.2: Schematic Representation Of Unique And Shared Age-Related Variance

tion modelling (SEM), which allows us to formulate and test the executive/non-executive model explicitly (for an example see Salthouse et al. 1998b). In SEM the mean reaction times obtained in the various experimental tasks can be related to common latent factors, which are hypothesized to explain the covariance among the mean reaction times and the mean differences between the age groups. The use of structural equation modelling to investigate covariance and mean structures is common in the psychometric literature (Bollen, 1989; Sörbom, 1974). For discussions of the application of SEM to response latencies see Donaldson (1983); Heuer (1985); Molenaar et al. (2001).

The hierarchical pattern of development of the brain (Spencer, 1855) is well established, both at the early developmental stages, as in older adulthood (see Section 1.2.3). These developmental changes in the brain underlie the differences in behavior that are manifest in childhood and old age. As mentioned, a central topic in the literature on lifespan development is the age-related increase in cognitive efficiency during childhood, and the decrease in cognitive efficiency during senescence. It is therefore not unreasonable to expect an hierarchical pattern of development of behaviour, being a manifestation of the changes that are taking place in the brain.

## 1.4 Research Questions

The central question that is addressed in the four empirical chapters of this thesis is whether executive control functions show differential age-related differences in processing efficiency. As mentioned before, executive functions are those functions that are responsible for the organization and management of more specialized cognitive processes. These functions are involved in error monitoring, interference control, task-set reconfiguration and context updating (e.g., Meyer and Kieras, 1997; Norman and Shallice, 1986; Shallice, 1994). Executive functions, or cognitive control functions, refer to the ability of the cognitive system to monitor the environment and modify behavior accordingly. One of the dominant

neurocognitive tests of executive functioning is the WCST. Aspects of the WCST that are especially relevant for the presence of age-related differences in adaptive behaviour are investigated. To this end several tasks that share meaningful characteristics with the WCST are devised. These relevant aspects are explored according to the theoretical framework proposed by Stuss et al. (1995) in the later parts of this thesis.

The global speed hypothesis and the specific loss hypothesis have been innovative in addressing old research questions by providing new perspectives that offer a richer understanding of the observed phenomena. The study presented in Chapter 2 evaluates the validity of these frameworks in one empirical study. We assess the extent to which age exerts an independent influence on the efficiency of executive control after the age-related covariance with global processing speed is partialled out, by means of a MANCOVA with mean response times on each non-executive task entered as covariates. We will test the regression model more directly by means of structural equation modelling (SEM). We will contrast regression models that incorporate only a general speed factor with a model that allows a separate, independent factor that loads only on tasks that require cognitive control. The models are used to investigate observed mean differences between the groups as a function of mean differences in the latent factors 'global speed' and 'executive control'.

Then, in Chapter 3, it is established if older adults' performance will or will not benefit from the presentation of explicit cues that tell them to shift to another sorting rule. Alternatively, if explicit cueing were to facilitate older adults performance such that they persevered less frequently in previously correct categorization rules, then it could be concluded that age-related differences in adaptive control processes are accounted for by deficits in performance monitoring rather than in rule-induction or set-shifting abilities. If age were to affect set-shifting abilities, then older adults should show perseverative behavior even when specific cues are provided, since the presentation of specific cues does not alter the need to engage basic set-shifting operations.

This set-shifting factor is measured in a more experimentally controlled setting in the later parts of this thesis. Stuss et al. (1995) proposed that the task-shift paradigm is more suitable to the investigation of cognitive flexibility. They suggested that the task switching paradigm might provide an experimental analogue of the WCST demands involving switching ability, flexibility and inhibition. In a group of subjects, ranging in age from young adolescence to senescence, the task-switching paradigm is used to investigate the cognitive efficiency of shifting behaviour. Age is considered to be the mediating factor in this efficiency. Using a regression approach, the effect of age on the speed of switching will be investigated. The results are compared to the effects of age on simple choice reaction time tasks (the pure blocks). If age affects response times in similar fashion for simple and complex tasks alike, regression functions describing the response latencies of the whole group will not discriminate between tasks. If set-shifting is a major factor in the age-related decline in the efficiency of cognition, estimated parameter values in the shifting tasks are expected to divert from parameters obtained in the pure blocks.

Using covariance analysis, the effect of development on cognitive flexibility will also be investigated using the task-switch paradigm. Several measures of set-switching costs can

be calculated and are attributable to different cognitive processes. *Switching costs* refer to latency differences between pure and mixed blocks. Switching costs are a composite of *shift costs* and *mixing costs*. Shift costs are expressed in the latency differences between repetitions and alternations in the mixed blocks. Mixing costs are represented by latency differences between pure blocks and repetitions in mixed blocks. To test the age-related effects on switching speed against effects on basic perceptual and motor speed, the response times on a simple reaction task are entered as a covariate into the analyses (see Figure 1.2). If basic perceptual and motor speed is the major factor underlying speed differences between age-groups, no residual affects on mixed blocks are expected. In contrast, if the speed of set-shifting is effected disproportionately by age, significant age  $\times$  type interactions are expected to be found after partialing out the covariance with basic speed measures.

#### **1.4.1 Outline Of This Thesis**

The empirical chapters of this thesis (Chapters 2–5) are focused on the age-related changes of the efficiency of cognitive processes. The efficiency of cognitive processes is inferred only from response time measures and error proportions. The discriminative and predictive power of the global speed hypothesis and the specific loss hypothesis is explicitly tested.

In the 2nd chapter assumption that executive control comprises a fundamental factor underlying the effects of aging on the efficiency of cognitive processing, independent of aging effects on global processing speed, is tested. This chapter is a direct test of the specific loss hypothesis against the global speed hypothesis, on both ends of the lifespan. In Chapter 3 of this thesis, The extent to which different endogenous adaptive control abilities are differentially sensitive to the effects of aging is explored, by testing young and older adults in two experiments using WCST-like tasks. This chapter enables us to identify the subprocesses in a well-established neurocognitive task that are the locus of the age-related differences in the speed of processing. The main objective of the study that is reported on in the 4th chapter is to establish the existence of differential patterns of aging effects in the speed of processing during tasks requiring set shifting processes. These set-shifting processes were found to be sensitive to effects aging in the second chapter, in the context of the WCST. The 5th chapter is concerned with changes in executive control processes involved in set shifting during cognitive development. In this chapter the same tasks are used as in the 4th chapter, but different analyses are performed. Using covariance analysis, the amount of unshared variance with basic processing speed is assessed.

These empirical chapters have been submitted to international psychological journals. They have been included in this thesis in submitted form. To acknowledge the important contributions of the co-authors, a list of references is presented.

1. Mark M. Span, K. Richard Ridderinkhof and Maurits W. van der Molen (submitted).  
Age-related changes in the efficiency of cognitive processing across the life span.
2. K. Richard Ridderinkhof and Mark M. Span and Maurits W. van der Molen (in press).  
Perseverative behaviour and adaptive control in older adults: Performance monitoring, rule induction and set shifting. *Brain and Cognition*
3. Mark M. Span, K. Richard Ridderinkhof and Maurits W. van der Molen (submitted).  
The speed of set shifting across the adult life span revealed by regression modelling.
4. Mark M. Span, K. Richard Ridderinkhof and Maurits W. van der Molen (submitted).  
Developmental differences in set-switching.



# AGE-RELATED CHANGES IN THE EFFICIENCY OF COGNITIVE PROCESSING ACROSS THE LIFE SPAN

The global speed hypothesis and the specific loss hypothesis are dominant theoretical frameworks in the recent literature on cognitive development and aging. Few attempts have been made to explicitly test the discriminative and predictive power of the two frameworks. Our sample of subjects consisted of children, young adults, adults and seniors. Analysis of covariance, revealed a mixed pattern of results for these groups. In the child group, partialing out global speed removed the differences with adults in the executive function tasks, suggesting that global processing speed was the primary factor underlying developmental changes in the efficiency of information processing. In older adults, differences with adults remained in each of the executive function tasks after controlling for global processing speed. These results suggest that executive control comprises a fundamental factor underlying the effects of aging on the efficiency of cognitive processing, independent of aging effects on global processing speed. These results were corroborated by the outcome of structural equation modelling (SEM).

## 2.1 Introduction

The literature on cognitive development and the literature on cognitive aging has been dominated by two main theoretical frameworks: the *global speed hypothesis* and the *specific loss hypothesis*. The fundamental assumption of the global speed framework is that a global speed factor accounts for all the relevant age-related variance in the efficiency of processing in a wide array of cognitive tasks, regardless of the componential make-up of these tasks. Within the specific loss framework, it is assumed that age-related differences in the speed of information processing are best understood in relation to concurrent age-related structural and functional changes in the brain. As explained in more detail below, the latter hypothesis predicts that age-related changes in tasks involving executive control, supported in large measure by the frontal lobes, should be more pronounced than age differences in tasks with lesser executive control demands.

Both frameworks have been innovative in addressing old research questions by providing new perspectives that offer a richer understanding of the observed phenomena. Both frameworks have also been used for generating testable predictions. However, while support has been amassed for both frameworks independently, there has been little convergence

between the two. The main objective of the present article is to contribute to such a convergence by evaluating the validity of these frameworks in one empirical study. Also we want to assess and compare the predictive and discriminative power of the two hypotheses.

To this end, we conducted a life-span developmental study, using a variety of tasks that vary in the demand on executive function in a within-subjects design. We used statistical methods to partition age-related variance on these tasks (analysis of covariance and structural equations modelling). These features allowed us to assess whether age-related changes in the efficiency of executive control can be explained satisfactory in terms of a global speed factor alone.

**The Specific Loss Hypothesis** ■ An increasing number of psychologists in the field of cognitive development and cognitive aging have expressed an interest in the neural underpinnings of age-related changes in cognitive functions (see, e.g., Howe and Pasnak, 1993; Raz, 2000; van der Molen and Ridderinkhof, 1998b). As a result, proponents of the neurocognitive change hypothesis, which can be seen as a derivative of the specific loss model, (e.g., Ardila and Rosselli, 1989; Dempster, 1992, 1993; Dempster and Brainerd, 1995; Diamond, 1990; Pennington, 1994; Stuss, 1992; Welsh et al., 1991; West, 1996; Whelihan and Lesher, 1985) have proposed that age related changes in cognitive function should be examined in relation to age-related changes in brain structure and function. They concluded that the frontal (specifically prefrontal, and more specifically dorsolateral prefrontal) brain structures and the cognitive functions that rely on these parts of the brain are most susceptible to effects of age on both ends of the life span. This frontal lobe hypothesis has generated a series of research efforts, generally concluding that frontally-supported executive control functions are more sensitive to age-related speed changes than functions supported by other parts of the brain.

One source of evidence stems from studies of development and aging that include executive-function tasks which are known to involve intact frontal functioning for efficient performance. In the field of cognitive child development, age-related improvement has been reported in inhibitory control (for review see van der Molen, 2000), working memory (for review see Pennington, 1994), response selection (e.g., Ridderinkhof and van der Molen, 1997), response competition (e.g., Ridderinkhof and van der Molen, 1995), task switching (Cepeda et al., 2000), adaptive problem solving (Chelune and Baer, 1986) and various other planning and problem-solving tasks (for review see Welsh et al., 1991). Likewise, in the field of cognitive aging, deterioration has been reported in inhibitory control (for review see Kramer et al., 1994), working memory (for review see Moscovitch and Winocur, 1992), response selection (e.g., Salthouse and Somberg, 1982), response competition (for review see Bashore and Smulders, 1995), task switching (Kray and Lindenberger, 2000), adaptive problem solving (for review see Ridderinkhof et al., in press) and various other planning and problem-solving tasks (for review see Pennington, 1994).

Neuroimaging studies of cognitive development and aging are another source of evidence (for a review see van der Molen and Ridderinkhof, 1998b). The results of studies examining brain growth in healthy children suggests that the frontal lobes are the last to

mature. This suggestion is based on EEG studies (e.g., Thatcher, 1994), ERP studies (e.g., Courchesne, 1978, 1990), MRI studies (e.g., Jernigan et al., 1991), and PET studies (e.g., Chugani, 1994). The greater vulnerability to the effects of aging of the frontal lobes compared to other brain regions has been highlighted in the recent neuroimaging literature, including PET studies (e.g., Loessner et al., 1995; Moeller et al., 1996; Petit-Taboué et al., 1998), MRI studies (e.g., Coffey et al., 1992; Cowell et al., 1994; Murphy et al., 1996; Raz et al., 1997), and ERP studies (e.g., Dustman et al., 1996; Fabiani and Friedman, 1995; Friedman and Simpson, 1994). It should be noted, however, that the recent neuroanatomy and neuroimaging literature suggest a pattern of more subtle differentiation in age-related decline between the (pre-)frontal and non-frontal areas as well as within the frontal cortex (see e.g., Raz, 2000; Uylings and de Brabander, in press).

**The Global Speed Hypothesis ■** In contrast to the specific loss hypothesis, the global speed hypothesis does not focus on the neural underpinnings of cognitive development and aging, although some work in this field is also done (e.g., Myerson et al., 1990). Within this framework, age-related changes in information-processing speed at both ends of the life span are considered to be global and generalized, in the sense that these changes are manifest to the same proportional extent in a wide array of cognitive operations. It has been observed that performance in many different speeded and non-speeded tasks is affected by age to the same proportional degree, irrespective of the nature and extent of processing required for successful task performance (e.g., Cerella, 1990; Hale, 1990; Kail and Salthouse, 1994; Myerson et al., 1990; Salthouse, 1996b; Salthouse et al., 1998a; for a review see, e.g., Bashore and Smulders, 1995). The global-change hypothesis (in its various forms) has explained large portions of age-related variance in an array of empirical and meta-analytical studies. Salthouse (2000) provides a review of recent ideas and procedures to partition age-related variance between tasks. Salthouse emphasizes the sheer number of variables that appear to be related to age, and suggests that these relations could be shared relations. Analyzing two major datasets Salthouse concludes that 'relative little of the effects on individual speed variables are independent of the effects on other speed variables' (Salthouse, 2000, page 48). He goes on to stress the importance of a biological plausible model of the origins of age-related speed changes. These models would have to be corroborated using psychophysiological or neuro-biological variables.

**Global Speed versus Specific Loss ■** Consistent with the support of the global-speed hypothesis, some studies report results emphasizing the role of global processing speed in age related changes in executive-function tasks (e.g., Kray and Lindenberger, 2000; Mayr, 2001; Salthouse et al., 1998a). A growing number of studies, however, reports evidence for process-specific age-related differences in the speed of cognitive control processes on top of the global speed trend (e.g., Bashore and Smulders, 1995; Kramer et al., 1999; Kray and Lindenberger, 2000; Mayr, 2001; Ridderinkhof et al., 1999; Ridderinkhof and van der Molen, 1997; van Asselen and Ridderinkhof, 2000). These findings underline the need to explicitly compare the global speed and specific loss hypotheses with respect to their discriminative and predictive power.

Several sources of variance may obscure observed differences in the proportion of age-related variance in executive functioning. The odds of finding superproportional age effects may depend on, for instance, differences in sample size, age range, experimental tasks, task demands, task formats and stimulus characteristics. Ridderinkhof and van der Stelt (2000) concluded from a review of the psychophysiological literature that most attentional selection functions are available even to young children. They also concluded, however, that developmental deficiencies in these attentional processes may emerge as a function of task demands and stimulus characteristics. Thus, such factors may contribute sources of variance that obscure attempts to assess whether the efficiency of cognitive control functions changes with age independently of global processing speed. A major objective of the present study is to provide a test of the two hypotheses in conditions where such sources of variance were minimized by using similar task formats for executive and non-executive tasks within the same groups of subjects.

**Executive Function Tasks** ■ Among the central cognitive functions of the frontal brain are response selection (e.g., Passingham, 1995; Pennington, 1994), response suppression (e.g., Fuster, 1997; Shimamura, 1995; West, 1996), working memory (e.g., Cabeza and Nyberg, 1997; Goldman-Rakic, 1987a,b; Petrides, 1995), and adaptive control or cognitive flexibility (e.g., Milner, 1963; West, 1996). Age-related changes have been reported for each of these functions during both childhood and later adulthood.

**Response selection** ■ Stimulus-response (S-R) translation or response selection processes are typically manipulated experimentally by varying the compatibility between stimulus position and the response side. The speed of response selection processes is delayed considerably when an incompatible S-R mapping is required compared to compatible responses (for a review see Kornblum et al., 1990). Response selection processes are mediated through frontal brain areas, in particular premotor cortex and supplementary motor area (for a review see Passingham, 1995). When incompatible responses are required, dorsolateral prefrontal cortex is engaged to hold the prepotent compatible response in check (for reviews see Fuster, 1997; West, 1996). The effect of S-R compatibility manipulations on the speed of response selection has been observed to decrease as children grow into adolescence and to increase again as adults grow into senescence (e.g., Kay, 1954; Ridderinkhof and van der Molen, 1997; Ruch, 1934; Salthouse and Somberg, 1982).

**Response suppression** ■ Response inhibition processes are often manipulated experimentally using one of two related paradigms: the Go/NoGo paradigm and the stop-signal paradigm. In Go/NoGo tasks, some stimuli require speeded responses whereas other stimuli require that overt responses are withheld. Often, one aspect of the stimulus suggests a particular predesignated response, whereas a second aspect indicates whether the response is to be given not. In stop tasks, one stimulus calls for a predesignated reaction, but incidentally presented stop signals demand the subject to inhibit the response. Electrophysiological evidence has demonstrated that, although subjects often refrain from overt responding to NoGo stimuli or on stop trials, the response direction feature of the stimulus has managed

to activate the associated response up to the level of the primary motor cortex (e.g., De Jong et al., 1990, 1995; Miller and Hackley, 1992; Osman et al., 1992). Subsequently, activity in prefrontal cortex is invoked to suppress the overt response (e.g., Band and van Boxtel, 1999; Clark, 1996; Shimamura, 1995). The efficiency of response inhibition has been observed to increase during childhood and decrease again during later adulthood (e.g., Kok and Talsma, 1999; Kramer et al., 1994; Ridderinkhof et al., 1999; van der Molen, 2000; Williams et al., 1999).

**Working memory ■** Several experimental and neuropsychological tasks have been used to manipulate the involvement of working memory. Central in these tasks is the notion that information should not only be kept on-line (in some short-term memory storage), but should remain available continuously for further operations necessary for proper task performance (cf. Pennington, 1994). One example is the so-called *n*-back task, in which responses are to be based on the stimulus material presented *n* trials ago (e.g., Jonides et al., 1997). While performing the primary task, the information presented on a given trial should be kept active during the next *n* trials. The working memory load increases with the value of *n*. The primary brain area involved in working memory is the prefrontal cortex, although modality-specific secondary association areas may also be important (cf. Cabeza and Nyberg, 1997; Cohen et al., 1994; d'Esposito et al., 1995; Fuster, 1997; Gabrieli et al., 1997; Goldman-Rakic, 1987a,b; Milner, 1995; Petrides, 1995; Smith et al., 1996). The efficiency and capacity of working memory is sensitive to age-related change at both ends of the life span (e.g., Halliday and Hitch, 1988; Pennington, 1994; Raz et al., 1998; Salthouse, 1994).

**Adaptive control ■** Several approaches have been used to examine the efficiency of cognitive flexibility and adaptive behavior. A popular paradigm in experimental psychology is task switching (Jersild, 1927), in which reaction time (RT) differences between task alternations and task repetitions (switch costs) reflect the speed of task-set reconfiguration processes. Recent neuropsychological and neuroimaging studies have identified brain areas involved in task-shifting competence, including primarily (left) frontal areas (most prominently dorsolateral prefrontal; Dove et al., 2000; Meyer et al., 1998; Rogers et al., 1998). Whereas older adults are capable of performing elementary reaction-time tasks relatively well, their performance deteriorates markedly when they are asked to switch back and forth between those tasks. (e.g., Botwinick et al., 1958b; Duncan et al., 1996; Hartley et al., 1990; Kramer et al., 1999; Kray and Lindenberger, 2000; Mayr, 2001; Salthouse et al., 1998a; van Asselen and Ridderinkhof, 2000).

The standard adaptive control task in neuropsychology is the Wisconsin Card Sorting Task (WCST; Grant and Berg, 1948). In the WCST, once subjects have classified cards according to one stimulus dimension (e.g., color) for a while, they experience some difficulty in shifting to another sorting principle (e.g., classifying the same cards according to shape). Milner (1963) reported that patients with dorsolateral frontal lobe lesions experienced more difficulties in shifting from one rule to another compared to patients with orbitofrontal or more posterior lesions. This greater difficulty was attributed to a greater susceptibility to the interference of responses made according to the previously correct rule. Since

Milner's seminal paper, many reports have confirmed the specific sensitivity of perseverative behaviors to deficient functioning of frontal cortex (e.g., Barceló et al., 1997; Barceló and Santome-Calleja, 2000; Drewe, 1974; Stuss and Benson, 1984). Recent neuroimaging studies suggest the activation of prefrontal structures in successful WCST performance (e.g., Barceló, 1999; Berman et al., 1995; Konishi et al., 1999, 1998; Omori et al., 1999; Ragland et al., 1997; Tien et al., 1998). Considering that WCST performance involves many different aspects of executive functioning (e.g., performance monitoring, integration of feedback, rule induction, set shifting, and suppression of previous sorting rules), this task is likely to engage activity of other cortical areas as well. The network of brain areas involved in WCST performance includes prefrontal cortex, the hippocampus and posterior association cortex (e.g., Anderson et al., 1991; Corcoran and Upton, 1993; Nagahama et al., 1996, 1998; Tien et al., 1998). Nonetheless, there appears to be general consensus both in clinical practice, in experimental neuropsychology, and in cognitive neuroimaging studies that prefrontal-cortex dysfunction is the main factor underlying deficient WCST performance, and, conversely, that perseverative behavior is a reflection largely of inefficient prefrontal activity (for a review see Barceló et al., 1997).

Performance in the WCST and similar tasks has been observed to change with age (cf. Heaton et al., 1993). In particular, the tendency to persevere in no-longer-correct sorting rules decreases as children grow older (e.g., Chelune and Baer, 1986; Zelazo et al., 1996), and increases during the later stages of life (e.g., Arbuckle and Gold, 1993; Dywan et al., 1992; Esposito et al., 1999; Fristoe et al., 1997; Kramer et al., 1994; Loranger and Misiak, 1960; Nagahama et al., 1998; Raz, 2000; Ridderinkhof et al., in press; Salthouse et al., 1996).

### **2.1.1 Experimental Approach**

In order to minimize the sources of variance related to general task and stimulus characteristics, we sought to administer a variety of tasks, that shared the same task format and stimulus materials. Some of these tasks were designed to engage executive functions, and some were not. Since one of our objectives was to address the global speed hypothesis, we designed a general speeded (reaction time) task format, varying the tasks to tap response selection, response inhibition, working memory, and adaptive control abilities. Within this format we also created tasks that do not tap these functions. Stimuli (see Figure 2.1) were always schematic faces, appearing in a four × four grid. The task format was adopted from a previous study of perseverative behavior in older adults (Ridderinkhof et al., in press).

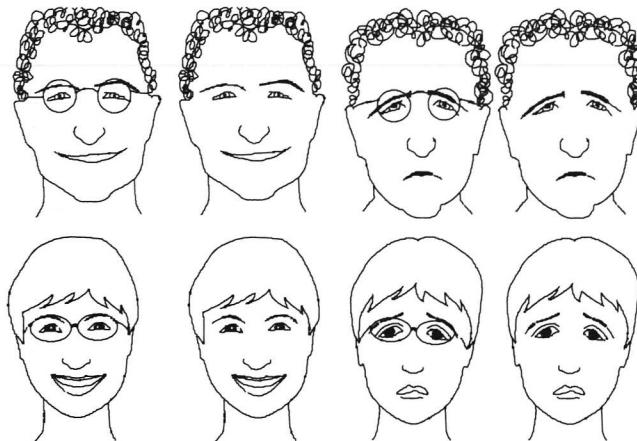


Figure 2.1: *Stimuli. Used by permission of the Center for Semiotic Research, Finlandgade 28, 8200 Aarhus N, Denmark*

**Response selection** ■ In one version of the task, if stimuli appeared in one of the grid positions on the left part of the presentation grid, a right-hand response was required (and vice versa). This task thus required the selective suppression of the prepotent (spatially compatible) response, and instead the preparation of an incompatible response.

**Response inhibition** ■ In another version, spatially compatible responses were required, that are relatively undemanding in terms of response selection processes. However, if a stimulus had appeared on a particular position in the grid, this position was visually marked; if, on subsequent occasions, a stimulus appeared on a marked position, the response was to be withheld. This task thus required the suppression of responses that were activated directly on the basis of compatible S-R mappings.

**Working memory** ■ In order to tax working memory, the same task as before (the response inhibition task) was applied, but in this version the positions in which stimuli had appeared previously were not visually marked. Thus, the participants were to keep the previously used grid positions in working memory, and to refrain from giving a (spatially compatible) response when a stimulus appeared in one of these positions. During a series of (up to ten) trials, the working-memory load thus increased from zero to nine items.

**Adaptive control** ■ In this WCST-like version of the task, subjects were to make discriminative responses to one of three binary features of the stimuli: female versus male, laughing versus not laughing, or wearing glasses versus no glasses. However, they were not told in advance which of these dimensions was the target one; they were to infer the appropriate sorting rule on the basis of (computer-generated) trial-by-trial feedback. After the subject had discovered and mastered the correct sorting rule, this rule was changed without announcement, and the subject was to detect this change and deduce the new sorting rule through the interpretation of feedback. This version of the task elicited typical patterns of perseverative behavior (similar to that seen in the WCST; cf. Heaton et al., 1993) in our previous study (Ridderinkhof et al., in press).

**Non-executive tasks** ■ The simplest version of the task required a speeded response to any stimulus appearing anywhere in the display (always with the subject's dominant hand). A slightly more demanding, but still fairly simple task was the spatially compatible choice task (similar to the response inhibition and working memory tasks, but without these components). A final task required gender discrimination (as in the adaptive control task, but without the rule induction and rule shifting components). This task calls on response selection processes, but the mapping of stimuli (female/male) on responses (left/right) is completely arbitrary.

### 2.1.2 Analytical Approach

Several analytical techniques are available for examining the extent to which executive functions are sensitive to the effects of age. Conventional procedures include analysis of variance and regression analysis. ANOVA is used to test the null hypothesis of zero age effects on response latency and error incidence (in any task) against the alternative hypothesis that (in any task) response latencies and error rates of children and older adults exceed those of young adults. Brinley analysis (a form of linear regression analysis, in which RTs of children or older adults are predicted from those of young adults), in contrast, is used to test the null hypothesis of global age effects on response latency (in any task) against the alternative hypothesis that age effects on response latency in some tasks depart from the global effect. ANOVA and Brinley analysis typically yield contradictory results (see, e.g., Bashore and Smulders, 1995), in the sense that ANOVA often indicates significant age effects on some tasks and not on others, whereas Brinley analysis usually indicates that the age-related variance in each of these tasks is well-described by a single global speed function.

To provide a direct statistical test of the differential sensitivity of executive and non-executive functions to the effects of age, we will examine the age-related variance that is unique to executive-function performance (that is, not shared with performance in the non-executive tasks). The global speed hypothesis predicts that after partialing out the covariance with non-executive task performance, little variance in executive-function performance remains to be explained uniquely by age. According to the neurocognitive change hypothesis, in contrast, age should affect performance in the executive-function tasks even when non-

executive task performance were entered as a covariate in a MANCOVA.

An alternative method of analyzing response time data is by means of structural equation modelling (SEM), which allows us to formulate and test the executive/non-executive model explicitly. In SEM the mean reaction times obtained in the various experimental tasks can be related to common latent factors, which are hypothesized to explain the covariance among the mean reaction times and the mean differences between the age groups. The model under investigation is shown in Figure 2.2. Performance on *all* tasks is influenced by a common latent variable, global speed (SP). In addition, performance on *executive-function* tasks (denoted T4–T7 in the equations and in Figure 2.2) is influenced by a second latent variable, viz., executive function (EF). The model equations may be written conveniently using matrix algebra, as follows:

$$T_j = v + \Lambda \eta_j + \varepsilon_j, \quad (2.1)$$

where subscript  $j$  denotes group, 1=young, 2=adolescent, 3=adult and 4=senior. In Equation 2.1  $\Lambda$  denotes the seven  $\times$  two matrix of factor loadings, the seven-dimensional factor  $v$  contains the constant intercepts (like an intercept in standard regression). The seven-dimensional random factor  $T_j$  contains the mean response latencies (Note that we do not use subject subscripts). The seven-dimensional random factor  $\varepsilon$  contains zero-mean residuals. The two-dimensional random factor  $\eta$  contains the scores on the two common factors. These vectors and matrix are shown below.

$$v = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \\ v_6 \\ v_7 \end{bmatrix} \quad T_j = \begin{bmatrix} T_{1j} \\ T_{2j} \\ T_{3j} \\ T_{4j} \\ T_{5j} \\ T_{6j} \\ T_{7j} \end{bmatrix} \quad \Lambda = \begin{bmatrix} \lambda_{11} & 0 \\ \lambda_{21} & 0 \\ \lambda_{31} & 0 \\ \lambda_{41} & \lambda_{42} \\ \lambda_{51} & \lambda_{52} \\ \lambda_{61} & \lambda_{62} \\ \lambda_{71} & \lambda_{72} \end{bmatrix}$$

and

$$\eta_j = \begin{bmatrix} SP_j \\ EF_j \end{bmatrix} \quad \varepsilon_j = \begin{bmatrix} \varepsilon_{1j} \\ \varepsilon_{2j} \\ \varepsilon_{3j} \\ \varepsilon_{4j} \\ \varepsilon_{5j} \\ \varepsilon_{6j} \\ \varepsilon_{7j} \end{bmatrix}$$

The model is used to investigate observed mean differences between the groups as a function of mean differences in the latent factors SP and EF. The use of structural equation modelling to investigate covariance and mean structures is common in the psychometric literature (Bollen, 1989; Sörbom, 1974). For discussions of the application of SEM to response latencies see Donaldson (1983); Heuer (1985); Molenaar et al. (2001).

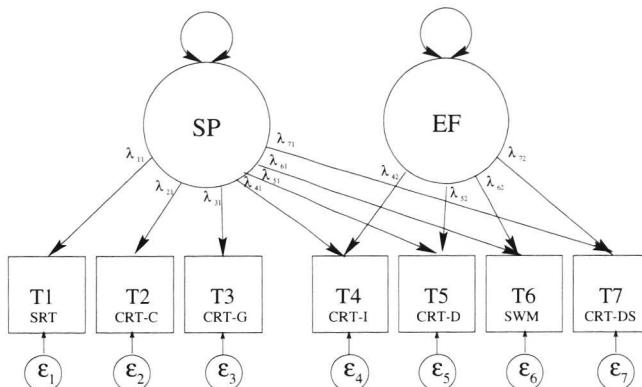


Figure 2.2: Graphical representation of the SEM: SP = Latent 'Speed' factor; EF = Latent 'Executive Function' factor.

## 2.2 Method

### 2.2.1 Participants

Subjects in four different age groups participated in this study. A group of 22 children (13 females; mean age: 9.2; age range: 8–11; Raven-quartile: 3.16; Raven-quartile sd: .95) was recruited from elementary schools in Amsterdam. A group of 17 adolescents (9 females; mean age: 15.4; age range: 15–16; Raven-quartile: 3.50; Raven-quartile sd: .78) were recruited from high-schools in Amsterdam. For all children and adolescents, informed consent was obtained from their parents and teachers. The children and adolescents received a small gift in return for their participation. A group of young adults consisted of 21 students from the University of Amsterdam (13 females; mean age: 24.1; age range: 19–33; Raven-quartile: 3.28; Raven-quartile sd: .90), who received course credits for their participation. A group of 19 older adults (13 females; mean age: 68.7; age range: 60–79; Raven-quartile: 2.90; Raven-quartile sd: 1.04) was recruited through local newspaper advertisements. Informed consent was obtained from all young and older adults. Children were tested simultaneously in groups of up to four in a quiet room at their local school; young and older adults were tested individually in a quiet university laboratory chamber. All subjects were healthy and had normal or corrected-to-normal vision. Subjects were screened for use of alertness-changing medication and subjective health-experience. Mean Raven-quartile scores did not differ between groups ( $F(3,79) = 1.397, p > .05$ ), suggesting that subjects in different age groups were comparable in terms of intelligence.

### 2.2.2 Stimuli and apparatus

The subjects were seated in front of computer monitor at a viewing distance of 40 cm. Stimulus presentation and response registration were controlled by an Apple Macintosh LC475 computer. The stimulus configuration consisted of a permanently visible four × four presentation grid with 16 possible stimulus positions. Each stimulus position was demarcated by a square of 37 × 37 mm, creating a grid with a size of 16 × 16 cm. The critical stimuli were drawings of faces (see Figure 2.1), each measuring 4.3° of visual angle (3 cm high), that could appear (one at a time) in any one of the possible stimulus positions. There were eight different stimuli, varying along three binary dimensions (male/female, laughing/not laughing, glasses/no glasses; see Figure 2.1). All stimulus elements were black line drawings presented against a white background. Feedback stimuli were the words “GOED” and “FOUT” (the Dutch words for correct and incorrect), presented in the center of the four by four grid in green and red, respectively (in the Geneva 12 standard computer font). In addition, the total number of correct answers was displayed continuously to the right of fixation. Cue stimuli consisted of the statement “WE ZIJN VERHUISD” (“we have moved”) or “NIEUWE SERIE” (“new series”), presented in red (Geneva 12) directly above the four by four grid.

### 2.2.3 Design and General Procedure

Task details varied from task to task, but stimulus materials and most procedural details were kept constant across tasks. In each task, on each individual trial, one stimulus (selected randomly and with equal probability) appeared in one of the possible stimulus positions on the grid (selected randomly and with equal probability unless specified otherwise). The stimulus designated a response with one of two response keys (the z and / keys of the computer keyboard, that were labelled with green and red colors), which were operated by the left and right index fingers, respectively. The subject’s task was always to respond as fast and accurate as possible with the designated response finger. The instruction was always “Respond as quickly as possible, but be sure not to make many errors”. Which response was the correct one on a given trial depended on the specific instruction, which varied (and was explained) from task to task. Task-specific instructions were explained extensively to the subject prior to each task. Stimulus presentation was response-terminated; in tasks that included trials in which subjects were to refrain from responding, the maximum response time was 3.5 seconds. Stimulus offset was followed immediately by the presentation of feedback. The stimulus associated with the next trial was presented one second after feedback onset.

Care was taken to ensure that all subjects understood the instructions and were able to perform the task. A practice block consisting of 50 trials preceded each task. Feedback was intended to motivate the subjects to perform accurately, but not at the expense of speed. Five points were earned for each correct response, and five bonus points could be gained for responses that were faster than the individual’s average response plus one standard deviation. The tasks were administered in random order, and were separated by short breaks (of one

to two minutes). A 12-minutes break followed the fourth task. The time taken to complete one task block varied between five and 20 minutes, depending on the specific task. Total test time amounted two and a half hours, including instruction, practice, and time spent on questionnaires. All tasks consisted of 160 trials, unless stated otherwise.

#### 2.2.4 Task Details

**Simple Reaction Time task** ■ In the Simple response time task, whenever a stimulus appeared in any of the possible stimulus positions of the presentation grid, the subject was to press the /-button with the index finger of the right hand as fast as possible, regardless of the identity or position of the stimulus.

**Compatible Spatial Discrimination task** ■ In this task, henceforth referred to as the *Compatible task*, stimuli that appeared in any of the possible stimulus positions to the left of the horizontal center of the grid designated a response with the index finger of the left hand, and vice versa. Thus, spatially compatible button-presses were required in response to the location of the stimulus.

**Incompatible Spatial Discrimination task** ■ In this task, referred to as the *Incompatible task*, stimuli that appeared in any of the possible stimulus positions to the left of the horizontal center of the presentation grid designated a response with the index finger of the right hand, and vice versa. Thus, spatially incompatible button-presses were required in response to the location of the stimulus.

**Gender Discrimination task** ■ In this task, referred to as the *Gender task*, any female face stimulus appearing in any position on the grid designated a response with the index finger of the left hand; male faces designated right-hand responses. Thus, stimuli required a discriminative response to the gender of the faces.

**Disjunctive Compatible Spatial Discrimination task** ■ The basic task was identical to the Compatible task: facial stimuli that appeared in any position to the left of the horizontal center of the presentation grid designated a response with the index finger of the left hand, and vice versa. In the present task (referred to as the *Disjunctive task*), however, trials were presented in sequential groups of nine. If on a particular trial a stimulus appeared on a particular position, that position would be accentuated visually with a black contour on subsequent trials. Thus, over the course of nine trials, more and more of the possible stimulus positions would be marked with a black contour.

The subject's additional task was to determine on each trial whether the actual stimulus position in which the stimulus was presented was marked with a black contour. If so, the subject was to refrain from responding on that trial (No-Go); if not, a discriminative response was required (Go) as in the compatible discrimination task. No-Go probability (i.e., the probability that a stimulus occurred on a marked position) was programmed to be .125 on each trial (except for each first trial in a series of nine, which was always a Go trial). Upon completion of a series of nine trials, before the next trial began, the message "NIEUWE

SERIE" ("new series") was presented, indicating the beginning of a new series of nine trials. At that time, all grid positions were cleared so that the computer screen retained its initial appearance. The disjunctive tasks consisted of 270 trials.

**Disjunctive Compatible Spatial Discrimination and Spatial Working Memory task ■** This task, referred to as the *Disjunctive Memory task*, was identical to the Disjunctive task, with one exception: grid positions that had been occupied in previous trials were not marked with a black contour. Thus, subjects were required to memorize each previously occupied position within the series of nine trials, and on each trial retrieve from their memory whether the grid position in which the present stimulus occurred was previously used. The requirement to refrain from responding when the stimulus occurred in a previously used position calls on spatial working memory, as on each trial a series of spatial positions should be updated and operated on. The working memory load increased from zero on the first to eight on the ninth trial in each series.

**Dimensional Discrimination and Shift task ■** This task, referred to as the *Dimensional Shift task*, was adopted from a previous study (Ridderinkhof et al., in press, experiment 1). In contrast to computerized versions of the WCST, which bear close resemblance to the original clinical test in many respects, the present implementation was designed to afford an analysis of the speed of information processing, which is critical for our central research questions. The subject's task was to sort the stimuli using one of the three stimulus-dimensions. For instance, male and female faces could require a left- and right-hand button response, respectively; laughing/not-laughing faces could require left/right responses, and so on. The critical sorting dimension was initially unknown to the subject, and could be altered afterwards. Subjects were told to apply the male/female, laugh/not-laughing, or glasses/no-glasses sorting rules, and in addition they were to use the trial-by-trial feedback to infer which sorting rule was relevant. They were also told that the relevant sorting rule could change from time to time, and that in that case they had to use the trial-by-trial feedback to infer a new sorting rule. The initial sorting rule was selected randomly. When the subject had correctly applied the relevant sorting rule in eight out of the last ten trials, the sorting rule was shifted to another. Intra-dimensional shifts (e.g., from female-left/male-right to female-right/male-left) never occurred; after a dimensional shift one of the other dimensions served as the basis for discriminative responding. The Dimensional Shift task consisted of 260 trials.

### 2.2.5 Dependent Measures

The main dependent variable in each task was the mean response latency for correct responses. All responses with a response latency exceeding the mean by more than three standard deviations (for each subject and each task separately; this amounted to less than 1.5% of all trials) were excluded from the response time analyses.

In the Dimensional Shift task, a variety of measures was obtained. A number of different phases were discerned. First, in accordance with Somsen et al. (2000), rule induction phases were distinguished from rule application phases. Subsequent to a dimensional shift, feedback stimuli are to be processed to infer the need to shift, the old rule is to be abandoned, hypotheses are to be formulated concerning the new rule, and these hypotheses are to be tested using feedback stimuli. Once the new discrimination rule has been discovered, none of these requirements hold any longer; the task is reduced to applying a known discrimination rule. The rule induction phase can be divided further into perseverative trials, in which the subject persisted in sorting according to the previous sorting rule even though feedback indicates that this rule is no longer correct, and rule search trials, in which the subject has abandoned the old rule and is trying to discover the new sorting rule. Since prior to the first dimensional shift there was no 'old rule', during this phase perseverative trials cannot occur, and rule search in this phase may differ from rule search in post-shift phases. Perseverative trials are defined as the number of errors per shift in which the response would be correct if the previous rule was still active.

Mean response latency was determined for rule search trials in the initial (pre-shift) phase, rule search trials in subsequent (post-shift) phases, perseverative trials, and rule application trials. In addition, a number of frequency measures was obtained. First, we measured the number of trials needed to learn and apply the first dimensional discrimination rule (the total number of trials preceding the first shift). Second, we measured the number of successfully learned dimensional discrimination rules (number of rule-shifts). Third, we measured the number of perseverative trials (as defined above) per rule shift.

### 2.2.6 Analysis of Variance

For each task separately, each of the dependent measures was submitted to MANOVA. Age Group was entered into these MANOVA's as a between-subjects factor with four levels (8–11 year-olds, 15–16 year-olds, 19–33 year-olds, and 60–79 year-olds). The combined results of the Compatible and Incompatible tasks were analyzed together, including Stimulus-Response Compatibility as a within-subjects factor with two levels (compatible, incompatible). The combined results of the Disjunctive and Disjunctive Memory tasks were also analyzed together, including the within-subjects factor Working Memory Load (absent, present). In the Dimensional Shift task, response latencies for the four response categories were submitted together to a MANOVA that included the factor Response Category (initial rule search, subsequent rule search, perseverative, and rule application).

### 2.2.7 Brinley Analysis

Brinley analysis is an analytical technique that has been used frequently to determine the extent to which age-related changes in cognitive task performance can be explained in terms of global processing speed. For each age group separately, all speed measures from all tasks were plotted against the corresponding measures from young adults; the proportion of variance in the resulting scatter that can be explained by a linear regression function indicates the fit of the global speed model, with the slope of the regression line reflecting the proportional extent by which global speed in the experimental group is slower than that of young adults.

### 2.2.8 Analysis of Covariance

In an alternative analysis aimed at identifying the unique contribution of executive functions to age-related trends in processing speed, mean response latencies were entered into a MANCOVA. Dependent variables were mean RTs from the Incompatible, Disjunctive, Disjunctive Memory, and Dimensional Shift tasks (thought to involve executive functions); mean Response latencies from the Simple Response Time, Compatible, and Gender tasks (thought to involve executive functions to a lesser extent) were entered as covariates, to assess whether the independent (between-subjects) variable Age Group exerts significant effects on response latency in the executive function tasks after the age effects on non-executive tasks are partialled out.

### 2.2.9 Structural Equation Modelling

Four of our tasks (the Incompatible, Disjunctive, Disjunctive Memory, and Dimensional Shift tasks, denoted T4 through T7) were designed to involve both executive functioning (EF) and speed (SP), whereas the three other tasks (the Simple RT, Compatible, and Gender tasks, denoted T1 through T3) were designed mainly as speed (SP) tasks. The model we fit thus incorporates two latent variables: a general speed factor (SP) and an executive function (EF) factor. Together these account for the covariance in Response latency among all seven tasks within the four groups, and for mean differences between the four groups. For all seven tasks, response times should load on the SP factor, as in all seven tasks the subjects were required to respond as quickly as possible. In addition, response latencies on executive tasks (T4-T7) load on the EF factor. The model equations for the observed response times are given in Equation 2.1.

Assuming that in Equation 2.1 the residuals  $\epsilon$  and the factors  $\eta$  are uncorrelated we have the following expression for the covariance matrix and the mean vector in each group:

$$\begin{aligned}\Sigma_j &= \Lambda \Psi_j \Lambda^T + \Theta_j \\ \mu_j &= v + \Lambda \alpha_j\end{aligned}$$

As above, the subscript  $j$  denotes group. The covariance matrix  $\Sigma_j$  is the expected (or model) covariance matrix in group  $j$ . The vector  $\mu_j$  is the expected (model) mean vector in group  $j$ . Furthermore,  $\Theta_j$  is the diagonal covariance matrix of the residuals ( $\epsilon$ ). This covariance matrix is diagonal because the residuals are assumed to be mutually uncorrelated. The matrix  $\Psi_j$  is the diagonal covariance matrix of the common factors that represent executive functioning (EF) and basic speed (SP). As above, the vector  $v$  is defined as a vector of constant intercepts. The vector  $\alpha_j$  represent the means of the common factor within each group, i.e.,

$$\alpha_j = \begin{bmatrix} E[SP_j] \\ E[EF_j] \end{bmatrix}$$

$$\Sigma_1 = \Lambda\Psi_1\Lambda^\top + \Theta_1$$

$$\Sigma_2 = \Lambda\Psi_2\Lambda^\top + \Theta_2$$

$$\Sigma_3 = \Lambda\Psi_3\Lambda^\top + \Theta_3$$

$$\Sigma_4 = \Lambda\Psi_4\Lambda^\top + \Theta_4$$

As it stands the model requires a number of restrictions to render the parameters identifiable. We set the vector  $\alpha_3$  to equal zero. This identifying restriction involves equating the constant intercepts and the means in the adult group:  $\mu_3 = v$ . As a consequence, the vectors  $\alpha_{1*}$ ,  $\alpha_{2*}$  and  $\alpha_{4*}$  are interpreted as mean differences in the common factors. This may be seen if we express the effect of equating  $\mu_3$  and  $v$  as follows:

$$\begin{aligned} \mu_1 &= v + \Lambda\alpha_1 & \Lambda\alpha_3 &= v + \Lambda(\alpha_1 - \alpha_3) = v + \Lambda\alpha_{1*} \\ \mu_2 &= v + \Lambda\alpha_2 & \Lambda\alpha_3 &= v + \Lambda(\alpha_2 - \alpha_3) = v + \Lambda\alpha_{2*} \\ \mu_3 &= v + \Lambda\alpha_3 & \Lambda\alpha_3 &= v \\ \mu_4 &= v + \Lambda\alpha_4 & \Lambda\alpha_3 &= v + \Lambda(\alpha_4 - \alpha_3) = v + \Lambda\alpha_{4*} \end{aligned}$$

In addition, we standardized the common factors EF and SP in all four groups ( $\Psi_1 = \Psi_2 = \Psi_3 = \Psi_4 = I$ ). In principle it is possible to standardize the common factors in one group and estimate the factor variances in the other three groups. The assumption of equal factor variances (i.e., standardized in all four groups) was tested and found to be tenable. The residual variances, however, were found to differ between the groups.

Note that in this model the common factors account both for the covariance between the reaction times within the groups and for the mean differences between the groups. This is consistent with our hypotheses that the groups differ with respect to the hypothetical constructs 'speed of responding' and 'executive functioning'. We are mainly interested in the estimates of  $\alpha_{1*}$ ,  $\alpha_{2*}$  and  $\alpha_{4*}$ , as these represent the differences in means between the groups.

**Table 2.1: Means (and standard deviations) of response latencies in ms. Acronyms are used for tasks: S=Simple Reaction Time task, C=Compatible task, I=Incompatible task, G=Gender task, D=Disjunctive task, DM=Disjunctive Memory task, DS=Dimensional Shift task**

Group	S	C	G	I	D	DM	DS
Child	319 (59)	467 (78)	693 (156)	584 (192)	675 (199)	768 (190)	996 (227)
Adolescent	287 (58)	397 (58)	615 (101)	467 (85)	562 (109)	694 (143)	864 (179)
Adult	274 (61)	362 (87)	560 (90)	444 (113)	515 (138)	623 (165)	830 (201)
Older Adult	314 (55)	467 (82)	728 (80)	729 (210)	801 (151)	978 (202)	1562 (351)

**Table 2.2: Means and Standard deviations of Error%. Acronyms are used for tasks: S=Simple Reaction Time task, C=Compatible task, I=Incompatible task, G=Gender task, D=Disjunctive task, DM=Disjunctive Memory task, DS=Dimensional Shift task**

Group	S	C	G	I	D	DM	DS
Child	—	7.6 (5.3)	21.2 (14.7)	14.9 (9.6)	6.6 (4.9)	9.4 (9.1)	22.2 (5.9)
Adolescent	—	3.1 (2.5)	9.9 (5.6)	6.2 (6.3)	4.1 (5.5)	4.7 (3.1)	19.4 (5.2)
Adult	—	2.8 (2.9)	7.6 (4.2)	4.9 (2.8)	2.9 (1.6)	3.2 (2.0)	19.3 (6.1)
Older Adult	—	4.7 (10.6)	2.8 (2.5)	5.2 (4.4)	1.6 (1.3)	4.8 (12.0)	26.2 (8.5)

## 2.3 Results and Discussion

The present sample consisted of 22 children, 17 adolescents, 21 young adults, and 19 older adults. Mean response latencies (and standard deviations) for correct responses in each task are presented for each Age Group in Table 2.1. Similarly, accuracy data are presented in Table 2.2. A graphical representation of these data is given in Figure 2.3.

### 2.3.1 Analysis of Variance

**Simple RT task** ■ Conforming to typical observations, response speed in the Simple RT task increases as children grow older and then decreases again as adults grow older. Pairwise comparisons between groups indicated that the 8–9 year old and the 60–79 year old were slower than the 19–33 year old. The 15–16 year old did not differ significantly from any of the other groups, nor did the 8–9 year olds differ from the 60–79 year old (see Table 2.3). No errors of omission were recorded for any subject.

**Table 2.3: Summary Table of ANOVA results on Correct Response Times in the Simple RT task**

		df	F	p
Age Contrast	Main Effect	(3,75)	2.84	.043
	8–11 vs 15–16	(1,38)	1.68	.096
	15–16 vs 19–33	(1,37)	0.70	.484
	19–33 vs 60–79	(1,39)	2.21	.030

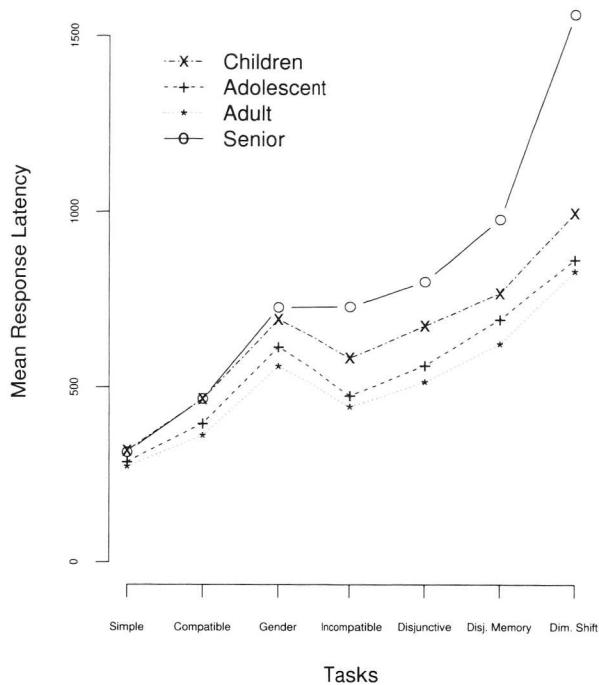


Figure 2.3: Graphical representation of the mean response latencies for all tasks.

**Compatible and Incompatible tasks** ■ Response latencies in the Compatible and Incompatible tasks varied as a function of S-R Compatibility and Age Group (see Figure 2.3). The effect of Age Group on response latency was such that adolescents were faster than children and young adults were faster than older adults, whereas 15–16 year-olds and 19–33 year-olds did not differ among each other (see Table 2.4). Incompatible responses were significantly slower than compatible responses. This S-R Compatibility effect was modulated by Age Group: it ranged from 117 ms in children to 70 ms in adolescents to 82 ms in young adults to 262 ms in older adults. Contrast analyses indicated that the S-R Compatibility effect was greater for 60–79 year-olds than for the other age-groups, whereas it did not differ between adolescents and young adults (see Table 2.4).

Response accuracy (error %) was also influenced by S-R Compatibility and Age Group (see Table 2.4). The effect of Age Group was such that 15–16 year-olds made fewer errors than did 8–11 year-olds. 60–79 year-olds made no more errors than 19–33 year-olds and also 15–16 year-olds and 19–33 year-olds did not differ among each other (see Table 2.4). The Incompatible task elicited significantly more errors than the Compatible task. This S-R

**Table 2.4: Summary Table of ANOVA results for the compatible and incompatible tasks, top half for response times, bottom half for the error %**

*Response times*

	<i>df</i>	<i>F</i>	<i>p</i>
Age	(3,75)	12.3	.000
Compatibility	(1,75)	99.0	.000
Age × Compatibility	(3,75)	9.87	.000
Age main Contrast	8–11 vs 15–16 15–16 vs 19–33 19–33 vs 60–79	(1,38) (1,37) (1,39)	2.47 .92 5.55
Age × Compatibility Contrast	8–11 vs 15–16 15–16 vs 19–33 19–33 vs 60–79	(1,38) (1,37) (1,39)	0.97 0.005 4.75

*Error %*

Age	(3,75)	9.06	.000
Compatibility	(1,75)	16.7	.000
Age × Compatibility	(3,75)	3.65	.016
Age main Contrast	8–11 vs 15–16 15–16 vs 19–33 19–33 vs 60–79	(1,38) (1,37) (1,39)	3.89 .48 .67
Age × Compatibility Contrast	8–11 vs 15–16 15–16 vs 19–33 19–33 vs 60–79	(1,38) (1,37) (1,39)	1.85 .44 .74

Compatibility effect was modulated by Age Group, ranging from 7.3% in children to 3.1% in adolescents to 2.1% in young adults to 0.5% in older adults.

**Gender task ■** Response latencies and accuracy in the Gender task varied as a function of Age Group (see Figure 2.3). The effect of Age Group on response latency can be described as follows: adolescents were faster than children and young adults were faster than older adults, whereas adolescents and young adults did not differ among each other (see Table 2.5). The effect of Age Group on errors of choice was such that 15–16 year-olds made fewer errors than did 8–11 year-olds. 60–79 year-olds did not make more errors than 19–33 year-olds; and again, no differences were observed between 15–16 year-olds and 19–33 year-olds (see Table 2.5).

**Table 2.5: Summary Table of ANOVA results on Response Times and Error% in the Gender RT task**

		<i>df</i>	<i>F</i>	<i>p</i>
<i>Response Times</i>				
Age	Main Effect	(3,75)	9.15	.000
Contrast	8–11 vs 15–16	(1,38)	2.15	.035
	15–16 vs 19–33	(1,37)	1.51	.134
	19–33 vs 60–79	(1,39)	4.71	.000
<i>Error %</i>				
Age	Main Effect	(3,75)	17.4	.000
Contrast	8–11 vs 15–16	(1,38)	4.07	.000
	15–16 vs 19–33	(1,37)	.083	.406
	19–33 vs 60–79	(1,39)	1.78	.078

**Disjunctive and Disjunctive Memory tasks** ■ Response latencies in the Disjunctive and Disjunctive Memory tasks varied as a function of Working Memory Load and Age Group (see Figure 2.3). The effect of Age Group on response latency showed that 15–16-year-olds tended to be faster than 8–11 year-olds and 19–33 year-olds were faster than 60–79 year-olds, whereas 15–16 year-olds and 19–33 year-olds did not differ (see Table 2.6. Responses were significantly slower in the load compared to no-load condition. This Working Memory Load effect was not modulated by Age Group. Contrast analyses indicated that the Working Memory Load effect tended to be smaller for 19–33 year-olds than for 60–79 year-olds (see Table 2.6).

The incidence of errors of choice was influenced by Age Group and tended to be influenced by Working Memory Load. Tests of the effect of Age Group showed that children committed more errors of choice than did adolescents, but adolescents, young and older adults did not differ among each other (see Table 2.6). The Working Memory Load condition tended to elicit more errors than the no-load condition. This Working Memory Load effect was equal between Age groups (see Table 2.6). Thus, the conspicuously small Working Memory Load effect on response latency observed in young children could not be explained by a trade-off between speed and accuracy.

**Dimensional Shift task** ■ First, response latencies in the Dimensional Shift task varied as a function of Response Category and Age Group (see Table 2.7). As in the other tasks, the effect of Age Group on response latency was such that 19–33 year-olds were faster than 60–79 year-olds, whereas 8–11 year-olds, 15–16 year-olds and 19–33 year-olds did not differ among each other (see Table 2.7 and 2.8). Response latencies differed between the four response categories: see Table 2.8.

The number of trials needed to learn and apply the first dimensional discrimination rule, the number of rule shifts, and the number of perseverative trials per rule shift (see Table 2.7) were submitted together as dependent measures to MANOVA. The multivariate test revealed a significant Age Group effect ( $\text{Wilks } \lambda = .793, F(3,73)=1.97, p=.044$ ). Contrast analysis on

**Table 2.6: Summary Table of ANOVA results for the Disjunctive and the Disjunctive Memory tasks, top half for response times, bottom half for the error %**  
**Response times**

		df	F	p
Age		(3,75)	15.8	.000
Memory Load		(1,75)	83.7	.000
Age × Memory Load		(3,75)	1.78	.157
Age main Contrast	8–11 vs 15–16	(1,38)	1.87	.065
	15–16 vs 19–33	(1,37)	1.17	.246
	19–33 vs 60–79	(1,39)	6.54	.000
Age × Memory Load Contrast	8–11 vs 15–16	(1,38)	0.98	.340
	15–16 vs 19–33	(1,37)	0.57	.537
	19–33 vs 60–79	(1,39)	1.77	.080
<b>Error %</b>				
Age		(3,75)	5.48	.002
Memory Load		(1,75)	3.63	.061
Age × Memory Load		(3,75)	0.63	.595
Age main Contrast	8–11 vs 15–16	(1,38)	2.45	.017
	15–16 vs 19–33	(1,37)	.089	.371
	19–33 vs 60–79	(1,39)	.008	.930
Age × Memory Load Contrast	8–11 vs 15–16	(1,38)	.79	.429
	15–16 vs 19–33	(1,37)	.124	.901
	19–33 vs 60–79	(1,39)	1.10	.264

**Table 2.7: Dependent Measures derived from the Dimensional Shift Task**

Group	RT Initial Rule Search	RT Subsequent Rule Search	RT Perseverative Responses	RT Rule Application	# Trials Preceding First Shift	# Rule Shifts	# Perseverative Responses per Shift
Child	1168	1011	990	977	19.0	13.5	4.19
Adolescent	1072	958	935	830	12.4	15.6	2.95
Adult	982	911	884	819	15.0	16.4	2.86
Older Adult	2008	1689	1672	1558	21.8	10.7	5.90

subsequent ANOVA's was performed to further examine the Age Group effects on each of these dependent measures separately (see Table 2.9).

The number of trials needed to learn and apply the first dimensional discrimination rule did not differ between Age Groups. The number of rule shifts did depend on Age Group: Adults made more rule shifts than older adults; Children, adolescents and young adults reached an equal number of rule shifts. Finally, the number of perseverative trials per rule shift varied with age: Older adults persevered more often than young adults; Children and young adults did not differ from adolescents.

**Table 2.8: Summary Table of ANOVA results on Response Times Measures in the Dimensional shift task**

		df	F	p
Age		(3,75)	32.7	.000
Response Category		(3,73)	11.8	.000
Age × Response Category		(9,177.8)	.866	.557
Age Main Contrast	8–11 vs 15–16	(1,38)	0.90	.365
	15–16 vs 19–33	(1,37)	0.50	.610
	19–33 vs 60–79	(1,39)	8.86	.000
Response Category Contrast	Initial Rule vs Subsequent rule search	(1,75)	13.7	.000
	Initial Rule vs Perseverative responses	(1,75)	16.9	.000
	Initial Rule vs Rule Application	(1,75)	25.5	.000
	Subsequent Rule vs Perseverative responses	(1,75)	4.1	.045
	Subsequent Rule vs Rule Application	(1,75)	22.6	.000
	Perseverative responses vs Rule Application	(1,75)	10.3	.002

**Table 2.9: Summary Table of ANOVA results on each of the frequency measures in the dimensional shift task. #Preshift = number of trials preceding the first shift; #Shifts = total number of rule shifts; #Pers = mean number of perseverative responses per shift.**

#Preshift				
Age		(3,75)	.755	.532
Contrast	8–11 vs 15–16	(1,38)	0.98	.328
	15–16 vs 19–33	(1,37)	0.10	.693
	19–33 vs 60–79	(1,39)	1.03	.303
#Shifts				
Age		(3,75)	6.14	.001
Contrast	8–11 vs 15–16	(1,38)	1.46	.147
	15–16 vs 19–33	(1,37)	0.53	.594
	19–33 vs 60–79	(1,39)	3.97	.000
#Pers				
Age		(3,75)	2.80	.049
Contrast	8–11 vs 15–16	(1,38)	0.99	.322
	15–16 vs 19–33	(1,37)	0.01	.943
	19–33 vs 60–79	(1,39)	2.54	.000

### 2.3.2 Discussion of ANOVA Results

The general pattern emerging from ANOVA is that on most of the tasks, children performed worse than adolescents and older adults performed worse than young adults, while performance in adolescents and young adults was comparable. For response latency measures, this U-shaped pattern was obtained in each task, although in some tasks (the Gender and Disjunctive tasks) the rise in response time in older adults may be explained in part by a tendency to trade speed for accuracy. The U-shaped pattern was also obtained for the size of the effect of S-R Compatibility on response time, although again for older adults the sizable effect on response time was accompanied by only a small effect on accuracy, suggesting a role for speed-accuracy trade-off in this effect. In the Dimensional Shift task, the Age Group effect on all four response time measures conformed to the general U-shaped pattern.

In most cases, the incidence of errors was consistent with the patterns observed in speed of responding, with the exceptions already mentioned above. The U-shaped pattern for Age Group effects also applied to the number of rule shifts and the number of perseverative errors (per shift) in the Dimensional Shift task, but not to the total number of trials needed to learn and apply the first dimensional discrimination rule. The latter finding diverges somewhat from the normative results for a similar measure derived from the WCST (Heaton et al., 1993), whereas the findings for the number of rule shifts and number of perseverative errors correspond more closely to typical findings. On the basis of this pattern, we may speculate that children and older adults are not necessarily deficient in rule-induction capabilities, as such deficiencies would have manifested themselves in the number of trials needed to infer the initial discrimination rule. This inference is consistent with the conclusion derived by another experiment in our laboratory where we used two different WCST-like tasks (one of which was identical to the one employed here), and concluded that the tendency to persevere in no-longer-correct behavior resulted not from deficient rule-induction or performance-monitoring abilities, but instead from deficient set-shifting abilities (i.e., the ability to implement appropriate task sets and suppress the no-longer relevant task set). Latent-variable also analysis indicates that this *set-shifting* component is central to WCST performance (Miyake et al., 2000).

To summarize the ANOVA outcomes, the speed of information processing in each task appeared to conform generally to a U-shaped pattern in which children performed worse than adolescents and older adults performed worse than young adults, whereas adolescents and young adults did not differ much from each other. We have designed four of our tasks (the Incompatible, Disjunctive, Disjunctive Memory, and Dimensional Shift tasks) to involve executive functions, whereas the three other tasks (the Simple RT, Compatible, and Gender tasks) were designed to call on executive functions to a lesser extent. If we compare the averaged age trends in the speed of 'executive' tasks (756, 647, 603, and 1018 ms in children, adolescents, young adults, and older adults, respectively) to the averaged age trends in the speed of 'non-executive' tasks (493, 433, 409, and 503 ms, respectively), then the effects of old age appear to be substantially more pronounced in the 'executive' compared to 'non-executive' tasks. This impression is illustrated by Figure 2.4, which plots

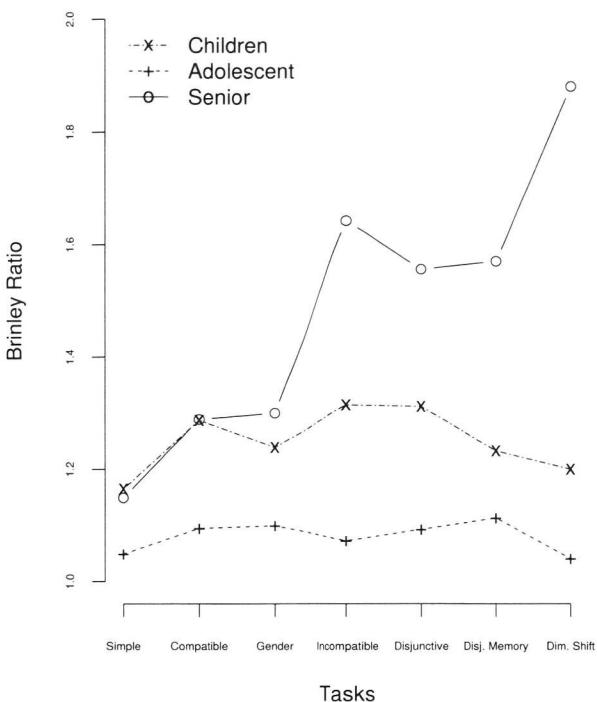


Figure 2.4: *Brinley Ratios: The ratio of the mean response latency of each age-group divided by the response latency of the young adults.*

per task the response latency of each Age Group proportional to the response latency of young adults in that task. The validity of this inference was tested using Brinley analysis and MANCOVA.

### 2.3.3 Brinley Analysis

The mean response times for correct trials on each task were submitted to Brinley analysis (a form of linear regression using a bivariate weighted least squares method) for each of the age groups (separately for children versus young adults, adolescents versus young adults, and older versus young adults). The offset and slope of the Brinley function were respectively 32 (ns) and 1.18 for the children, 15 (ns) and 1.04 for adolescents and -310 and 2.14 for the senior group. The linear fit of the Brinley plots was excellent for children ( $R^2=.98$ ,  $F(1,5)=391$ ,  $p<.001$ ), adolescents ( $R^2=.99$ ,  $F(1,5)=696$ ,  $p<.001$ ), and older adults ( $R^2=.95$ ,  $F(1,5)=100$ ,  $p<.001$ ), indicating that a general speed factor accounts for most of the age-related variance in each of the tasks. This conclusion is at odds with the pattern of ANOVA

**Table 2.10: Residual Group effects on executive functioning after partialing out the covariance with generic "speed" response speed.** I=Incompatible task, D= Disjunctive task, DM=Disjunctive Memory task, DS=Dimensional Shift task.

	Children vs. Adults	Adolescent vs. Adults	Seniors vs. Adults
I	$F(1,38)=.050, p=.824$	$F(1,33)=.095, p=.760$	$F(1,35)=5.182, p=.029$
D	$F(1,38)=.144, p=.707$	$F(1,33)=.154, p=.697$	$F(1,35)=9.399, p=.004$
DM	$F(1,38)=.006, p=.940$	$F(1,33)=.037, p=.848$	$F(1,35)=7.759, p=.009$
DS	$F(1,38)=.122, p=.729$	$F(1,33)=.085, p=.772$	$F(1,35)=20.66, p<.001$

outcomes, which suggested that the effects of age were substantially more pronounced in the ‘executive’ compared to ‘non-executive’ tasks. A more direct test of the amount of age-related variance in executive functioning after the contribution of a general speed factor is partialled out is provided by the results of covariance analysis.

#### 2.3.4 Analysis of Covariance

The mean response times for correct trials on each task (as displayed in Figure 2.1) were submitted to MANCOVA, to assess whether the independent (between-subjects) variable Age Group exerts significant effects on response latency in the executive function tasks after the age effects on non-executive tasks are partialled out. Mean response times from the Incompatible, Disjunctive, Disjunctive Memory, and Dimensional Shift tasks (thought to involve executive functions) were entered as dependent variables whereas mean response times from the Simple RT, Compatible, and Gender tasks (thought to involve executive functions to a lesser extent) were entered as covariates. MANCOVA results are shown in Table 2.10.

A significant effect of Age Group was obtained for each of the dependent variables. This result indicates that when the global age-related variance resulting from age changes in global processing speed is partialled out, Age Group still explains a significant amount of variance in the speed of executive function measures. Contrast analyses revealed that older adults were significantly slower on each of the executive function tasks (after partialing out non-executive processing speed), whereas children, adolescents, and young adults did not differ from each other.

**Table 2.11:** Percentage of variance explained by the common factors. Acronyms are used for tasks:  
*S=Simple Reaction Time task, C=Compatible task, I=Incompatible task, G=Gender task,  
D=Disjunctive task, DM=Disjunctive Memory task, DS=Dimensional Shift task*

	S	C	G	I	D	DM	DS
children	74%	74%	36%	50%	61%	60%	51%
adolescent	56%	99%	38%	78%	85%	71%	47%
adults	53%	94%	53%	87%	96%	64%	40%
older adult	57%	63%	48%	33%	72%	53%	15%

**Table 2.12:** Maximum Likelihood estimates of difference in common factor mean (standard errors in parentheses).

	$\alpha 1^*$		$\alpha 2^*$		$\alpha 4^*$	
	est	se	est	se	est	se
Generic Speed	1.29	(0.35)	0.44	(0.34)	1.41	(0.37)
Executive Function	0.11	(0.72)	-0.35	(0.62)	6.88	(2.84)

### 2.3.5 Structural Equations Modelling

We fit the model as presented above using LISREL 8.30 (Jöreskog and Sörbom, 1993) using normal theory maximum likelihood estimation. As computation problems may arise when the variances of the variables differ greatly (as is the case here) we opted for the following procedure. We rescaled the tests so that the variances were all about 1.0. Rescaling the variables does not alter the groups differences in any meaningful way. The  $\chi^2$  goodness of fit for the full model equaled  $\chi^2(88) = 100.58, p = .17$ . This shows that the model provided an adequate description of the data. The adequacy of fit was also apparent in the standardized residuals (i.e. the differences between the observed means and covariance matrices and the expected (*model*) means and covariance matrices, see Figure 2.5). In this figure both the observed means and the expected means are shown. The variances of the 7 tasks explained by the two common factors are shown in Table 2.11.

The maximum likelihood estimates and standard errors of the parameters in the vectors  $\alpha 1^*$ ,  $\alpha 2^*$  and  $\alpha 4^*$  are show in table 2.12. These parameters represent differences in common factor means relative to the adult group. Judging by the standard errors of the estimates, we find that the children differ from the adult only with respect to the SP factor. The difference in mean of the EF factor is not significant. The adolescents do not differ from the adults on any of the dependent measures. We refit the model with these two groups pooled to test this hypothesis. The  $\chi^2(97)$  goodness of fit now equals 110.06,  $p=.17$ , showing that pooling the two groups does not alter the fit of the model. The main test for our model is the test whether a model without an executive factor would describe the data significantly worse. Fixing the mean difference in the EF factor to zero, we found an  $\chi^2(91)$  is 139.17,  $p=.00087$ , showing that the mean differences in latent 'executive' factor are important in our model. Our conclusion from these data is that children differ from adults only on the SP

factor, adolescents do not differ from adults on any of the latent factors, and older adults differ from young adults on both the SP and the EF latent factors. This pattern is apparent in Figure 2.6.

A post hoc comparison of the full model with a model where an executive factor was postulated only for the older adults revealed a  $\chi^2$  of 100.08,  $p=.22$ . This confirms our observation that only older adults show a significant effect of the latent executive function factor on response speed.

Figure 2.5 displays plots of the observed and fitting mean vectors in the three groups. Figure 2.6 provides plots of the decomposition of means relative to the adult group. Here we consider the contribution of each of the common factors to the mean differences. For instance, the mean difference on test 4 is decomposed into a part that is due to the EF factor ( $\lambda_{41} SP_j$ ) and a part that is due to the SP factor ( $\lambda_{42} EF_j$ ) - see Equation 2.1. The plots indicate that the older adults and children differ from the adults with respect to the speed factor in the about same way. The EF factor contributes very little to the child-adult differences in means (not significant). The EF factor does contribute considerably to the response latency for seniors.

To summarize the SEM results, the EF factor was necessary only to account for older adults's response latency data of the executive-function tasks. In all other cases, the SP factor was sufficient to explain the age-related variance. Thus, developmental changes in the speed of processing in those tasks that rely on cognitive control could be adequately accounted for by the general speed factor. In contrast, the effects of aging on processing speed in executive-function tasks cannot be accounted for by global slowing alone; additional factors (compressed into a single EF factor) contribute independent age-related variance.

## 2.4 General Discussion

Two different theoretical frameworks, the global speed hypothesis and the specific loss hypothesis, have driven a great deal of the research efforts in the areas of cognitive development and aging over recent years. Few attempts have been made to evaluate explicitly the discriminative and predictive power of the global speed and specific loss hypotheses against each other, or to evaluate the extent to which the two hypotheses complement each other. The main objective of the present study was to fill this hiatus by conducting a life-span developmental study, using a series of tasks that vary in executive control demands. In order to minimize sources of age-related variance that originate in differences in general task and stimulus characteristics, all tasks were speeded response tasks sharing the same task format and stimulus materials. Parametric variations of the basic task yielded a battery of tasks that varied response selection, response inhibition, working memory, and adaptive control demands, while in other tasks these executive control demands were reduced or absent. Analysis of covariance was aimed at identifying whether age-related changes in the efficiency of executive control can or cannot be explained in terms of a global speed factor; structural equations modelling was used to evaluate a model that included both global speed and executive control as latent factors underlying age changes in cognitive task performance

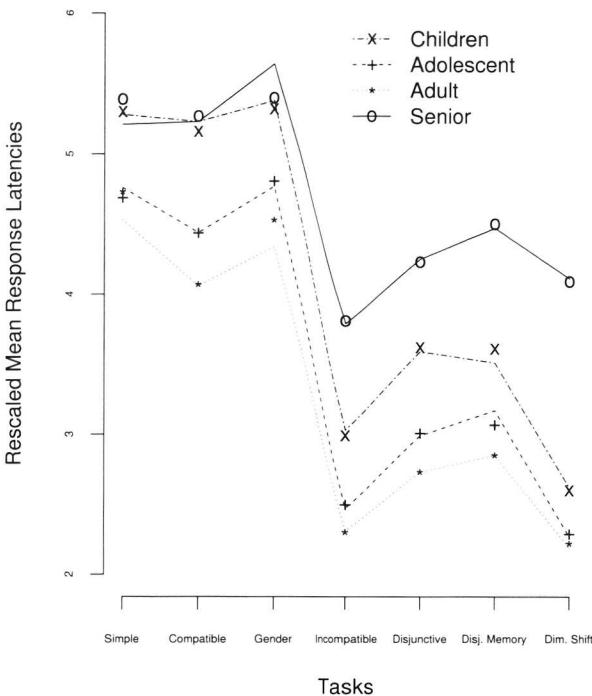


Figure 2.5: *Observed and modelled rescaled response latencies: Lines represent the observed data, markers the modelled means. Dash-dotted lines and 'x' markers represent children, dashed lines and '+' markers represent adolescents, dotted lines and '\*' markers represent adults, solid lines and 'o' markers represent seniors.*

against a model that included only the global speed factor.

## 2.4.1 Evaluation of Results

### Conventional Analyses

The ANOVA suggested that, in general, performance on each task improved between childhood and adolescence and deteriorated between young adulthood and senescence, while performance was comparable for adolescents and young adults. The age-related differences appeared to be considerably more outspoken for the Incompatible, Disjunctive, Disjunctive Memory, and Dimensional Shift tasks (entailing executive control demands) compared to the Simple RT, Compatible, and Gender tasks (designed to involve executive functions to a lesser extent). The Brinley analyses, however, provided adequate fits for each of the age groups, indicating that a general speed factor explained most of the age-related

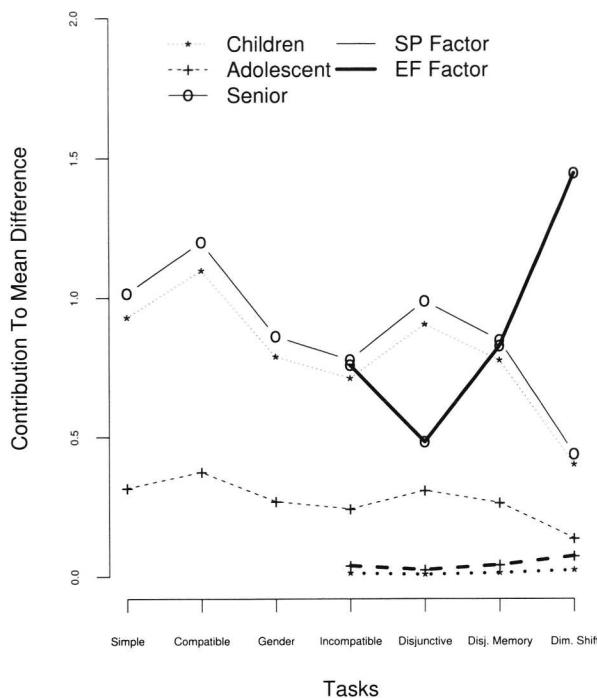


Figure 2.6: Dashed lines through '\*' to the Child-Adult comparison, dashed lines through '+' to the Adolescent-Adult comparison and solid lines through 'o' to the Senior-Adult comparison. The thin lines represent the contribution of the latent 'speed' factor to the mean differences, the thicker lines represent the contributions of the latent 'executive' function.

variance in each of the tasks, thus dismissing the need to invoke a separate executive control factor.

Thus, while ANOVA (suggesting greater age effects on executive control tasks) fails to take global age changes in information-processing speed into account, Brinley analysis (suggesting indiscriminate age-related changes) neglects differential age effects altogether. Many researchers have questioned the validity of Brinley analysis in assessing process-specific age-related trends (e.g., Bashore and Smulders, 1995; Fisher and Glaser, 1996; Perfect, 1994; Ratcliff et al., 2000), suggesting that it may lead to premature acceptance of global models of cognitive changes in processing speed with age. In particular, Ratcliff et al. (2000) argued that the slope of Brinley functions is sensitive to the relative spread of reaction time distributions rather than to the mean, and demonstrated (through simulation studies) that Brinley analysis is insensitive to over-additive process-specific age effects on

processing speed. Thus, rather than relying on techniques that are not optimally suited to determine the contribution of global processing speed (ANOVA) or executive control function (Brinley analysis) to age-related changes in the efficiency of cognitive processing, we turned to other statistical techniques.

### **Analysis of Covariance**

To provide an unbiased assessment of the extent to which age exerts an independent influence on the efficiency of executive control after the age-related covariance with global processing speed is partialled out, mean response times for each executive function task were submitted to MANCOVA with mean response times on each non-executive task entered as covariates. These analyses revealed a mixed pattern of results. For the child group, partialing out global speed served to remove the differences with adolescents in each of the executive function tasks, suggesting that global processing speed was the primary factor underlying developmental changes in the efficiency of information processing, regardless of the involvement of executive control functions. In contrast, for the older adults, substantial residual differences with young adults remained in each of the executive function tasks after controlling for global processing speed. Thus, executive control comprises a fundamental factor underlying the effects of aging on the efficiency of cognitive processing, independent of aging effects on global processing speed.

The striking discrepancy between the results at the opposite ends of the life span attests to the sensitivity of the covariance analysis to both the global speed and executive control factors. Insensitivity of the method to any of these factors would have resulted in patterns of results going in similar directions for development and aging, which is clearly contradicted by the present outcome. Thus, when assessing age-related changes in the speed of cognitive processes, the present MANCOVA approach should be preferred over the more conventional ANOVA or Brinley regression techniques.

Before interpreting the validity of the global speed and specific loss hypotheses, and the differential age effects observed in MANCOVA, we first turn to the results of the SEM tests of the explicit model.

### **Structural Equations Modelling**

The model presented in Figure 2.2 provided a reasonably adequate description of the response latency data from each age group. Adolescents and young adults differed neither in the SP factor nor in the EF factor; by the age of 15, the efficiency of information processing has approached that of young adults, regardless of the type of task included in this study. Children differed from adolescents, but only in the SP factor; blocking out the EF factor from the model did not result in a poorer model fit. According to the parsimony principle, if two models provide an equal goodness of fit, the one that has fewer free parameters should be preferred. Thus, for the child group, the model without the EF factor should be preferred over the extended model. In accordance with the MANCOVA results, this outcome suggests

that global processing speed was the primary factor underlying developmental changes in the efficiency of information processing, regardless of the involvement of executive control functions. Young and older adults differed not only in the SP factor but also in the EF factor; blocking out the EF factor from the model resulted in a considerable deterioration of the model fit. Again consistent with the MANCOVA results, this outcome suggests that both global processing speed and executive control are important and independent factors contributing to the effects of aging on the efficiency of cognitive processing.

In addressing age changes in information-processing speed, the SEM approach not only shares the advantages described above for the MANCOVA approach, but also makes use of the full covariance structure to afford a statistical evaluation of the goodness of fit. Most importantly, it enables us to formulate an explicit model we can test against alternatives with a different factor structure.

## 2.5 Differential Patterns of Development and Aging

The results of the covariance analyses and of structural equations modelling indicated that the speed of information processing in older adults was slowed (beyond global slowing) on tasks that placed serious demands on response selection, response suppression, working memory, and adaptive control. These findings are consistent with the literature on neurocognitive change, which suggests that tasks that involve executive control are more sensitive to the effects of aging than tasks that can be performed without invoking executive control mechanisms extensively (for reviews see, e.g., van der Molen and Ridderinkhof, 1998a; West, 1996). This literature also suggests that executive control tasks are especially sensitive to the effects of age during childhood development. However, the SEM and MANCOVA results indicated that the developmental differences in information-processing speed in tasks involving response selection, response suppression, working memory, and adaptive control could be explained almost completely by the global speed factor.

This differential pattern of age effects is difficult to explain, either from the global speed perspective or from the neurocognitive change perspective. If global speed can explain age changes in cognitive control task performance in children, there is no good reason (*a priori* or *a posteriori*) to expect that it can not explain such age changes in older adults. Likewise, if frontal-lobe changes during senescence can predict the effects of aging on cognitive control task performance, then similar developmental patterns should accompany the apparently similar frontal-lobe changes during childhood.

A possibility to be considered is that the age-related changes in the structure and function of frontal brain areas during childhood and later adulthood are not as symmetrical as previously supposed. In fact, the processes of growth and deterioration are qualitatively different in many respects (see review in van der Molen and Ridderinkhof, 1998a), and do not necessarily involve the same structures or substructures (Casey et al., 2000; Raz, 2000). Yet, the literature by and large suggests that children and older adults are subject to similar performance deficiencies on cognitive tasks that involve executive control functions, including the response selection, response suppression, working memory, and adaptive

control functions tapped in the present study.

On a more structural level, the data can also be interpreted in the context of development of basic cognitive functions. The response latencies of young children are indifferentially slower in both simple and complex tasks, whereas older adults show a differential pattern of slowing between task-types. This pattern would be expected if the executive tasks (which are experimental derivatives of clinical tasks) do not engage structures that are sensitive to development. This hypothesis is not likely, given the differential pattern found in the older population. However, this pattern would also be observed if in children simple response tasks also rely on these (prefrontal) structures. A possible explanation for the observed pattern of development can therefore also be involvement of executive, prefrontal structures in simple response type tasks, leading to an indistinguishable slowing in all tasks.

Another possibility to be considered pertains to performance strategies. Although in our sample of children the effects of task difficulty on response latency were generally matched by effects on accuracy, the latter effects were conspicuously large when compared with the corresponding effects for older adults. Thus, although children obviously did not trade accuracy for speed to the extent that they became *faster* in more difficult task conditions, their speed/accuracy balance may have differed in more subtle ways from that in older subjects. In particular, they may have favored accuracy over speed (rather than trade accuracy for speed), such that effects of task difficulty were expressed in accuracy relatively more than in speed. Thus, task difficulty effects would be visible in response speed, but only marginally so; they would be most pronounced in accuracy. Such subtle balance differences would have the strongest effects (in absolute terms) in conditions that were most challenging to the children, that is, in the task conditions that called for executive control. As a result, developmental changes in executive control function might not exceed the global-speed effects for reasons of differential speed/accuracy balance (note that we do not mean to imply intentional effects; speed/accuracy balance differences may be either intentional or unintentional). If in older adults, in contrast, effects of task difficulty were expressed equally in speed and accuracy, or in speed relatively more than in accuracy, then the effects of aging on executive control function would exceed the global-speed effects.

**The Global Speed and Specific Loss Frameworks ■** Both the global speed hypothesis and the specific loss hypothesis have 1) been able to explain a wide spectrum of data; 2) offered a new and/or richer understanding of these phenomena; and 3) generated new (empirically verifiable) hypotheses concerning the underlying mechanisms. The considerable merits of these theoretical frameworks notwithstanding, however, recent reports have consistently diminished the fruitfulness and devalued the general parsimony of both frameworks.

The global-speed hypothesis has received overwhelming support by the outcomes of empirical and meta-analytical studies, but the present study has made out a case adding to the increasing evidence for process-specific age-related differences on top of the global trend (Bashore and Smulders, 1995; Kramer et al., 1999, 1994; Kray and Lindenberger, 2000; Mayr, 2001; Ridderinkhof et al., 1999; Ridderinkhof and van der Molen, 1997; van Asselen

and Ridderinkhof, 2000). Although some findings emphasize the role of global processing speed in age changes in cognitive control tasks (e.g., Salthouse et al., 1998a), there is now sufficient evidence against a singular global-speed model of age-related changes. As has been demonstrated in the present study, the global speed hypothesis is faced with findings that are difficult to incorporate or account for without making further assumptions, and in its present form it does not readily offer hypotheses to gain a deeper understanding of these discrepant findings.

The frontal-lobe hypothesis is also beginning to lose some of its attractiveness, since evidence is surfacing that the frontal lobes are not universally affected by age; substantial differentiation has been reported (especially in the aging brain) with some areas even within prefrontal cortex being relatively spared (cf. Raz, 2000; Uylings and de Brabander, *in press*). Likewise, executive control functions appear to be differentially sensitive to age. Not only do developmental outcomes appear to depend on differences in terms of tasks or task formats (cf. Kok, 2000; Kramer et al., 1994; Ridderinkhof et al., *in press*; van der Molen et al., 2000), but also on differences in the specific demands on executive control functions (cf. Kray and Lindenberger, 2000; Ridderinkhof et al., *in press*). In addition, the present study indicates that, where the frontal-lobe hypothesis predicted similar outcomes for cognitive development and aging, differential patterns emerged. All in all, the universal frontal-lobe hypothesis, although able to account for many findings, is now faced with new discrepant findings. As a result, the frontal-lobe hypothesis fails to provide an integral account for some of the relevant phenomena, and thus faces difficulties in generating hypotheses concerning the mechanisms underlying these intricate age-related changes.

Thus, it is time to augment the original versions of the global-speed and neurocognitive-change approaches, and focus more on the extent to which different cognitive control functions are differentially sensitive to age effects, and identify the factors that influence these patterns (cf. Ridderinkhof and van der Stelt (2000), who concluded from a review of the psychophysiological literature on age changes in attention and selection that most attentional functions are in essence available even to young children, but that these functions are deficient in young children as a function of task demands, stimulus characteristics, and other). While global speed will continue to account for large proportions of age-related variance in our data, we will at the same time have to look further at process-specific changes in cognitive functions, and their relations to brain change. For instance, in a recent study we decomposed the factors underlying perseverative behavior in WCST-like tasks and observed that the effects of aging were manifest on set-shifting abilities but not rule-induction or performance monitoring abilities (Ridderinkhof et al., *in press*). Modern neuroimaging techniques can be used to help refine the picture of age-related changes, and of the brain areas involved.



# **PERSEVERATIVE BEHAVIOR AND ADAPTIVE CONTROL IN OLDER ADULTS: PERFORMANCE MONITORING, RULE INDUCTION, AND SET SHIFTING**

Older adults, like patients with dorsolateral frontal lobe lesions, have been shown to be progressively susceptible to errors of perseveration in the Wisconsin Card Sorting Test (WCST). This deficit may result from several types of endogenous adaptive control abilities. First, to enable behavioral modifications in response to sudden changes in task demands, one has to consider and evaluate the possible alternative categorization rules and select one for further testing (rule induction). Second, to perform the required shift appropriately, one should suppress the no-longer relevant task set and replace it by an appropriate new one (set shifting). Third, however, proper application of rule-induction and set-shifting abilities requires the ability to monitor and interpret task cues and feedback signals appropriately to guide behavior and to recognize the need to apply rule-shift operations (performance monitoring).

To explore the extent to which these different endogenous adaptive control abilities are differentially sensitive to the effects of aging, young and older adults were tested in two experiments using WCST-like tasks. From the finding that older adults were not able to capitalize on explicit shift cues (either non-specific or specific) the inference can be drawn that basic set-shifting abilities, rather than rule-induction or performance-monitoring abilities, were the primary factor responsible for the increased tendency to persevere as adults grow into senescence.

During the later stages of adult life, cognitive flexibility deteriorates and older adults experience a progressive decrease in their ability to deal with change in their daily life. This inflexibility pertains not only to habitual behavioral patterns, but also to acting adequately in response to rapidly changing demands, such as in busy traffic. Cognitive flexibility requires the operation of adaptive control abilities, that are central to executive functions. According to widely held views, the frontal lobes play an important role in executive functioning; in addition, frontal brain structures are especially sensitive to the effects of age (cf. Raz, 2000; van der Molen and Ridderinkhof, 1998b; West, 1996). It should be noted, however, that the frontal lobes show substantial differentiation in age-related deterioration (cf. Band et al., in press; Uylings and de Brabander, in press). Similarly, the recent literature on cognitive aging reveals patterns of differentiation in the age-related decline in executive functions (e.g., Kramer et al., 1994; Mayr, 2001). Different facets of adaptive control abilities as involved in cognitive flexibility may also be differentially susceptible to the effects of age.

In clinical and experimental neuropsychology, the Wisconsin Card Sorting Test (WCST; Grant and Berg, 1948) has become one of the primary tools to examine cognitive flexibility and adaptive control abilities. Older adults' WCST performance bears resemblance to performance of frontal-lobe patients, in that they tend to persevere in old task sets when changing task demands call for a shift to new task sets (for a review see, e.g., West, 1996). In the present study we set out to empirically decompose and explore the adaptive control abilities involved in perseverative behavior, and determine which of the constituent control functions are deficient in older adults.

### **3.1 Perseverative Behavior**

In interacting with the environment, one is often required to shift rapidly from one task to another, suppressing old action schemes and adopting new ones, reconfiguring task sets so as to allow appropriate actions in response to environmental demands and changes therein. Specific task sets are often activated directly by specific environmental stimuli, since strong associations have been formed between such stimuli and action schemes (through, e.g., prior experience, habitual tendencies, or prepotent relationships). According to Norman and Shallice, 1986, appropriate action schemes are selected automatically through a competition among the alternative associations. This process (which they termed "contention scheduling") is sufficient to afford suitable performance unless the actions resulting from the winning task set are in some way inappropriate. Natural response tendencies must often be overridden to prevent undesirable behavior. In the view of Norman and Shallice (1986), in that case a "supervisory attention system" (SAS) will intervene. The SAS deliberately modulates the levels of activation of the action schemes involved, thus reconfiguring the task set to meet the behavioral objectives as prompted by the changed environmental demands. A similar distinction between task-set configuration processes has been drawn by Rogers and Monsell, 1995, who used the term "exogenous control" to refer to those task set configuration processes that are triggered more or less automatically by external events, and "endogenous control" to refer to the executive task-coordination processes that are initiated at will and in advance of the up-coming stimulus.

Failures to exert endogenous control may under some circumstances lead to capture errors. Examples of capture errors are everyday action slips, such as the person who picks up his tooth brush and automatically starts brushing his teeth when his intention was in fact to pack his tooth brush for a conference trip. These perseverative action slips can occur when specific stimuli and actions have come to be associated with a particular context (through, e.g., frequent practice); a stimulus then automatically activates the habitually associated action schema instead of the action actually intended.

Strong habitual associations of particular stimuli with particular task sets are not the only conditions under which perseverative errors can be observed. Even recently formed arbitrary associations may yield a task set strong enough to yield perseverative behavior when a shift to alternative arbitrary associations is required. In the well-known WCST, once subjects have classified cards according to one stimulus dimension (e.g., color) for a while,

they may experience some difficulty in shifting to another sorting principle (e.g., classifying the same cards according to shape). In an extreme example using an appropriately adjusted version of the WCST, Zelazo et al., 1996 reported that many three-year-old (as opposed to four-year-old) children persevere in sorting cards according to color, even when an explicit verbal instruction told the children to now sort cards according to shape, and even when prior to the shift only one single card had been sorted according to color (or vice versa).

These examples illustrate that when circumstances require a shift of tasks and, therefore, a re-configuration of task set, failures to exert endogenous control can yield perseverative errors in at least two ways. One condition under which perseverative behavior can occur is when strong habitual associations exogenously trigger inappropriate action schemes. Another such condition may occur when exogenous control is less apparent, for instance when the stimuli are mapped arbitrarily onto action schemes, so that the stimulus (or the context in which it appears) does not inherently activate some action schema. In such a situation, the action schema that happened to be activated prior to the shift-signal will remain active after the shift-signal because of a failure to reconfigure the task set endogenously.

### 3.1.1 Perseverative Behavior in Frontal Patients

In a study using the WCST, Milner, 1963 observed that patients with dorsolateral frontal lobe lesions experienced more difficulties in shifting from one categorization rule to another compared to patients with orbitofrontal or more posterior lesions. These impairments were attributed to an increased susceptibility to the perseverative interference of responses made according to the previously correct rule. Since Milner (1963)'s seminal paper, many reports have confirmed the specific sensitivity of perseverative behaviors to deficient functioning of frontal cortex (e.g., Barceló et al., 1997; Barceló and Santome-Calleja, 2000; Drewe, 1974; Stuss and Benson, 1984). Such reports have received support from recent neuro-imaging studies, suggesting the activation of prefrontal structures in successful WCST performance (e.g., Barceló, 1999; Berman et al., 1995; Konishi et al., 1999, 1998; Omori et al., 1999; Ragland et al., 1997; Tien et al., 1998). For instance, a recent event-related fMRI study showed that a dimensional shift in the WCST elicited activation of the posterior part of the inferior prefrontal sulci that occurred time-locked to the dimensional shift (Konishi et al., 1999).

Considering that WCST performance involves many different aspects of executive functioning (e.g., performance monitoring, integration of feedback, rule-induction, set-shifting, and suppression of previous sorting rules), this task is likely to engage activity of other cortical circuits as well. The network of brain areas involved in WCST performance includes not only prefrontal cortex, but also the hippocampus and posterior association cortex (e.g., Anderson et al., 1991; Corcoran and Upton, 1993; Lombardi et al., 1999; Nagahama et al., 1997, 1996; Tien et al., 1998). Nonetheless, there appears to be general consensus both in clinical practice, in experimental neuropsychology, and in cognitive neuro-imaging studies that prefrontal-cortex dysfunction is the main factor underlying deficient WCST performance, and, conversely, that perseverative behavior is a reflection largely of inefficient

prefrontal activity (for a review see Barceló et al., 1997).

### **3.1.2 Perseverative Behavior in Older Adults**

Compared to young adults, older adults display more perseverative behavior in the WCST (e.g., Arbuckle and Gold, 1993; Dywan et al., 1992; Fristoe et al., 1997; Kramer et al., 1994; Loranger and Misiak, 1960; Raz, 2000; Salthouse et al., 1996). Indeed, the age-related deficits observed in these tasks resemble closely the corresponding deficits seen in frontal patients. Evidence has been amassed for the decline of frontal function as adults grow older (for reviews see Raz, 2000; van der Molen and Ridderinkhof, 1998b). The greater vulnerability of the frontal lobes compared to other brain regions has been highlighted in the recent neuro-imaging literature, including PET studies (e.g., Loessner et al., 1995), MRI studies (e.g., Coffey et al., 1992), and ERP studies (e.g., Dustman et al., 1996; Fabiani and Friedman, 1995; Friedman and Simpson, 1994). It should be noted, however, that the frontal-lobe hypothesis of cognitive aging (e.g., Dempster, 1992) is no longer held to apply as generally as believed originally (see Band et al., in press; Uylings and de Brabander, in press). Nonetheless, many authors have attributed the increase in perseverative behavior in senescence to deterioration in frontal-lobe functioning (e.g., Duncan et al., 1996; Kramer et al., 1994; Span et al., 2001a), a notion receiving further support from recent neuro-imaging work (Esposito et al., 1999; Nagahama et al., 1997).

## **3.2 Factors Underlying Perseverative Behavior**

Tasks like the WCST are quite complex and efficient performance in such tasks involves many different cognitive operations. One approach to establish in greater detail why older adults and frontal patients experience difficulties in endogenous adaptive control in these tasks, is decomposition into component processes. In principle, three distinct classes of endogenous adaptive control abilities may be involved in perseveration in previously correct categorization rules after a sudden and unannounced change in the sorting rule in tasks like the WCST. First, in order to enable behavioral adjustments to sudden changes in task demands, one has to generate hypotheses concerning the new rule (i.e., consider and evaluate the possible alternative categorization rules and select one for further testing). This *rule-induction* component plays an important role in other well-known problem-solving tasks as well (e.g., The Tower of Hanoi, Tower of London, and Raven's Progressive Matrices). Frontal patients typically experience difficulties in such problem-solving tasks, and older adults are also often reported to perform worse than young adults in these tasks (for a review see Pennington, 1994). A recent PET study suggested, however, that age-related changes in WCST performance involved dorsolateral prefrontal cortex, whereas age changes in Raven's Progressive Matrices involved other (non-frontal) areas, thus suggesting (at least partially) different mechanisms of rule induction (Esposito et al., 1999). In a recent fMRI study, rule induction was observed to involve dorsolateral prefrontal activation (Osmon et al., 1996).

Second, to perform the required shift appropriately, one should reconfigure the task set to

test the hypotheses concerning the new rule. Set shifting abilities include the suppression of no-longer relevant task sets and the implementation of the appropriate new task set. Latent-variable analysis indicates that this *set-shifting* component is central to WCST performance (Miyake et al., 2000). Set shifting is also central to performance in the task-shifting paradigm, in which performance is typically observed to be slowed considerably when the current task is different from the one performed just before compared to when the current task is similar to the immediately preceding one (see, e.g., Monsell, 1996). Frontal patients have been observed to perform less efficient on task-shifting tasks (e.g., Mecklinger et al., 1999). Likewise, older adults typically experience greater shift costs than young adults (e.g., Kramer et al., 1999; Kray et al., in press).

Nagahama et al. (1997) used the WCST in a PET study and observed that, compared to a task that featured the same stimuli but that did not involve rule-induction and set-shifting abilities, WCST performance yielded the most significant activation in dorsolateral prefrontal cortex (although other structures were activated as well). Importantly, in older adults (persevering more frequently than young adults) activation in the prefrontal areas was reduced, suggesting a relation between reduced rule-induction and set-shifting capabilities and reduced prefrontal activation in aging. A further PET study indicated that the dorsolateral prefrontal activation occurred during set shifting even when rule-induction requirements were lifted (Nagahama et al., 1998).

Third, however, a prerequisite for the proper application of rule-induction and set-shifting abilities is the ability to monitor one's performance adequately. That is, behavior must be fine-tuned to current task goals and adapted in response to changing task demands. To that end, task cues and feedback signals are to be interpreted appropriately to guide behavior and to recognize the need to apply rule-shift operations. A recent fMRI study suggested the involvement of prefrontal cortex in this *performance-monitoring* component of WCST performance (Konishi et al., 1999). Involvement of orbito-frontal cortex in altering task strategies in response to feedback is also suggested by a lesion study by Oscar-Berman et al., 1991.

In accordance with the distinction outlined above, frontal-lobe patients may persevere in previously correct sorting rules more often than controls for at least three different reasons: they may have difficulties in the ability to conjecture viable hypotheses and induce appropriate rules, they may suffer from a deficit in basic set-shifting abilities, or their performance-monitoring abilities may be disrupted. Likewise, older adults may be more susceptible to perseveration errors than young adults because they may have difficulties in rule induction, in applying basic set-shifting operations, or in monitoring their performance in face of changing task objectives.

### **3.2.1 Performance Monitoring in Frontal Patients' Perseverative Behavior**

Duncan et al., 1996 had frontal-lobe patients and posterior-lesioned patients as well as matched normal controls perform in a letter-monitoring task (LMT) that, although quite different from the WCST, allowed to examine perseverative behavior. In this task, subjects saw two streams of alphanumerical characters, one on each side of a computer screen. Characters succeeded each other rapidly, and the subject's task was to detect the presence of a letter character in the stream on one side of the screen. From time to time, a control character appeared indicating the side at which the remaining letters were to be detected. The control character could thus designate either a shift of attention to the stream of stimuli on the opposite side, or a non-shift. In case of a shift, subjects should disengage their attention from one position in space and re-direct it to the alternative position, and then continue to perform the same task; the shift does not require the subject to generate hypotheses concerning the new rule, nor to reconfigure the task set.

Compared to their posterior patients and controls, Duncan et al.'s frontal patients failed more frequently to perform a shift. That is, they appeared to ignore the control character more often and continued to perform the letter-detection task on the pre-shift stream of characters. When asked (after the fact), they reported to have seen the control stimuli and to be aware in general of the need to shift sides in response to the presentation of control stimuli. Yet, in concrete instances they were often unable to recognize in the control character a signal to make the shift and, as a consequence, they frequently failed to apply rule-shift operations. Interestingly, the occurrence of such failures was substantially reduced or even eliminated after verbal prompting, that is, after repeated questioning about the presence and meaning of the control characters. Since these patients were able to perform more adequately after verbal prompting, Duncan and colleagues argued that the perseverative behavior in frontal-lobe patients in the LMT should be attributed to a deficit in performance monitoring, a deficit they termed 'goal neglect'. Goal neglect refers to the finding that subjects are aware of specific task goals, yet fail to activate these task goals when circumstances call for it. In the LMT, the relevant goal was to interpret a task cue and recognize that it signals a shift; this goal was disregarded even though it had been understood and remembered.

It is conceivable that frontal patients in the LMT did not persevere in old behavior after verbal prompting because the rule-induction and set-shifting requirements were relatively undemanding. Nelson (1976) reported a study using a modified WCST in which an important aspect of performance monitoring was brought under control, but in which rule induction and set-shifting requirements were left intact (unlike the Duncan et al. study). Whenever a sorting rule was changed, she told her (frontal, non-frontal, and extra-cerebral lesion) patients "the rules have now changed, I want you to find another rule" (p.316). Hereafter we shall refer to this version of the task as the 'cued WCST'. Through this cueing procedure, the patients were confronted verbally and explicitly with the need to apply rule-shift 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 induced

and applied (as inferred from exit interviews), the frontal patients persevered much longer than the other patient groups in no-longer correct categorization rules. Nelson mentioned also (without further detail) that a pilot study had pointed out that the tendency to persevere in frontal patients was not affected by the explicit rule-change instructions (this suggestion received support from a recent comparison between the cued and regular WCST; Van Gorp et al., 1997). She compared her findings with the occasional observation of dissociations in frontal-lobe patients who can verbally demonstrate their full understanding of what they ought to be doing in the sorting test, but who nevertheless continue to persevere with an incorrect categorization response, often much to their own frustration. Thus, the perseverative behavior in frontal-lobe patients in the cued WCST appears to be due not to performance-monitoring deficits.

In accordance with the PET findings discussed above by Nagahama et al., 1997, this finding suggests that perseveration results either from deficient rule induction (i.e., forming hypotheses concerning the new rule) or from deficient set-shifting abilities (i.e., the configuration of appropriate task sets to test these hypotheses, and the suppression of no-longer relevant task sets), or both.

### **3.2.2 Performance Monitoring in Older Adults' Perseverative Behavior**

Duncan et al. (1996) administered the LMT to young and older adults and observed that older adults persevered more frequently in monitoring one stream of characters when a shift to the other stream had been designated by a control character. As in frontal patients, the occurrence of such failures was reduced or eliminated after verbal prompting, suggesting a performance-monitoring deficit (i.e., goal neglect) in older adults.

In terms of performance monitoring requirements, both Nelson's cued WCST and the LMT provide the subject with an explicit task cue that indicates the need to shift (a verbal instruction in the cued WCST, an abstract symbol in the LMT), yet in both tasks the explicit cue fails to trigger a shift. In the LMT, however, verbal prompting served to eliminate perseverative errors in frontal patients; in the cued WCST, the task cue resembled verbal prompting, but this cueing did not affect the perseverative behavior displayed by frontal patients relative to controls. In the cued WCST, subjects should generate hypotheses concerning the new rule, reconfigure the task set correspondingly, and resist interference from the preceding task set. In the LMT subjects need neither to generate hypotheses concerning the new rule, nor to reconfigure the task set; instead they should disengage their attention from one position in space and re-direct it to the alternative position, and then continue to perform the same task. Thus, it is conceivable that older adults in the LMT (after verbal prompting) did not persevere in old behavior because the rule-induction and set-shifting requirements were relatively undemanding.

The main thrust of the present study was to identify which of the endogenous adaptive control abilities involved in perseverative errors in WCST-like tasks are sensitive to the effects of aging. In face of the evidence that 1) the integrity of frontal cortex function is compromised during senescence, and 2) the perseverative behavior in frontal-lobe patients

in the cued WCST appears to be due not to performance-monitoring deficits but to rule-induction or set-shifting deficits, a straightforward prediction would be that in older adults, as in frontal patients, perseveration in previously correct categorization rules does not result from declines in the ability to monitor performance against the backdrop of changing task demands.

The purpose of Experiment 1 was to verify this hypothesis, that is, to establish that older adults' performance will not benefit from the presentation of explicit cues that tell them to shift to another sorting rule. Alternatively, if explicit cueing were to facilitate older adults' performance such that they persevered less frequently in previously correct categorization rules, then it could be concluded that age-related differences in adaptive control processes are accounted for by deficits in performance monitoring rather than in rule-induction or set-shifting abilities. To examine these alternative predictions, young and older adults were administered cued and non-cued versions of a dimensional shift task bearing resemblance to the WCST.

### 3.3 Experiment 1

#### 3.3.1 Method

**Subjects ■** A total of 40 subjects participated in the experiment. Sixteen young adults (mean age = 24.4) were first-year psychology students from the University of Amsterdam and received course credits in return for their participation. Twenty-four older adults, ranging in age from 62 to 81 (mean age = 68.1), were recruited from the local community through newspaper advertisements. They were non-paid volunteers, but they received a small gift in return for their participation. All were tested individually in a quiet university chamber. All subjects were screened (through self-report) for use of alertness-changing medication, psychiatric or neurological disorders, subjective health-experience, and normal vision. Informed consent was obtained from all participants.

**Stimuli and Apparatus ■** <sup>1</sup> The subjects were seated in front of a computer monitor at a viewing distance of 95 cm. Stimulus presentation and response registration were controlled by an Apple Macintosh LC475 computer. The stimulus configuration consisted of a permanently visible "apartment building" with 16 windows (in a four by four grid). The critical stimuli were faces ("of the persons living in that apartment"), each measuring 1.5° of visual angle, that could appear (one at a time) in any one of the windows. There were eight different faces, varying along three binary dimensions (male/female, laugh/solemn, glasses/no glasses; see Figure 2.1). All stimulus elements were black line drawings presented against a white background. Feedback stimuli were the words "GOED" and "FOUT" (the Dutch words for correct and incorrect), presented in the center of the four by four grid in green and red, respectively (in the Geneva 12 standard computer font). A cue

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<sup>1</sup> The format of this task was developed in a separate study (Span et al., 2001). This life-span developmental study featured many different reaction-time tasks that all shared a highly similar task format to reduce non-developmental sources of performance variance across tasks.

stimulus consisted of the statement “WE ZIJN VERHUISD” (“we have moved”), presented in red (Geneva 12) directly above the four by four grid.

### 3.3.2 Design and Procedure

On each individual trial, one face (selected randomly but equiprobable) appeared in one of the windows (selected randomly but equiprobable). The face designated a response with one of two response keys (the z and / keys of the computer keyboard, that were labeled with green and red colors), which were operated by the left and right index fingers, respectively. The subject’s task was to sort the stimuli using one of the three stimulus-dimensions. For instance, male and female faces could require a red- and green-button response, respectively; laughing/solemn faces could require red/green responses, and so on. The instruction was “Respond as quickly as possible, but be sure not to make many errors”.

The critical sorting dimension was initially unknown to the subject, and could be altered afterwards. After each response, feedback stimuli informed the subject about the correctness of the sort. These feedback stimuli were to be used to detect a change of sorting principle and to infer the correct rule. The initial sorting rule was selected randomly. When the subject had correctly applied the relevant sorting rule in eight out of the last ten trials, the sorting rule was shifted to another. The new sorting rule was selected randomly. In one condition (the cued dimensional shift task) a shift of sorting rule was announced by the cue stimulus; in another condition (the non-cued dimensional shift task) rule shifts were not accompanied by cue stimuli, that is, the subject learned of the change from the feedback only.

To familiarize the subjects with the stimuli and procedure, they received one block of 160 practice trials, in which they were asked to issue a left- or right-hand button-press (with the green and red buttons) in response to the spatial position of the stimulus (left or right of the vertical meridian of the grid). Next, it was explained to the subjects that this left/right sorting rule was not to be used in the remainder of the experiment. They were told to apply the male/female, laugh/solemn, or glasses/no-glasses sorting rules, and in addition they were to use the trial-by-trial feedback to infer which sorting rule was relevant. They were also told that the relevant sorting rule could change from time to time, and that in that case they had to use the trial-by-trial feedback to infer a new sorting rule. Subjects who started with the cued dimensional shift task were instructed that shifts of sorting rule were announced by the “we have moved” cue, and that whenever they saw that announcement they were to abandon the current sorting rule and look for the new one. Subjects who started with the non-cued dimensional shift task were not given this additional instruction. Care was taken to ensure that all subjects understood the instructions and were able to perform the task. The task consisted of 160 trials (with a maximum of 15 shifts), lasting 15 to 20 minutes (depending on the subject’s speed). After a 10-minutes break, those subjects (half of the subjects in each age group) that had started with the cued task now were explained and administered the non-cued task, and vice versa.

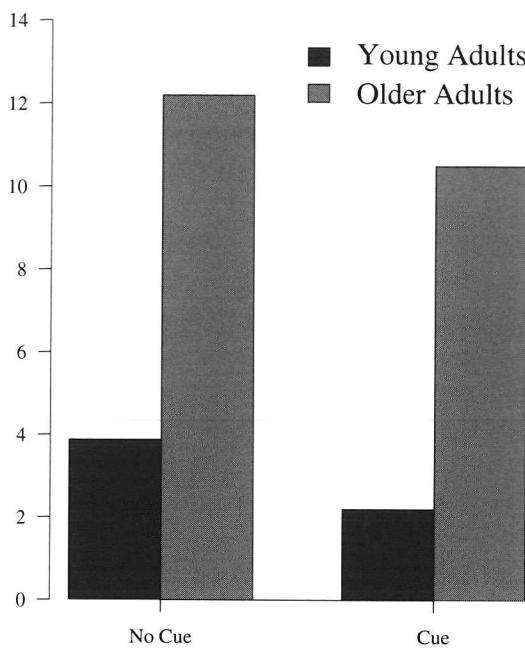


Figure 3.1: *Perseveration scores in Experiment 1 for young and older adults.*

### 3.3.3 Results and Discussion

Perseveration scores were computed as the total number of perseverative responses divided by the number of sorting-rule shifts. Higher perseveration scores thus imply fewer quadrant shifts. These perseveration scores were submitted to analysis of variance with the between-subjects factor Age Group (young, old) and the within-subjects factor Cue Type (cued, non-cued).

Consistent with other findings from our laboratory using this task (Span et al., 2001), perseveration scores increased with age, from 2.96 in young adults to 11.4 in older adults ( $F(1,38) = 14.4, p < .001$ ). The age trends in perseveration scores in the non-cued task were qualitatively similar to the normative data described by Heaton et al. (1993) for the original WCST.

Although Cue Type appeared to influence perseveration scores in the expected direction (7.2 in the cued condition, 8.8 in the non-cued condition), this effect failed to attain statistical significance ( $F(1,38) = 1.245, p = .272$ ). Importantly, the Age Group effect was not modulated by Cue Type ( $F(1,38) = .002, p = .963$ ; see Figure 3.1).

Thus, the age-related increase in perseverative errors is not attenuated by the presentation of shift cues. Even though they were confronted explicitly with the fact that the previous categorization rule was no longer correct and that a new rule was to be induced and applied, older adults' perseverative behavior did not improve significantly. Thus, their perseverative behavior in the cued dimensional shift task appears to be due not to performance-monitoring deficits. The fact that older adults persevere more often than young adults even in the face of explicit shift cues suggests that the age-related increase in perseveration results from deficient rule induction or deficient set-shifting abilities (or both). A second experiment was performed to replicate this finding in a different task and to discriminate between the two remaining sources of age-related differences in adaptive behavior.

### 3.4 Experiment 2

**Rule Induction in Older Adults' Perseverative Behavior ■** We have argued that if the increase in perseverative behavior observed in older compared to young adults does not result from a deficit in performance-monitoring abilities, then it must result either from a deficit in the ability to generate suitable hypotheses concerning the new sorting rule, or from a deficit in the ability to reconfigure the task set in such a way that these hypotheses can be tested and the new sorting rule can be discovered and applied. To assess the role of these respective factors we adopted an experimental strategy similar to that used in Experiment 1, that is, we attempted to eliminate the need to employ one of the constituent abilities and then examined whether the problems in adaptive control experienced by older adults would be alleviated. In Experiment 2, a WCST-like task was administered to young and older adults in three versions: one version without explicit shift cues, one version with explicit but non-specific shift cues (like in Experiment 1), and one version with explicit and specific shift cues that not only tell the subjects to shift, but also informs them exactly where to shift to. The latter type of shift cue eliminates the need to infer the new categorization rule, since the new rule is given explicitly in the cue. Presenting this type of specific shift cue has been shown to reduce the prefrontal activation elicited by the dimensional shift in the WCST (Konishi et al., 1999).

As in Experiment 1, if *non-specific* cueing serves to reduce or eliminate the age-related increase in perseveration, then the cause of age-related increase in perseverative behavior resides primarily in performance monitoring; if not, then these age effects pertain to rule-induction or set-shifting abilities. The latter case would comprise a replication of the results of Experiment 1. Continuing the same subtraction logic, if *specific* cueing would then serve to remove the age-related increase in perseveration, then the age-related deficit primarily involves rule induction (since the specific cues eliminate the need to generate hypotheses); if not, then the age-related deficit pertains to basic set-shifting capabilities.

The logically possible outcomes of the experiment include a null interaction effect (i.e., cueing may *not* serve to eliminate age-related deficiencies in perseverative behavior). The obvious danger of accepting null hypotheses is that factors other than the 'true absence of effects' may contribute to the null finding, thus reducing discriminative power and obscuring

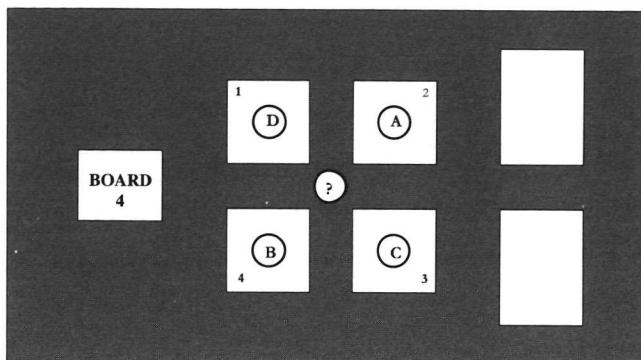


Figure 3.2: Train schedule board used as stimulus display in Experiment 2: the platform task. The four central quadrants each contain a platform letter; the subject's task is to replace the "?" in the central circle by the letter displayed in the appropriate quadrant. In this example, a specific cue (in the panel on the left) signals that the subject should now shift to quadrant 4 for the appropriate platform information

the effect of interest. In Experiment 2, to facilitate the chances of finding that age differences in perseveration depend on cue type, a secondary working-memory task was added to the primary dimensional-shift task, since it has been demonstrated that perseverative behavior is more pronounced when working memory is taxed by external loads (cf. Lehto, 1996).

### 3.4.1 Method

**Subjects ■** A total of 54 subjects participated in the experiment. Thirty young adults (mean age = 22.1) were first-year psychology students from the University of Amsterdam and received course credits in return for their participation. Twenty-four older adults, ranging in age from 65 to 83 (mean age = 70.9), were recruited from the local community through newspaper ads. They were non-paid volunteers, but they received a small gift in return for their participation. All were tested individually in a quiet university chamber. All subjects were screened (through self report) for use of alertness-changing medication, psychiatric or neurological disorders, subjective health-experience, and normal vision. Informed consent was obtained from all participants.

**Stimuli and Apparatus ■** The subjects were seated in front of a computer monitor at a viewing distance of 50 cm. Stimulus presentation and response registration were controlled by an Apple Plus computer. The stimulus configuration consisted of a permanently visible "railway station schedule board" (see Figure 3.2). The schedule board contained information concerning the arrival time and arrival platform of "the next train to Zwolle". Tasks and procedural details are described in the next sections. For a more detailed description of stimulus characteristics the reader is referred to the *Stimulus Details* section below.

**Tasks** ■ The job of the participant was to read out the schedule board, decide on the arrival platform and arrival time of the next train to Zwolle, and to display that information correctly on the schedule board. Each individual trial consisted of two consecutive parts. The first part, the arrival-platform aspect, represented the primary dimensional-shift task. This task was used to manipulate the conditions thought to play a role in perseverative behavior (using specific shift cues, non-specific shift cues, or no shift cues at all). The second part, the arrival-time aspect, reflected the secondary working-memory task.

**The primary dimensional-shift task: arrival platforms** ■ The correct arrival platform was presented systematically in one of four quadrants of the schedule board (see Figure 3.2); the participant was to discover which quadrant contained the correct platform information (the *target quadrant*). In the first part of each trial, four platform letters (A, B, C, and D) were presented simultaneously, one in each quadrant (assigned randomly but equiprobable). The correct platform information was presented systematically in the target quadrant, but the subject was not told which quadrant was the target one—the subject was to find out through the feedback that was presented after each trial. The subject selected the target quadrant and responded by entering the platform letter contained in the selected quadrant. The correctness of this response was indicated immediately by a positive or negative feedback symbol. If the choice were correct, then the subject was to continue selecting the same quadrant on the next trials; if the choice were incorrect, then the subject should on subsequent trials try other quadrants until positive feedback confirmed the selection of the proper quadrant.

The critical target quadrant, that was selected randomly, was initially unknown to the subject. The feedback stimuli were to be used to infer which quadrant was the target. When the subject had correctly selected the platform letter from the target quadrant in eight out of the last ten trials, the target quadrant was shifted to a (randomly selected) other quadrant. The feedback stimuli were to be used to detect a change of target quadrant and to infer which quadrant was the new target.

In one condition (the specific-cue condition) a shift of target quadrant was announced by a cue stimulus, which mentioned the new target quadrant (see Figure 3.2). In another condition (the non-specific cue condition) the cue stimulus would contain the message “ANOTHER BOARD” without mentioning the identity of the new target quadrant. In a third condition (the no-cue condition) shifts in target quadrant were not accompanied by any cue stimuli.

**The secondary working-memory task: arrival time** ■ The correct arrival time was to be calculated by the subject through simple clock-arithmetic. In the second part of each trial, the four quadrants and the central circle were emptied, and instead the schedule board displayed arrival time information (see Figure 3.3). In one field, the message “THE NEXT TRAIN WILL ARRIVE IN xxx MINUTES” was displayed (with xxx drawn randomly from the set 0, 10, 20, 30, 40, and 50). In another field, the message “ARRIVAL TIME: ??? MINUTES” was displayed. On the first trial, the subject was to enter the value of xxx. On subsequent trials, the subject was to remember the arrival time of the previous trial, and to calculate the new arrival time by adding the value of xxx to this previous arrival time. For

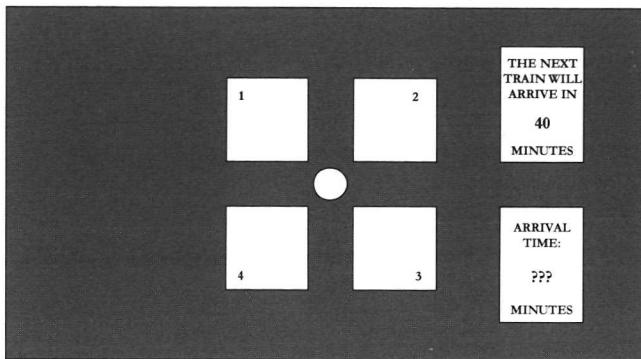


Figure 3.3: *Train schedule board used as stimulus display in Experiment 2: the arrival-time task.* The panel on the upper right indicates the number of minutes to wait before the next train will arrive. The subject was to remember the arrival time of the previous trial, and to calculate the new arrival time by adding the time to wait to this previous arrival time. For instance, if the previous train had arrived at 30 minutes past the hour, and the next train was to arrive in 40 minutes, then the subject was to replace the “???” in the lower right panel by “10”, since the arrival time of the next train would be 10 minutes past the hour.

instance, if the previous train had arrived at 30 minutes past the hour, and if the next train was to arrive in 40 minutes, then the arrival time of the next train would be 10 minutes past the hour. We displayed only minutes, not hours, since initial pilot work had indicated that the requirement to remember both hour and minute produced poor performance in the memory (arrival time) task even in young adults.

Thus, on each trial, the subject had to keep arrival-time information active in working memory during the arrival-platform task (or, conversely, had to perform the arrival-platform task during the retention interval between trials of the arrival-time task). The instructions to the subjects emphasized that they were to always remember the arrival times and not let the intermittent platform task interfere with memory for arrival time. This instruction certified that working memory was taxed by the arrival-time task to the same extent in all subjects. The instruction for the arrival-platform part of the task was “Respond as quickly as possible, but be sure not to make many errors”.

### 3.4.2 Design and Procedure

To familiarize the subjects with the stimuli and procedure, they received three blocks of 16 practice trials: the first block contained only the arrival-time task, the second only the arrival-platform task, and the third combined the two tasks (during practice blocks, the first quadrant was the target quadrant for the arrival-platform task, and no shift of target quadrant was applied). Next, it was explained to the subjects that in addition to performing the two tasks, they were to use the trial-by-trial feedback to infer which quadrant was the target quadrant for the arrival-platform task. They were also told that the target quadrant could

change from time to time, and that in that case they were to use the trial-by-trial feedback to infer a new target quadrant. Subjects that started with the specific-cue condition were instructed that shifts of target quadrant were announced by the “BOARD X” cue, and that whenever they saw that announcement they were to abandon the target quadrant rule and shift to the quadrant indicated by the cue. Subjects that started with the non-specific cue condition were instructed that shifts of target quadrant were announced by the “ANOTHER BOARD” cue, and that whenever they saw this announcement they were to abandon the current target quadrant and look for the new one. Subjects that started with the non-cued condition were not given additional instructions. Care was taken to ensure that all subjects understood the instructions and were able to perform the task. Each condition consisted of a block of 40 trials (with a maximum of four quadrant shifts), lasting 12 to 20 minutes (depending on the subject’s speed). Blocks were separated by 5-minutes breaks. The order of the three conditions was counterbalanced within each age group.

**Stimulus Details ■** The schedule board (see Figure 3.2 for a schematic illustration) consisted of white fields (in black contours) against a gray background (20.0 cm horizontally by 10.0 cm vertically). In the center of the board there was a circular field measuring 1.0 cm in diameter. Symbols that appeared insides the circular fields were printed in the standard Geneva 16 computer font; all other texts and numbers were printed in Geneva 12. Four square fields (2.5 by 2.5 cm each) surrounded the central circle, forming the four quadrants of a larger square, all separated 1.0 cm from each other. The four quadrants were numbered 1 through 4, clockwise (these numbers were printed in black in the outer corner of each quadrant). In the right part of the schedule board, two rectangular fields (2.5 cm x 3.5 cm horizontally and vertically, respectively) were separated 1.0 cm from each other and 2.0 cm from the central squares. The central circle, the four numbered squares, and the two rectangles were permanently visible.

Further stimulus details are illustrated in Figures 3.2 and 3.3. Circular contours (1.0 cm in diameter) could appear simultaneously in each of the four quadrants in the center of each square. Each circle featured one of the letters A, B, C, and D, such that each of the four letters would appear in one and only one of the four circles. Inside the circle in the screen center, one of several stimuli could appear: a question-mark; the letter A, B, C, D, or X; or a simple smiling face (similar in dimension to the letter X). Inside the upper-right rectangle, the Dutch equivalent of the message “THE NEXT TRAIN WILL ARRIVE IN xxx MINUTES” could appear, where xxx was either “0”, “10”, “20”, “30”, “40”, or “50”. Inside the lower-right rectangle, the Dutch equivalent of the message “ARRIVAL TIME: xxx MINUTES”, where xxx could have the same values as above or could be “??”. Finally, a rectangular field (2.0 cm vertically and 2.5 cm horizontally) could appear in the left part of the schedule board, horizontally separated from the central squares by 2.0 cm and vertically centered in the display. This field could contain the Dutch equivalent of the message “ANOTHER BOARD”, “BOARD 1”, “BOARD 2”, “BOARD 3”, or “BOARD 4”.

Subjects used keyboard buttons to indicate their response. The “/”-key was labeled as [+], the “;”-key was labeled as [-], and the “z”-key was labeled as [OK]. In one task, the

first button-press with either the [+] or [-] button served to turn the “?” in the central circle into the letter “A”; subsequent button-presses served to scroll up ([+]) and down ([-]) the list of available letters (A, B, C, or D). Repeated or continuous button depressing could be used for faster scrolling. Once the desired letter was selected, this choice was to be confirmed by pressing the [OK] button. The letter in the central circle was then replaced by either the smiling face or the letter “X”, representing positive and negative feedback, respectively.

In the second task, the first button-press with either [+] or [-] served to turn the “????” in the lower-right rectangle into the number “0”; subsequent button-presses served to scroll up and down the list of available numbers (0, 10, 20, 30, 40, or 50). Once the desired number was selected, this choice was to be confirmed by pressing [OK]. If the correct number was entered in this way, the lower-right rectangle would be emptied; if not, the display would remain unaltered until the correct number was entered through the procedure described above.

### 3.4.3 Results and Discussion

Perseveration scores were computed as the ratio of the total number of perseverative responses divided by the total number of trials in which perseverative responses could have occurred, expressed in percents. Higher perseveration scores imply fewer quadrant shifts. These perseveration scores were submitted to analysis of variance with the between-subjects factor Age Group (young, old) and the within-subjects factor Cue Type (no cue, non-specific cue, specific cue). Consistent with the instructions, few errors were made on the arrival-time memory task; these data were not analyzed further.

Perseveration scores increased with age from .35% in young adults to 3.55% in older adults ( $F(2, 51) = 10.49, p < .001$ ). Although Cue Type appeared to influence perseveration scores in the expected direction (2.11% in the no-cue condition, 1.86% in the non-specific-cue condition, and 1.36% in the specific-cue condition), this effect failed to attain statistical significance ( $F(2, 102) = 1.74$ ). The Age Group effect was not modulated by Cue Type ( $F(4, 102) = 1.46$ ; see Figure 3.4). Older adults persevered more often than young adults even when specific shift cues were presented.

These results replicate and extend those reported in Experiment 1. Before interpreting these results, however, let us first inspect the data more closely. Consistent with the widely reported observation that performance variability is much greater among older adults compared to young adults (cf. West et al., in press), some of the older adults in our sample displayed pronounced perseverative behavior, whereas others (like most young adults) never persevered at all. Thus, if explicit cues were to affect perseverative behavior, this effect could only be seen in the data from subjects that experience a substantial amount of perseverative errors. To establish whether relatively severe perseverators were able to benefit from explicit cues, a second analysis included only the 16 worst performers in the older adults group. Even within this group of relatively severe perseverators (mean score: 5.11), non-specific and specific cues failed to alleviate the incidence of perseverative errors ( $F(2, 30) = .39$ ). This pattern did not change when the group of perseverators was confined further to the

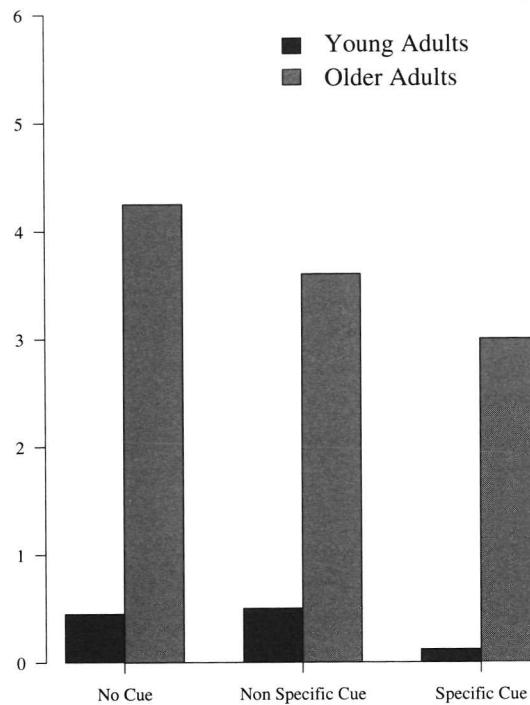


Figure 3.4: *Perseveration scores in Experiment 2 for young and older adults.*

worst twelve performers (mean score: 6.19;  $F(2, 22) = .80$ ) or to the worst eight performers (mean score: 7.98;  $F(2, 14) = .58$ ).

Thus, the initial analysis and the additional examinations converge on the conclusion that the age-related increase in perseverative errors is not attenuated by the presentation of informative shift cues. If age were to affect the ability to monitor performance, then older adults should have showed perseverative behavior only in the no-cue condition, since the informative cues would have helped them overcome the performance-monitoring problem. This predicted pattern was not observed, lending additional support to the inference from Experiment 1 that the age changes in perseverative behavior do not result from deficient performance monitoring. If age were to affect rule-induction abilities, then older adults should have showed perseverative behavior in the non-specific cue condition more than in the specific-cue condition, since the non-specific cues would not have helped them to generate hypotheses concerning the new sorting principle. This predicted pattern was also not observed, indicating that the age-related increase in perseverative responses does not result from deficiencies in rule-induction capacities.

If, finally, age were to affect set-shifting abilities, then older adults should show perseverative behavior even in the specific-cue condition, since the presentation of specific cues does not alter the need to engage basic set-shifting operations. From the consistent finding that older adults were not able to capitalize on specific (compared to non-specific) shift cues it can thus be inferred that, instead of performance monitoring or rule induction, the basic set-shifting ability was the factor responsible for the increased tendency to persevere as people grow older.

### **3.5 General Discussion**

Failures to exert endogenous control can yield perseverative errors not only when strong habitual associations exogenously trigger inappropriate action schemes, but also when exogenous control is less apparent. In the WCST, in which the stimuli are mapped arbitrarily onto action schemes so that the stimuli cannot activate some inherent task set, the currently activated task set may remain active even though environmental cues call for an endogenously controlled reconfiguration of task set. Milner (1963) and others have shown that patients with dorsolateral frontal lobe lesions are more susceptible to this perseverative capture of action schemes than patients with other lesion sites. This deficit may result from several types of endogenous adaptive control abilities. First, to enable behavioral modifications in response to sudden changes in task demands, one has to consider and evaluate the possible alternative categorization rules and select one for further testing (rule induction). Second, to perform the required shift appropriately, one should suppress the no-longer relevant task set and replace it by an appropriate new one (set shifting). Third, however, proper application of rule-induction and set-shifting abilities requires the ability to monitor and interpret task cues and feedback signals appropriately to guide behavior and to recognize the need to apply set-shifting operations (performance monitoring). Nelson (1976) observed that explicit cues, announcing loud and clear the need to shift to new action schemes, failed to alleviate frontal patients' perseverative behavior, suggesting that their deficit in adaptive control is not due to disrupted performance-monitoring capacities. Thus, perseveration in frontal patients appears to result from deficiencies in rule induction or set shifting.

As adults grow older, they are progressively susceptible to the perseverative capture errors in the WCST (e.g., Kramer et al., 1994). As with frontal patients, older adults may persevere in previously correct sorting rules more often than young adults because of difficulties in the ability to generate viable hypotheses and induce appropriate rules, deficits in basic set-shifting abilities, or disruptions in their performance-monitoring abilities. The main thrust of the present experiments was to determine the extent to which these different endogenous adaptive control abilities are sensitive to the effects of aging.

Experiment 1 was designed to examine whether deficits in performance monitoring (rather than in rule-induction or set-shifting abilities) account for age-related differences in adaptive control processes. If so, then explicit cueing should facilitate older adults' performance such that they persevere less frequently in previously correct categorization

rules. If not, then the incidence of perseverative errors should not be reduced in older adults. The results were straightforward: age-related increases in perseverative errors were not attenuated by the presentation of explicit shift cues. Thus, as was the case with Nelson's (1976) frontal-lobe patients, older adults' perseverative behavior in the cued dimensional shift task appeared to be due not to performance-monitoring deficits.

This result was confirmed in Experiment 2, in which a WCST-like task was administered to young and older adults in three versions: a condition without explicit shift cues, another condition with explicit but non-specific shift cues (as in Experiment 1), and a third condition with specific shift cues that not only tell the subjects to shift, but also informs them exactly where to shift to.

The results replicated those of Experiment 1 in that age-related increases in perseverative errors were not attenuated by the presentation of explicit but non-specific shift cues. If such age changes do not result from deficient performance monitoring, they may result either from deficient rule induction or deficient set shifting. In the former case, older adults' perseverative behavior is predicted to be reduced in the specific-cue condition compared to the non-specific cue condition, since the specific cues would have helped them overcome their problem with generating hypotheses concerning the new sorting principle. The results failed to provide support for this prediction. From the combined set of findings that older adults were not able to capitalize on explicit shift cues (either non-specific or specific) the inference can be drawn that basic set-shifting abilities, rather than rule-induction or performance-monitoring abilities, were the primary factor responsible for the increased tendency to persevere as adults grow into senescence. Set shifting abilities include the suppression of no-longer relevant task sets and the implementation of the appropriate new task set; the present analysis was not designed to discriminate further between these aspects.

### 3.5.1 Set Shifting and Aging

The basic set-shifting abilities involved in WCST performance are also crucial to successful performance in choice reaction time tasks in the task-switching paradigm. The typical finding is that, when two different tasks are mixed within blocks and on each trial a task cue informs the subject about the up-coming task, response times are slower on task-alternation trials compared to task-repetition trials, and this shift cost decreases as more preparation time elapses between presentation of the task cue and the imperative stimulus. One explanation of shift costs is in terms of task-set reconfiguration (e.g., Rogers and Monsell, 1995). If a shift of task is required, then the components of the associated task set are reconfigured to allow accurate performance of the new task. This process of task-set configuration can be initiated endogenously as soon as implicit or explicit task cues indicate that a new task is coming up, and is completed after presentation of the stimulus associated with the new task. Shift costs reflect the fact task-set reconfiguration processes take more time in case of a task alternation compared to a task repetition. An alternative view of shift costs is in terms of proactive interference (e.g., Wylie and Allport, 2000). When a task alternation requires the performance of a task that differs from the preceding one, there remains some

residual activation for the task set associated with the preceding trial by the time that the task set associated with the present trial gets activated. This residual task-set activation then interferes with the activation for the new task for many successive trials after switching from the competing task; the cost of this interference is a time penalty, reflected in shift costs.

The precise nature of the processes underlying shift costs in task switching studies is still subject to debate (for a recent overview see Vandierendonck, 2000), but this debate is beyond the scope of the present empirical work. Since the present results point to set-shifting as the primary explanatory factor in age-related changes in perseverative behavior, the processes involved in set shifting are of obvious relevance to understanding these age changes. However, the purpose of the present study was to identify the extent to which age-related changes set-shifting, rule-induction, and performance-monitoring abilities were responsible for the observed effects of age on perseverative behavior; whether these age changes in set-shifting involves task-set reconfiguration or proactive task-set interference remains to be established in future studies.

From the present pattern of findings we inferred that, rather than performance monitoring or rule induction, set-shifting was the factor responsible for the increased tendency to persevere as people grow older. It should be noted, however, that the factor set shifting was not controlled experimentally. Thus, accepting the conclusion that set-shifting was the primary factor underlying the influence of age on the incidence of perseverative behavior bears resemblance to accepting a null hypothesis: it may be that other factors that were also not under experimental control were responsible for the age effects. Such factors may include factors like group differences in stimulus perception, on-line memory for relevant stimulus dimensions, *etcetera*. Even though there is no *a priori* reason to assume that these factors play a role in the group differences in perseverative errors (unlike the case for set shifting), the present study does allow suggestive but not definitive conclusions about the role of set shifting. There is no direct way of addressing this complication (e.g., reducing the demand on set shifting and then inspecting whether the age difference in perseveration goes away would trivialize the task and preclude the occurrence of perseverative errors altogether). Indirect evidence for the importance of set shifting in perseveration may be obtained, however, by examining within-individual correlations between perseverative errors and task-switching performance. If such correlations are observed, and if they are found to be specific for performance in task switching (and not generalized to just any measure of speeded performance), our inference would receive support. In an unpublished study, completed recently in our lab, we assessed performance in a WCST-like task and in task switching across the life span. In this study, we administered three types of tasks to the same (young and old) subjects: 1) the non-cued dimensional shift task from Experiment 1; 2) a speeded switch task (involving switching between three different tasks, using the same facial stimuli) to the same subjects; and 3) a speeded non-switch task (using the exact same stimuli and tasks as in the switch task, but now administered by themselves instead of mixed with each other). Adult age trends in perseveration scores were not observed to correlate significantly with reaction times in the non-switch task (that could not be linked, *a priori* or *a posteriori*, to adaptive and perseverative behavior) whereas they did correlate

significantly (Spearman's  $\rho = .454$ ) with reaction times in non-switch tasks (that differed from the non-switch tasks only in terms of the set-shifting requirement). The finding of a specific correlation between perseverative errors in the WCST-like task and set-shifting performance in task switching underlines further the importance of set-shifting capabilities in the age trends typically observed in perseverative errors.

Recent neuropsychological and neuroimaging studies have started attempts to identify the brain areas central to the adaptive control processes involved in task-shifting competence. Shift costs are larger in patients with left-sided compared to right-sided brain damage (Mecklinger et al., 1999), and more specific in patients with left-sided compared to right-sided frontal damage (Rogers et al., 1998). An initial PET study also emphasized activity of a left-sided network in task-alternation compared to task-repetition blocks, showing enhanced regional blood flow in left dorsolateral prefrontal, premotor, anterior cingulate, and parietal cortex, and also in the right cerebellum (Meyer et al., 1998).

As argued before, these frontal structures, and in particular dorsolateral prefrontal cortex, are also among the structures that are affected most prominently by aging. Accordingly, an observation reported some forty years ago by Botwinick et al. (1958a) illustrates that although older adults are capable of performing elementary reaction-time tasks relatively well, their performance drops markedly when they are asked to switch back and forth between those tasks. The finding that the adverse effects of the requirement to shift between tasks are progressively more dramatic as adults grow older, combined with the evidence from cognitive neuroscience studies that aging affects specifically those brain areas that are involved in cognitive control processes, has in recent years stimulated a number of new studies into the effects of age on shift costs (e.g., Duncan et al., 1996; Hartley et al., 1990; Kramer et al., 1999; Kray et al., in press; Kray and Lindenberger, 2000; Mayr, 2001; Ridderinkhof, 2000; Salthouse et al., 1998a). All studies replicate the basic finding, first documented by Botwinick et al. (1958a), that shift costs increase with age. This age-related increase was magnified when subjects were not prepared to switch (i.e., expected a task repetition; van Asselen and Ridderinkhof, 2000).

Thus, the task-set reconfiguration processes underlying task switching are observed ubiquitously to deteriorate with age. On the basis of the experiments reported above, we contend that age-related changes in task-set reconfiguration abilities also play a major role in the perseverative behavior seen in WCST-like tasks.



# THE SPEED OF SET SHIFTING ACROSS THE ADULT LIFE SPAN REVEALED BY REGRESSION MODELLING

The main objective of this study is to establish the existence of differential patterns in the speed of processing during tasks requiring set shifting processes. To reach this objective we used a three-tasks set shifting paradigm. We compared the response latencies in the shift blocks with the response latencies in pure blocks using regression modelling. This made it possible to identify aspects of age-related changes in the speed of information processing during adult life-span that are attributable to this shifting component.

Regression analysis (see Cerella and Hale, 1994) revealed that pure block response latencies are best described by a linear function and response latencies in a task-shift setting are best described by a (nonlinear) exponential function. The results are discussed in the context of generalized and process-specific theories of cognitive aging.

To date, several studies have revealed that compared to young adults, older adults are less capable of holding several task sets available in working memory and of shifting flexibly between these task sets when so prompted by environmental cues. The requirement to maintain and coordinate multiple task sets as compared to a single task set invokes a time penalty in the execution of these task set, as expressed in so-called mixing costs in reaction time (RT). Within the context of multiple task sets, the requirement to shift between two different task sets as compared a repetition of the same task set also invokes time costs, as expressed in so-called shift costs in RT. Several studies have identified age-related increases in mixing costs, shift costs, or both. The present study contributes to this literature by focusing on gradual age-related changes rather than on group differences, thus allowing to capture the continuous trajectory of age changes in both mixing costs and shift costs. The regression-analytical approach that is appropriate for examining such continuous changes allows us to assess not only quantitative differences between the age trends associated with single-set task-repetitions, multiple-set task repetitions, and multiple-set task alternations (as expressed in parameter values of the regression models), but also qualitative differences (as expressed in the nature of the best fitting regression model). These combined merits yield inferences that could not be derived from an ANOVA-based approach only.

## 4.1 Introduction

In the mid-nineties, Cerella and Hale (1994) published an extensive review of the literature on the nature of age-related changes in processing speed. They reviewed a large body of developmental and aging literature, concluding that age-related slowing is mediated by a uniform, global mechanism. For tasks such as same-different decisions, two or four choice reactions, multiplication, mental rotation, word recognition, and visual search, the results are the same: a progressive decrease in the speed of responding. As the subject ages, all processes are executed more slowly. The suggestion that age-related changes in the speed of information processing are mediated by a single, global mechanism receives strong support from meta-analytic studies (e.g., Cerella et al., 1980; Hale et al., 1987; LaVoie and Light, 1994; Verhaeghen and de Meersman, 1998; Verhaeghen and Salthouse, 1997). Cerella and Hale (1994) describe the age-trend by a two-variable function that combines the multiplicative effect of process-duration and exponential effects of age. Most interesting, it seems that this function is similar for a wide variety of speeded response tasks.

The notion of such a global mechanism has been criticized on many counts, ranging from methodological issues to demonstrations of differential age changes (e.g., Cerella, 1991; Fisk and Fisher, 1994; Fisk et al., 1992; Fisk and Rogers, 1991. For a review see Bashore and Smulders, 1995). The regression-analytic procedures, commonly used in the meta-analytic literature, may conceal task-dependent and process-specific age changes in processing speed that can be revealed using ANOVA techniques (for an example see van der Molen and Ridderinkhof, 1998b). Simulation studies have shown that models invoked to explain age-related changes in processing speed may not be able to distinguish between global and local effects on the reaction process (Molenaar and van der Molen, 1994). In this article we adopt a regression approach to quantify the course of age-related slowing on task that draw upon different aspects of cognition.

A growing number of cognitive aging researchers expressed an interest in the neural underpinnings of age-related changes in cognitive functions (see, e.g., Raz, 2000; van der Molen and Ridderinkhof, 1998b). Several researchers (e.g., Ardila and Rosselli, 1989; Dempster, 1992; Dempster and Brainerd, 1995; West, 1996; Whelihan and Lesher, 1985) proposed that age related changes in cognitive function should be examined in relation to age-related changes in brain structure and function. A typical conclusion drawn by these researchers is that the frontal (specifically prefrontal, or dorsolateral prefrontal) brain structures and the cognitive functions that rely on these parts of the brain are most susceptible to effects of aging. This conclusion generated a series of studies, generally concluding that frontally-supported executive control functions are more sensitive to age-related speed changes than functions supported by other parts of the brain (e.g., Dempster, 1992; Dempster and Brainerd, 1995; West, 1996). It should be noted, however, that the recent neuroanatomy and neuroimaging literature suggest a pattern of more subtle differentiation in age-related decline between the (pre) frontal and non-frontal areas as well as within the frontal cortex (see e.g., Band et al., in press; Raz, 2000; Uylings and de Brabander, in press).

Age-related slowing has been reported to be manifest in inhibitory control (for review

see Kramer et al., 1994), working memory (for review see Moscovitch and Winocur, 1992), response selection (e.g., Salthouse and Somberg, 1982), response competition (for review see Bashore and Smulders, 1995), task shifting (Kray and Lindenberger, 2000), adaptive problem solving (for review see Ridderinkhof et al., in press) and various other planning and problem-solving tasks (for review see Pennington, 1994). The focus of the present study is on age-related changes in speeded performance in adaptive-control tasks, in particular tasks that involve set-shifting.

#### 4.1.1 Task-Set shifting

Using confirmatory factor analysis Miyake et al. (2000) established the separability of the executive functions 'mental set shifting', 'inhibition of prepotent responses' and 'information updating' in several frontal lobe tasks, including the Wisconsin Card Sorting Test (WCST), random number generation and the 'Tower of Hanoi'. The WCST requires set-shifting from one perceptual dimension to another. Omori et al. (1999) observed activation patterns in the prefrontal cortex during a set shifting task that were similar to those observed during the performance of the WCST. They concluded that the dorsolateral prefrontal cortex including the middle and inferior frontal gyri are involved in attentional set-shifting of both perceptual and non-perceptual characteristics.

Successful interaction with the environment requires the ability to form appropriate sets of constraints to guide perception-action coupling, and the ability to adapt these sets rapidly in response to changing environmental demands. A growing literature documents that these time-consuming control processes are affected by advancing age. Efficient performance requires that some components of the task set (associated with the preceding task) be abandoned and replaced by others (associated with the subsequent task). As was noted in the early days of psychology (Jersild, 1927), adaptive control involved in establishing a shift in task-set is a time-consuming process. More recently, cognitive psychologists have begun to express a renewed interest in the adaptive control processes involved in shifting between tasks (e.g., Rogers and Monsell, 1995). The typical finding is that when two different tasks are mixed within blocks and on each trial an explicit or implicit task cue informs the subject about the up-coming task, response times are slower on task-alternation trials compared to task-repetition trials. This decline in performance is believed to reflect the operation of cognitive control via the selection of task sets (Rogers and Monsell, 1995) and entails two components: mixing costs and shift costs. The former refer to the performance loss associated with performing a task within the context of a shift task, the latter refer to the time needed to actually shift between relevant task-sets.

Process models of task-set shifting are only beginning to emerge (e.g., Meiran et al., 2000). According to Meiran et al., set shifting entails three component processes: the passive dissipation of the previously relevant task set, the active preparation required for the selection of a new task set and a residual, stimulus triggered cost that is neither affected by set dissipation, nor by set preparation. Meiran et al. suggest that age-related differences in shifting costs result primarily from slower dissipation of the previously relevant task set.

#### **4.1.2 Aging and shift costs**

Task shifting has been studied extensively in the aging population. Large age-related differences have been found in situations where on-line selection among competing sets is required (e.g., Mayr et al., 1996). However, these age-related differences disappear when (complex) processing takes place without the help of reliable mental sets (e.g., Mayr and Kliegl, 2000; Verhaeghen et al., 1997). The general finding that the adverse effects of the requirement to shift between tasks increase with age, combined with the evidence from neurocognitive studies that aging affects specifically those brain areas that are involved in cognitive control processes, has inspired a number of new studies of the effects of age on shift costs (e.g., Duncan et al., 1996; Hartley et al., 1990; Kramer et al., 1999; Kray and Lindenberger, 2000; Mayr and Kliegl, 2000; Salthouse et al., 1998a; van Asselen and Ridderinkhof, 2000). All studies replicate the basic finding (Botwinick et al., 1958b; Brinley, 1965) that shift costs increase with age. Given that the brain structures involved in adaptive control processes are especially sensitive to the effects of aging, we may ask whether shift-cost patterns for different set-shifting components differ between young and older adults.

#### **4.1.3 The present study**

The major purpose of the present study is to describe, within the regression-framework as proposed by Cerella and Hale (1994), the age-related performance deficits observed in speeded tasks that involve set-shifting abilities, and to investigate whether and how these deficits are different from cognitive slowing in similar tasks that do not involve set shifting. This goal is accomplished by administering shift tasks as well as pure tasks to subjects who differ in age (distributed across the adult life span), and evaluating the estimated parameter values and goodness of fit of different regression models that describe age-related changes in processing speed in each of the task conditions. This regression-analytical approach allows us to assess quantitative differences between the age trends associated with the different task conditions (as expressed in parameter values of the regression models), as well as qualitative differences (as expressed in the nature of the best fitting regression model).

In a previous study (Ridderinkhof et al., in press), we focused on a specific aspect of executive control, that is, the ability to adapt one's behavior in response to changes in environmental demands. This study showed that, while perseverative behavior in WCST-like tasks is affected not only by set-shifting abilities but also by rule-induction and performance-monitoring abilities, age-related deficits in perseverative behavior resulted primarily from basic set-shifting abilities. The present study follows up on this previous study.

#### 4.1.4 Regression approach

Age-related changes in processing speed across the adult life span can be captured by several different regression models. The simplest model is the linear model, in the nomenclature of Cerella and Hale (1994) expressed as Eq. 4.1.

$$RT_e = [(d * age) + 1] * \widehat{RT}_c \quad (4.1)$$

where  $RT_e$  is the predicted response time on the task under observation,  $\widehat{RT}_c$  is the mean response time of a control group (typically young adults), and  $d$  is the decay parameter indicating the slope of the regression function (reflecting the degree of age-related slowing) scaled by the offset  $\widehat{RT}_c$ . This function was used by Cepeda et al. (2001) to show that age-related slowing was more pronounced for shift trials compared to repetition trials.

Cerella and Hale (1994) argued that adult age-related changes in processing speed are better captured by the exponential decay function expressed in Eq. 4.2:

$$RT_e = [c * (e^{d*age} - 1) + 1] * \widehat{RT}_c \quad (4.2)$$

where  $d$  is the decay parameter (reflecting the degree of age-related slowing),  $c$  is a magnitude parameter (reflecting relative age effects), and  $RT_e$  and  $\widehat{RT}_c$  are the same as in Eq. 4.1. For technical reasons, the decay component is corrected to be zero at age=0 (by subtracting 1). A second correction is performed to equate  $RT_e$  to  $\widehat{RT}_c$  when the decay component is close to zero (by adding 1). Cerella and Hale demonstrated that this generic exponential function can be used to capture age-related changes in processing speed on a wide array of cognitive tasks.

In the decay function in Eq. 4.2, both the decay parameter  $d$  and the magnitude parameter  $c$  are expected to vary with task type. Ridderinkhof and van der Molen (1997), albeit with children and, hence, exponential growth rather than decay functions, noted that the magnitude and decay (or growth) parameters are highly correlated ( $r > .98$ ). When in a two-parameter function the parameters are highly correlated ( $r \approx 1$ ) the model is not identifiable: the parameters convey approximately the same information. For any value of one of the parameters (within a sizeable interval) a value for the other parameter can be found that generates a similar function. This leads to extreme confidence intervals for the parameter estimates (although a linear combination of the two parameters can be estimated more reliably<sup>1</sup>).

<sup>1</sup> Let  $\theta = (c, d)^T$ , the transposed vector containing the parameter estimates: The F-test for differences between linear combinations of correlated parameter estimates is:

$$F = \frac{(\theta_1 - \theta_2)\mathbf{S}^{-1}(\theta_1 - \theta_2)}{q}$$

Where  $\mathbf{S}$  is the covariance matrix of the parameters and  $q$  is the number of parameters in each model. With  $(q, n - p)$  degrees of freedom, where  $p$  is the total number of estimated parameters and  $n$  the total number of observations

Therefore, we compare the model described in Eq. 4.2 with a restricted model, with the magnitude parameter fixed at the value 1. This model is expressed in Eq. 4.3. This constraint was applied to arrive at meaningful confidence intervals for the parameter estimates.

$$RT_e = [e^{d*age}] * \widehat{RT}_c \quad (4.3)$$

where the parameter  $d$  is the same as in Eq 4.2.

#### 4.1.5 Predictions

We expect that parameter estimates of the lifespan function describing the mean response latencies in the set shifting task (mixed blocks) will diverge from those estimated in simple reaction time tasks (pure blocks). The nature of Eq. 4.2 leads to the prediction that the magnitude parameter ( $c$ ) and the rate parameter ( $d$ ) will be highly correlated. Both the magnitude parameter (describing the relative age-effects) and the decay parameter (describing the decay of performance across the life span) are expected to vary with task-type: age-related slowing is expected to be more pronounced in the task-shift setting as compared to the pure blocks. Moreover, we expect that the effects on parameters estimated in the mean responses on repetitive trials are less pronounced than the effects on the alternating responses in the task-set shift task. This reflects the more pronounced age-related slowing on shift costs when compared to mixing costs.

## 4.2 Method

### 4.2.1 Participants

42 subjects participated in the present study. The ages of the subjects were between 19 and 84, and are shown in the histogram in Figure 4.1. Two of the subjects were left-handed. 20 were female, 22 were male. All subjects were healthy and had normal or corrected-to-normal vision. Subjects were screened for use of alertness-changing medication and subjective health-experience. Mean Raven-percentile scores did not differ with age, suggesting that all subjects were comparable in terms of intelligence: only three subjects (aged 19, 25 and 73) did not perform within the 90th percentile of their age-group.

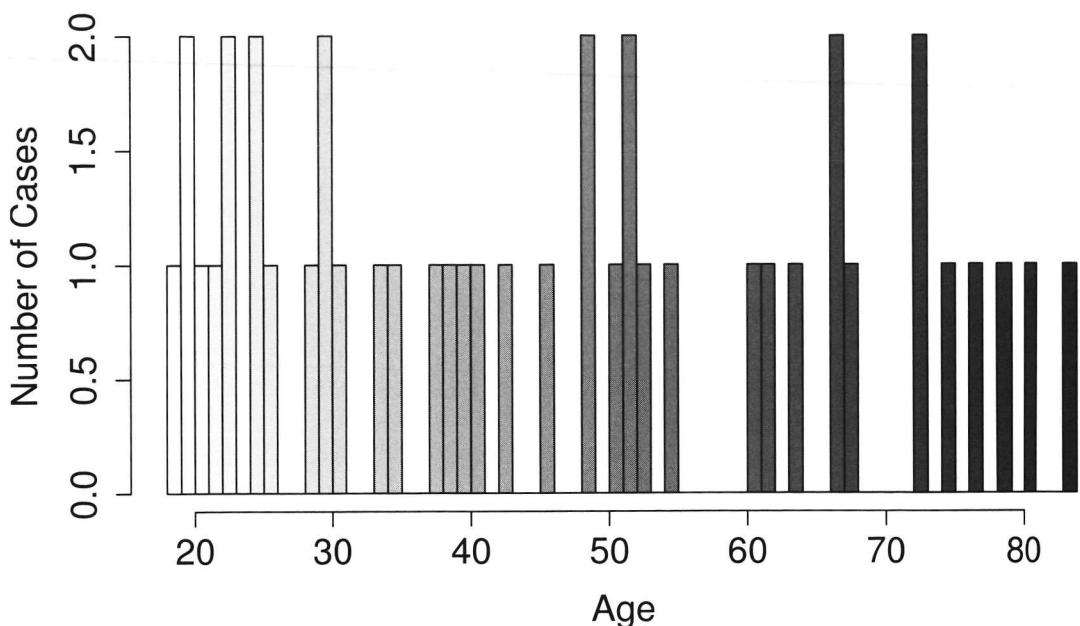


Figure 4.1: Ages of the subjects participating in the experiment.

#### 4.2.2 Stimulus material and apparatus

The participants were seated in front of a computer monitor at a viewing distance of 40 cm. Stimulus presentation and response registration were controlled by an IBM compatible 486 computer. Stimuli are shown in Figure 2.1. Stimuli varied in three dichotomous dimensions. These dimensions were: man-woman, happy-sad and wearing glasses or not. All stimulus elements were black line drawings presented against a white background. Stimuli were presented in a square of 3x3 cm in the middle of the computer screen.

#### 4.2.3 Tasks and procedure

A fixation cross was presented before each trial for 500 ms at the middle of the presentation square. Then the fixation cross disappeared and after an interval of 100, 500 or 1500 ms (selected at random) the stimulus was shown. The stimulus presentation was response terminated. Subsequent to the subject's response, visual feedback was presented (after a delay of 100, 500 or 1500 ms, selected at random). Feedback consisted of the presentation of the words 'GOED' (correct) or 'FOUT' (incorrect) just below the presentation square. On each individual trial, one stimulus (selected randomly and equiprobable) appeared in the square in the middle of the screen. The stimulus elicited a response with one of two response keys (the 'z' and '/' keys of the computer keyboard that were operated by the left and right index fingers, respectively). The subject's task was always to respond as fast and accurately as possible with the designated response finger. The definition of a correct response on a

given trial depended on the specific instruction, which varied from task to task. This was explained in detail to the subject prior to each task. The next trial was started after exactly 1 second. The instruction for all tasks was to respond as fast as possible, but not to make many errors.

#### **4.2.4 Pure Blocks: Choice Reaction Time Tasks (CRT-1, CRT-2 and CRT-3)**

Three highly comparable tasks were administered. The difference between the tasks is the stimulus dimension that was selected for discrimination. In the CRT-1 female faces designated left-hand responses; male faces designated right-hand responses. In the CRT-2 laughing faces designated left-hand responses; sad faces right hand responses. In the CRT-3 faces with glasses designated left-hand responses; glassless faces right-hand responses. Each of these three CRT tasks was presented once in a block of 50 trials, preceded by a practice block of 20 trials.

#### **4.2.5 Shift Blocks: Choice Reaction Time/Task Shift (CRT-TS) task**

The CRT-TS task is the implementation of a three-set task-shift paradigm. The three task sets used are the three choice reaction time tasks that were practiced in the beginning of each session. The subjects had to respond to each stimulus using the task-set that was cued before the stimulus appeared. The cue used consisted of two words: "Man-Vrouw" (man-woman) for the CRT-1 task, "Lachen-Niet" (laugh-not) for the CRT-2 task and "Bril-Geen" (glasses-none) for the CRT-3 task. This cue was presented for 500 ms, and was followed by an interval of 33, 166 or 500ms (selected at random) preceding the stimulus. On each trial there was a 50% chance of a shift in rule-set. Therefore about 50% of the trials were preceded by trials of the same task-set, and 50% of the trials were preceded by trials of a different task-set. The CRT-TS task consisted of 150 trials. An additional 30 were included as practice trials.

Care was taken to ensure that all subjects understood the instructions and were able to perform the task. Before the experimental session all the tasks were practiced. Feedback was intended to motivate the subjects to perform as fast and accurately as possible. The four tasks were administered in random order, and were separated by short breaks of one to two minutes. A four-minute break followed the second task. The time taken to complete one task block varied between 5 and 11 minutes, depending on the specific task. Total test time amounted to about one hour, including time spent on breaks and a short intelligence test.

#### 4.2.6 Data Analysis

#### 4.2.7 Dependent Measures

Mean RT on trials that were responded to correctly was the dependent measure in the fitting procedures. One subject missed the CRT-1 task, and two subjects missed the CRT-3 task. All response times faster than 75 ms were discarded. No subject showed extreme error-scores, although upon visual inspection older subjects tended to make more errors than younger subjects.

#### 4.2.8 Regression Procedure

We fitted the linear, nonlinear, and restricted nonlinear regression models (expressed in equations 4.1-4.3, respectively) to the observed RT data from the pure-repetition, mixed repetition, and mixed alternation conditions, and compared the proportions of variance explained by each model. The intercept of the linear model was calculated from the control group data (young adults, aged 19–30, N=11) in a similar fashion as in the nonlinear model, by inserting the mean response times of the young adults.

We used the NLS library for the R statistical package (Ihaka and Gentleman, 1996), to obtain the unweighted least squares estimates (Bates and Watts, 1988) of the two parameters in the exponential curves as described in Eq. 4.2, and the single parameter in Eq. 4.3. The parameter estimate in the linear model, Eq. 4.1, was derived using unweighted linear least squares. NLS provided the parameter estimates and their standard deviation. To test differences between task-types, we compared the parameter values using a t-test.

### 4.3 Results

Figure 4.2 shows the proportion of errors made by each subject for the three main categories: Pure blocks, repetitions and alternations. The number of errors made in the alternations in the task-shift setting grows with age ( $\text{slope} = 0.0023, t = 4.245, p < .001$ ). In the alternations a trend is observed ( $\text{slope} = 0.0012, t = 1.928, p = 0.06$ ), whereas the proportion of errors in the pure blocks is not age-related ( $\text{slope} < .00001, t = -0.583, p = 0.562$ ). This pattern complies with the response time data reported on below, and therefore speed-accuracy trade-offs cannot explain the behavioral data in general.

The mean response latencies and the resulting linear and nonlinear fits are shown in Figure 4.3. The proportion explained variance for each of the fits is shown in Table 4.1. When evaluating this table, remember that  $R^2$  gives the squared linear correlation which can be used for comparisons.

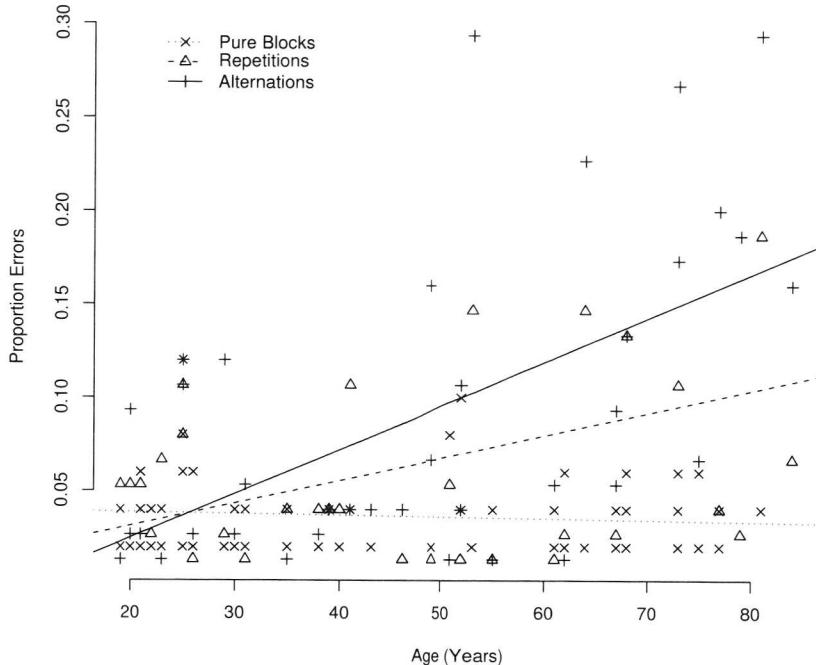


Figure 4.2: Proportion of errors made, grouped by type: Pure=Pure blocks, Repetitions=Repetitions in the task-shift setting, Alternations=Alternations in the task-shift setting.

Table 4.1: Proportion explained variance ( $R^2$ ) for the linear, the unrestricted nonlinear and the restricted nonlinear, in the control tasks (Pure) and the task-set shift task (Repetitions and Alternations).

Function	Pure	Repetitions	Alternations
Linear	.68	.705	.677
Exponential	.68	.735	.712
Restricted	.68	.726	.702

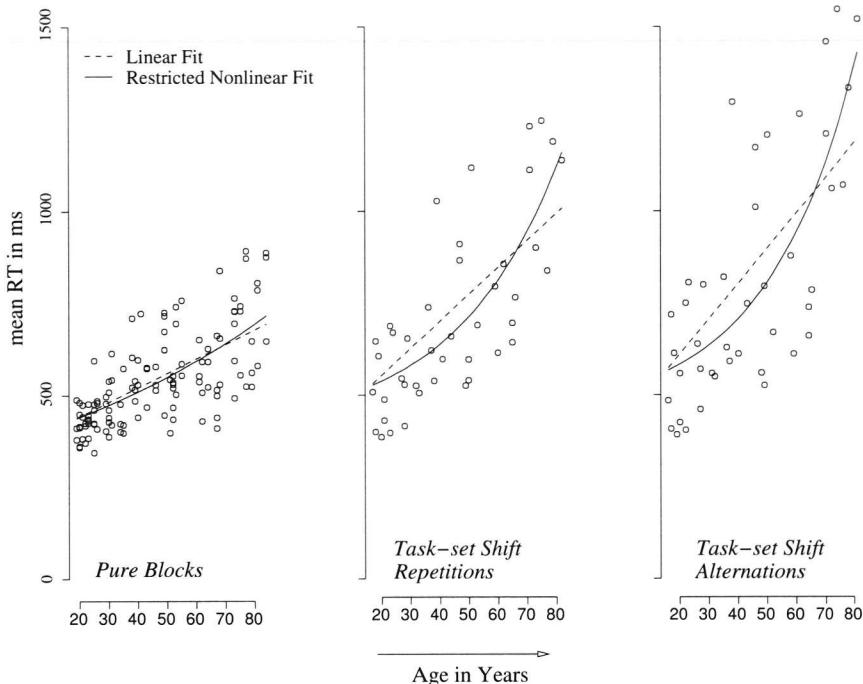


Figure 4.3: Mean response latencies in the control tasks (Pure) and the task-set shift task (Repetitions and Alternations). Continuous lines represent nonlinear function fits, dashed lines represent linear fits.

Table 4.2: ANOVA tables comparing the amount of explained variance of the linear, the unrestricted nonlinear and the restricted nonlinear models. \* $p < .05$

Pure Blocks:					
	Res.Df	Res. SS	$\Delta$ SS	F	Pr(>F)
Linear	122	1086349			
Unrestricted	121	1078025	8323	.93	.34
Restricted	122	1078381	-355	.04	.84
Shift Blocks:					
Task-set shift Repetitions					
Linear	41	1137289			
Unrestricted	40	1024046	113243	4.423	.04 *
Restricted	41	1070377	-46331	1.810	.19
Task-set shift Alternations					
Linear	41	2216119			
Unrestricted	40	1975508	240611	4.872	.03 *
Restricted	41	2073754	-98246	1.990	.17

**Table 4.3:** *AIC for the linear, the unrestricted nonlinear and the restricted nonlinear, in the control tasks (Pure) and the task-set shift task (Repetitions and Alternations). Lowest values in italics.*

Function	Pure	Repetitions	Alternations
Linear	<i>1468.65</i>	549.86	577.88
Exponential	1468.71	<i>545.46</i>	<i>573.05</i>
Restricted	1468.75	547.32	575.09

**Table 4.4:** *Parameter estimates in the linear model for each of the tasks. The estimate is the slope (or decay) parameter, scaled by the offset  $RT_c$ .*

	Estimate	Std. Err	t-value	Pr(> t )
Pure Blocks	.0091	.000561	16.1	<.001
Repetitions	.0140	.00141	9.91	<.001
Alternations	.0170	.00183	9.17	<.001

### 4.3.1 Qualitative Differences: Model fits

Qualitative differences between the age trends associated with pure tasks, mixed-task repetitions, and mixed-task alternations were assessed by examining the nature of the best fitting regression model. To determine the preferred regression function for each condition, several criteria are available. First, the parsimony principle holds that more parsimoniously parameterized models should be preferred if the proportion of variance explained by the models does not differ significantly. This rule can be applied to the comparison of the unrestricted nonlinear model against both the restricted nonlinear model and the linear model. Since the latter two models are equally parameterized (i.e., they both contain one free parameter), their model fits cannot be compared using the parsimony principle. Technically, when models are equally parameterized, the best fitting model can be determined by examining the residual sums of squares, which are lower for the better fitting model. A final criterion that may help decide on the preferred model is the Akaike information criterion (AIC). Conclusions about preferable regression functions are strengthened if the different criteria converge.

Thus, we started by comparing the model fit of each of the proposed life-span functions (Eqs. 4.1–4.3) consecutively. The results, summarized in Table 4.2, show that in the pure-task setting, the linear model was able to fit the data equally well as the nonlinear models, and the model fit did not differ between the restricted and unrestricted nonlinear models. In the multiple-task setting the nonlinear model (Eq. 4.2) explained a greater proportion of variance than did the linear model (Eq. 4.1), while the unrestricted nonlinear model (Eq. 4.3) did not fit the data significantly better than did the restricted model (Eq. 4.2).

For pure-task settings, according to the parsimony principle the linear and restricted nonlinear models should be preferred over the unrestricted nonlinear model. Numerically, the restricted nonlinear model does appear to explain more variance than the linear model

(Table 4.2), but a statistical test of this difference is lacking since direct sequential comparisons between the linear and restricted nonlinear model are not allowed. According to the AIC (Table 4.3), the linear model should be preferred, although the difference is minimal.

For mixed-task settings, the unrestricted nonlinear model captured the variance significantly better than the linear model, both for repetitions and alternations. Numerically, the unrestricted nonlinear model left less residual variance unexplained than the restricted nonlinear model (Table 4.2), but this difference was not statistically significant. To determine which of the latter two models should be preferred, the additional criteria converge: For task repetitions and alternations, both the variance accounted for and the AIC would lead to acceptance of the nonlinear model. In both cases, the nonlinear models explain significantly more variance and produce lower AIC values than the linear model.

Thus, for mixed-task repetitions and alternations, all indices point to the nonlinear model. The pure-task setting is ambiguous: the nonlinear model does not explain more variance than does the linear model. However, the AIC shows a difference in favor of the linear model. In describing data as provided by this study, the nonlinear models have the advantage above the linear model in that they can *locally* become linear. Inspecting Figure 4.3, left panel, we can see that the restricted nonlinear model mimics the linear model in the range specified for the fit. Since the observed departures from the linear model are equivocal and very small, we suggest that the most parsimonious interpretation of the present pattern of findings is in terms of the linear model. Thus, we conclude that qualitative differences exist in the type of function that best describes the age trajectories for RTs in pure tasks, mixed-task repetitions, and mixed-task alternations. We now turn to an evaluation of quantitative differences between the parameters of the restricted nonlinear model for the different task conditions.

#### 4.3.2 Quantitative Differences: Parameter estimates

Quantitative differences between the age trends associated with pure tasks, mixed-task repetitions, and mixed-task alternations were assessed by examining the free parameter of the restricted nonlinear regression model. The estimated parameter is the decay parameter  $d$  (reflecting the degree of age-related slowing), scaled by the offset  $RTc$ . Parameter estimates are presented in Table 4.5.

In the task-set shift the nonlinear fit explains an additional 10% of the residual variance for both the repetitive and the alternating trials. The linear combination of the magnitude ( $c$ ) and decay ( $d$ ) parameters in the two-parameter nonlinear model in Eq. 4.2 shows the same pattern as the parameter of the linear fit in Eq. 4.1. Both the parameters of the fit for the repetitive trials as parameters of the fit for the alternations differ from the pure blocks ( $F(2, 159) = 3.63, p < .05$  and  $F(2, 159) = 5.17, p < .05$ , respectively), but do not differ from each other ( $F(2, 78) = 2.53, p > .05$ ). When we analyze the differences in the decay parameter ' $d$ ' (see Table 4.5) estimates obtained in the restricted model fit between the pure and shift blocks we find a significant difference for the repetitions ( $t(157) = 3.55, p < .001$ ) and for the alternations ( $t(157) = 4.76, p < .001$ ). The difference between the repetitions

**Table 4.5: Parameter estimates in the restricted nonlinear model for each of the tasks. The estimate is the rate parameter 'd', scaled by the offset  $RT_c$ .**

	Estimate	Std. Err	t-value	Pr(> t )
Pure Blocks	.0074	.00038	19.55	<.001
Repetitions	.0107	.00079	13.57	<.001
Alternations	.0125	.00093	13.35	<.001

and alternations is again not significant.

The estimated parameter values for the linear fit are mentioned in Table 4.4. As can be seen here, all parameter values differ significantly from 0. This observation means nothing more than the existence of age-related slowing in all tasks. Moreover, the decay parameter in the linear fit for repetitive and alternating trials in the task-shift setting is significantly higher than the parameter estimated in the pure blocks ( $t(157) = 3.24, p < .001$ , and  $t(157) = 4.14, p < .001$ , respectively). The slopes did not differ between repetitions and alternations ( $t(84) = .176, p > .05$ ).

#### 4.4 Discussion

Summarizing, the main objective of this study was to establish the existence of differential patterns in the speed of processing for tasks that differ in the engagement of cognitive control processes, in particular those adaptive control processes involved in rapid set shifting. The tasks we used were identical in most respects. The shifting component was present only in the task-set shift task, making it possible to identify aspects of developmental changes on the speed of information processing that result from this shifting component.

In our analysis we used linear and exponential models to describe the age-related changes in the speed of information processing across the life span. These models were developed to accommodate the observed changes in speed in our control tasks. The results demonstrate that choice reaction time tasks show a different pattern of age-related slowing when performed in pure blocks, then when the same tasks are performed in a task-set shift situation.

The global-speed hypothesis has received extensive support by empirical and meta-analytical studies, but the present study has demonstrated the presence of process-specific age-related differences in addition to the global trend (Bashore and Smulders, 1995; Kramer et al., 1999, 1994; Ridderinkhof et al., 1999; Ridderinkhof and van der Molen, 1997; Span et al., 2001a). Although some studies emphasize the role of global processing speed in age changes in cognitive control tasks (e.g., Salthouse et al., 1998a), there is now sufficient evidence against a singular global-speed model of age-related changes. As demonstrated in the present study, the global speed hypothesis is faced with findings that are difficult to incorporate or account for without making further assumptions. These findings are consistent with the literature on neurocognitive change, which suggests that tasks that involve executive control are more sensitive to age-related changes in the speed and efficiency of the cognitive

functions than tasks that can be performed without invoking executive control mechanisms extensively (for reviews see, e.g., van der Molen and Ridderinkhof, 1998b; West, 1996).

The ability to adapt to rapidly changing task requirements is one of the cognitive control functions reported to decline with age as people grow older (e.g., Botwinick et al., 1958b; Cepeda et al., 2001; Duncan et al., 1996; Hartley et al., 1990; Kramer et al., 1999; Kray and Lindenberger, 2000; Mayr, 2001; Ridderinkhof et al., in press; Salthouse et al., 1998a; van Asselen and Ridderinkhof, 2000). Given that task-set coordination and reconfiguration processes appear to involve specifically those structures in the brain (frontal cortex, more specifically dorsolateral prefrontal cortex; Dove et al., 2000; Meyer et al., 1998; Rogers et al., 1998) that are known to deteriorate earliest and fastest during senescence (Raz, 2000; van der Molen and Ridderinkhof, 1998b; West, 1996), it is not surprising that our study established a distinction between age-related changes in these control abilities and in the more elementary cognitive abilities that are involved in both the basic (pure) tasks and the set-shifting (mixed) tasks.

#### 4.4.1 Aging and task shifting

Two types of task-shift costs are manifest in the literature: mixing costs (the difference in RT between pure and mixed blocks) and shift costs (the difference in RT between task alternations and task repetitions within mixed blocks). In general, age-related changes in both mixing costs and shift costs are observed, although the former are sometimes found to be more pronounced (cf. Kray and Lindenberger, 2000; Mayr, 2001). In the present study, mixing costs were assessed by comparing the regression functions of the task-set repetition trials in pure and mixed contexts. The parameters found for these regression lines differed significantly, which is interpreted as evidence for significant age-related changes in mixing cost. Shift costs were assessed by comparing the parameter estimates of task-set alternation trials with those of task-set repetition trials within mixed blocks. Although the difference found was in the expected direction, it was not significant. This result was previously reported by e.g., Kray and Lindenberger (2000) but only in the absence of external cues. Our result don't imply equality of specific shift cost between age-groups.

A main finding of this study is the dissociation of the type of function that best describes the age-related changes in response speed in pure blocks and in a task-shift setting. Whereas the pure blocks are best described using a simple linear function, both the repetitive trials and the alternating trials in the task-shift setting are better described by an exponential function. The limited set of tasks and the limited number of subjects used in the present study does not allow direct generalization to other task domains. Nonetheless, the present regression-analytical approach contributes to the existing literature by demonstrating that age trends in the efficiency of adaptive control abilities become progressively more pronounced at the more extreme part of the adult life span, providing a significant nuance that is not revealed when the more conventional group-based ANOVA design is used.



# DEVELOPMENTAL DIFFERENCES IN SET-SWITCHING

This study is concerned with changes in executive control processes involved in set shifting during development. We examined performance on a cued task-shift task of children (N=17, aged 6–10), adolescents (N=17, aged 11–14), and adults (N=13, aged 16–26). We tested age related differences in shift costs (latency differences between repetitions and alternations) and mixing costs (latency differences between pure blocks and repetitions in mixed blocks). Age related differences in shift costs were found to be significant, with largest costs found for the youngest groups, and partly independent of global speed performance. Mixing costs did not show a differential pattern with age. The results are discussed in terms of development of executive processes.

## 5.1 Introduction

Executive control functions are those cognitive functions that are concerned with the selection, scheduling, and coordination of computational processes. These processes are involved in perception, memory, and action. Executive control functions play an important role in the flexible transition between different tasks. There is currently a renewed interest in executive control functions among researchers of cognitive development and aging. This interest in the development of control of cognitive processes is manifest in the development of models of cognition that attribute an important role to these functions (e.g., Meyer and Kieras, 1997; Norman and Shallice, 1986; Schneider and Oliver, 1991; Stuss, 1992), and in empirical studies on subsets of executive control processes in young and old adults (e.g., Gopher, 1996; Kramer et al., 1995; Mayr and Kliegl, 1993; Mayr et al., 1996; Rogers and Monsell, 1995). One paradigm to study cognitive control and flexibility is task-switching, in which participants switch between a set of choice response time tasks. In this study we will use this paradigm to measure cognitive flexibility and inhibition. The main goal of the present study is to examine developmental changes in set-switching abilities. Thus, we hope to gain insight into the developmental course of cognitive processes that are relevant to performance on switching tasks.

### 5.1.1 Neurocognitive Development

Clearly, a requirement in the study of executive functions is an understanding of the nature of these functions. An influential model in the field of (neuro-)cognitive development and aging which emphasizes the role of executive functions is the *Frontal Lobe Hypothesis*. Proponents of this frontal lobe hypothesis (e.g., Ardila and Rosselli, 1989; Dempster, 1992, 1993; Dempster and Brainerd, 1995; Diamond, 1990; Pennington, 1994; Stuss, 1992; Welsh et al., 1991; West, 1996; Whelihan and Lesher, 1985) propose that developmental trends in the speed of cognitive functioning should be examined in relation to age-related changes in brain structure. They conclude that the frontal, specifically prefrontal (PFC), and more specifically dorsolateral prefrontal (DLPFC) brain structures, and the cognitive functions that rely on these parts of the brain, are most susceptible to effects of age at both ends of the life span. Neuroimaging studies of cognitive development and aging are also inspired by this biological framework (for a review see van der Molen and Ridderinkhof, 1998b). The results of studies which examine brain maturation in healthy children, using different imaging techniques, suggest that the frontal lobes are the last to fully develop (e.g., Chugani, 1994; Courchesne, 1978, 1990; Jernigan et al., 1991; Thatcher, 1994). Localization studies in task-switch settings showed a network of frontal, prefrontal, and parietal areas more active in set switching (e.g., Dove et al., 2000; Kimberg et al., 2000; Meyer et al., 1998). We conclude that executive functions relevant in flexible task-shifting performance are likely candidates for showing age-related performance differences.

One of the standard tasks in neuropsychology used to test executive functions, specifically cognitive flexibility and inhibitory functions, is the Wisconsin Card Sorting Task (WCST; Grant and Berg, 1948). In the WCST, subjects experience difficulty in switching to another sorting criterion (e.g., classifying the same cards according to shape) once they have for some time classified cards according to one stimulus dimension (e.g., color) in a series of trials. Milner (1963) reports that patients with dorsolateral frontal-lobe lesions experience greater difficulties in switching from one rule to another compared to patients with orbitofrontal or more posterior lesions. This specific behavioral pattern is attributed to a greater susceptibility to the interference of responses made according to the previously correct rule. Since Milner, many studies have confirmed the specific sensitivity of perseverative behaviors to deficient functioning of frontal cortex (e.g., Barceló et al., 1997; Barceló and Santome-Calleja, 2000; Drewe, 1974; Stuss and Benson, 1984). Recent neuroimaging studies implicate the activation of prefrontal structures in successful WCST performance (e.g., Barceló, 1999; Berman et al., 1995; Konishi et al., 1999, 1998; Omori et al., 1999; Ragland et al., 1997; Tien et al., 1998). As WCST performance involves many different aspects of executive functioning (e.g., performance monitoring, integration of feedback, rule induction, set switching, and suppression of previous sorting rules), this task is likely to engage activity of other cortical areas as well. The network of brain areas involved in WCST performance includes prefrontal cortex, the hippocampus, and posterior association cortex (e.g., Anderson et al., 1991; Corcoran and Upton, 1993; Nagahama et al., 1996, 1998; Tien et al., 1998). Nonetheless, there appears to be general consensus both

in clinical practice, in experimental neuropsychology, and in cognitive neuroscience that prefrontal-cortex dysfunction is the main factor underlying deficient WCST performance. More generally, it is believed that perseverative behavior is largely a reflection of inefficient prefrontal activity (for a review see Barceló et al., 1997).

Performance on the WCST and similar tasks has been observed to change with age (cf. Heaton et al., 1993). In particular, the tendency to persevere in obsolete sorting rules decreases as children grow older (e.g., Chelune and Baer, 1986; Zelazo et al., 1996), and increases in the later stages of life (e.g., Arbuckle and Gold, 1993; Dywan et al., 1992; Esposito et al., 1999; Fristoe et al., 1997; Kramer et al., 1994; Loranger and Misiak, 1960; Nagahama et al., 1998; Raz, 2000; Ridderinkhof et al., in press; Salthouse et al., 1996).

### 5.1.2 Task-switching

A limitation of studies utilizing the WCST is that the WCST is a highly complex task that involves other abilities in addition to flexibility and inhibitory functions. Thus, Stuss et al. (1995) argued that more specific tests are needed to describe cognitive flexibility. They suggested that the task switching paradigm might provide an experimental analogue of the WCST demands involving switching ability, flexibility and inhibition.

Results of studies utilizing the WCST in young children typically show a robust effect of age on the number of perseverative errors. This also suggests that interference of irrelevant information is manifest in development. The number of perseverative errors made in the WCST is tentatively linked here with switching costs, as they both involve set-shifting abilities. In an aging study using WCST type tasks, Ridderinkhof et al. (in press) found that older adults were unable to capitalize on explicit switch cues (either non-specific or specific). They concluded that basic set-switching abilities, rather than rule-induction or performance-monitoring abilities, are the primary factor responsible for the increased tendency to persevere as adults grow into senescence. If this conclusion is valid, we would expect subjects that are vulnerable to perseveration in the WCST to have difficulties in switching set in the task-switch paradigm.

The present research focuses on developmental changes in executive control processes. As executive control of cognition is most likely not unitary in nature (e.g., Gopher, 1996; Stuss, 1992; West, 1996) in this study a specific paradigm, referred to as 'task switching' is utilized, which is relatively well characterized in terms of executive control. This paradigm, introduced by Jersild (1927), requires subjects to perform a set of relatively simple tasks such as judging whether a letter is a vowel or a consonant, judging the number of elements present in a display, or comparing two multidimensional stimuli. Initial task-switch procedures examined differences in response times of continuous alternations of two tasks on successive trials (e.g., ABAB) and response times on successive trials of the same task (e.g., AAAA). This procedure is now called the *task-alternation procedure*, and is used for instance by Allport et al. (1994). Rogers and Monsell (1995) used an adjusted procedure, in which subjects switch every *n*th trial, instead of every trial (e.g., ABBA). In this procedure (the *alternating runs procedure*), repetitive trials and alternating trials from the same run can

be examined. This procedure has the advantage over the task-alternation procedure that the latter may involve varying memory loads between blocks. On the alternating blocks, subjects have to maintain task instructions for both tasks in memory, in contrast to the repetitive blocks, where only one of the task sets has to be maintained. Meiran (1996) argued that a more representative picture of switching behaviour could be obtained if differences in working-memory demands could be lifted altogether. Meiran extended the task-alternation procedure by abandoning the fixed order in which tasks were switched. Instead, the two tasks were presented in random order, with a task-cue preceding every trial. In this procedure, the *cued task-switch procedure*, on some trials the cue designates a task repetition, whereas on the other trials the cue designates alternations between tasks. Using this procedure, working-memory demands are reduced to the interpretation of the cue, and the selection of the required stimulus-response couplings.

**Mixing costs and Shift costs** ■ Several measures of set-switching costs can be calculated and are attributable to different cognitive processes. In the literature on task-switching the term 'switching costs' is used for any of these measures. According to one of the definitions used in this literature, switching costs are calculated using only mixed blocks: switching costs are defined as latency differences of responses on trials that are preceded by trials of the same tasks (repetitions), and trials that are preceded by a different task (alternations, e.g., Monsell et al., 2000). This type of switching cost is also termed 'specific switching costs' (e.g., Kray and Lindenberger, 2000; Mayr, 2001) or 'shift costs' (Rogers and Monsell, 1995). Using a combination of pure blocks and mixed blocks, switching costs can be defined as latency differences between blocks (e.g., Allport et al., 1994; Los, 1996; Mayr, 2001). This type of switching costs is also known as 'mixing costs' (Los, 1996) or 'general switching costs' (Kray and Lindenberger, 2000). Another variable that can be derived from the mixed-pure blocks is also termed 'mixing cost', or 'mixed-list costs', but refers to latency differences between pure blocks and repetitions in mixed blocks (e.g., Fagot, 1995, van Asselen and Ridderinkhof, 2000). In the current experiment we will use three of the above terms. *Switching costs* refer to latency differences between pure and mixed blocks. Switching costs are a composite of *shift costs* and *mixing costs*. Shift costs are expressed in the latency differences between repetitions and alternations in the mixed blocks. Mixing costs are represented by latency differences between pure blocks and repetitions in mixed blocks.

### 5.1.3 Component processes

Several different conjectures have been submitted to account for the costs observed in task switching, and several different processes have been considered to be involved in shift costs and in mixing costs. Here we review only the more mainstream theoretical positions. Although the present study does not allow to distinguish between alternative accounts, it does allow us to discriminate developmental trends in the different types of processes underlying shift costs and mixing costs.

**Shift costs ■** One explanation of shift costs is in terms of task-set reconfiguration (e.g., Rogers and Monsell, 1995). This view holds that active control processes are engaged in case of a task switch to reconfigure the task set for the appropriate task, while no such control processes are necessary in case of a task repetition. If the switch of task is predictable, then part of this task-set reconfiguration is performed in advance of the task stimulus; the more time to complete this endogenous task-set reconfiguration, the smaller the shift costs. However, shift costs do not disappear altogether even if there is ample time to complete the endogenous task-set reconfiguration processes. To account for these residual shift costs, Rogers and Monsell argued that a second, exogenous component of task-set reconfiguration is triggered by the presentation of the actual task stimulus.

A third component was proposed by Meiran et al. (e.g., Meiran et al., 2000; Meiran and Gotler, 2001), who argued that activation of the new task set is preceded by dissipation of the old task set (as shown by the finding that local shift costs dissipated during the response-cue interval (RCI), in which subjects awaited the instructional cue indicating the task for the next trial). Evidence for inhibition of task sets was also provided by Mayr and Keele (2000), who showed that shift costs were larger if the new task set had recently been activated compared to when it had not.

An alternative view of shift costs is in terms of proactive interference (e.g., Allport et al., 1994). In this view, that has recently been modified an extended (e.g., Wylie and Allport, 2000), when a task alternation requires the performance of a task that differs from the preceding one, there remains some residual activation for the task set associated with the preceding trial by the time that the task set associated with the present trial gets activated. This residual task-set activation then interferes with the activation for the new task for many successive trials after switching from the competing task (Wylie and Allport, 2000).

**Mixing costs ■** The finding that task repetitions are responded to more slowly when the repetition occurs in a mixed block compared to a pure block may emanate from several origins. Los (1996) distinguishes two possible mechanisms, one top-down and the other bottom-up. The top-down mechanism rests on the assumption that subjects are less well prepared in mixed compared to pure blocks, due to greater uncertainty about the task to be presented in the forth-coming trial; the bottom-up mechanism consists of proactive interference of recent task sets, much as in Allport's original conjecture (Allport et al., 1994).

Whether generated bottom-up or top-down, mixing costs are generally considered to reflect the inability to efficiently maintain and coordinate multiple alternative task sets in working memory, and to actively update relevant task sets in mixed blocks (cf. Kray and Lindenberger, 2000; Mayr, 2001).

### 5.1.4 Development of Switching Speed

The present study is concerned with developmental changes in set switching speed. Whereas the literature on cognitive aging now includes many studies of age-related changes (across the adult life span) in the speed of set-switching using the task-switch paradigm, such studies are still scarce in the literature on childhood development. Studies in the area of adult age-related changes usually show a robust interaction between age and switch-conditions (e.g., Kray and Lindenberger, 2000; Span et al., 2001b). Kray and Lindenberger (2000) found shift costs (or specific switching costs) and mixing costs (or general switching costs) to be larger in older adults. Most importantly, age-associated increments in costs were significantly greater for general than for specific switching costs. Span et al. (2001b), using the same tasks as described below, but in an senior population, performed regression analysis on pure blocks, repetitive trials in mixed blocks, and alternating trials. They concluded that parameter estimates in the mixed conditions deviated from parameter estimates in pure blocks. Moreover, age-related changes in response latencies in pure blocks could be described using a linear function, whereas mixed blocks were better described by an exponential function. Although no significant difference between repetitions and alternations was found, the age-related effect on alternations tended to be larger than the effect on repetitions. These results are consistent with the results of Kray and Lindenberger (2000), indicating that the ability to efficiently maintain and coordinate two alternating task sets in working memory (instead of one) is more negatively affected by advancing age than by the ability to execute the task switch itself.

Only recently, results are starting to appear on lifespan trends (e.g., Cepeda et al., 2001) in task-shifting performance. Cepeda et al. studied changes in preparatory and interference processes which underlie switching between different tasks. In their study, switching costs were calculated by subtracting pure-block latencies from mixed-block latencies. Using a set of two tasks (deciding whether the number 1 or the number 3 was presented, vs. whether 1 or 3 numbers were presented on the computer screen), they observed that switching costs followed a U-shaped function across the life span. Although they did not contrast young age-group performance with adult performance, they reported an interaction between age-group and switching costs, with switching cost being largest in young children (aged 7–9) and older adults (aged 60+). Children benefited as much as older adults from a prolonged Cue-Target Interval (CTI), associated with preparation processes. However, children did not benefit from a longer Response-Cue Interval (RCI) associated with inhibition of the previously performed task. In general the data of Cepeda et al. are consistent with the frontal lobe hypothesis, with comparable effects on both end of the lifespan. Their study provides evidence of a differential time course for the development of active preparatory processes and inhibition, with preparatory processes becoming efficient during early development.

### 5.1.5 The present study

The main goal of the present study is to examine developmental changes in set-switching abilities. It also focuses on the similarities and dissimilarities between the pattern of behavior found in our sample of children (6–10 years old), adolescents (11–14 years old) and adults (16–26 years old), and the effects found in the literature on aging and set-switching.

In this study, a cued three-set switch task is used. The response latencies on this task (mixed blocks) are compared to the response latencies on blocks without switches (pure blocks). In all choice tasks, the stimulus material and the response mappings were identical: stimuli are pictures that have three discriminating dimensions. The instruction was either to continuously adopt one of the discriminating dimensions (Pure Blocks), or to use the cued discriminating dimension (Switch Blocks).

In order to investigate the underlying processes that contribute to the developmental changes in task-switching, both shift costs (differences between non-switch and switch trials within heterogeneous blocks) and mixing costs (latency differences between repetitive trials in homogeneous and heterogeneous blocks) are analyzed. Shift costs are associated with the ability to execute the task-switch itself. Mixing costs are associated with the ability to efficiently maintain and coordinate three alternating task sets in working memory (instead of one). Thus, the present study allows to examine the extent to which developmental trends in task-shifting performance (as reported by Cepeda et al., 2001) involve basic set-shifting abilities, global task-set coordination abilities, or both.

The response times on a simple reaction time task are entered as covariate into the analyses to test the age-related effects on switching speed against general, non-specific effects of age on basic perceptual and motor speed. This task shares as many features as possible with the choice reaction time tasks to minimize the contribution of unrelated error variance elicited by task differences.

## 5.2 Method

### 5.2.1 Participants

47 subjects participated in the present study. The participants were subdivided into three age groups. The child group comprised 17 subjects (range=6–10, mean=8.23, sd=1.07), 17 subjects were in the adolescent group (range =11–14, mean=11.8, sd=.97) and the young adult group consisted of 13 subjects (range =16–26, mean=21.07, sd=3.2). Mean Raven-percentile scores did not differ with age ( $F(2,44) = 1.4, p > .2$ ), suggesting that groups were comparable in terms of intelligence.

### 5.2.2 Stimulus material and apparatus

The participants were seated in front of a computer monitor at a viewing distance of 40 cm. Stimulus presentation and response registration were controlled by an IBM compatible 486 computer. Stimuli are shown in Figure 2.1. Stimuli are distinct with respect to three dichotomous dimensions. These dimensions are: man-woman, happy-sad and wearing glasses or not. All stimulus elements were black line drawings presented against a white background. Stimuli were presented in a square of  $3 \times 3$  cm in the center of the computer screen.

### 5.2.3 Tasks and procedure

A fixation cross was presented before each trial for 500 ms in the middle of the presentation square. After 500 ms the fixation cross disappeared and following an interval of 33, 166 or 500 ms (selected at random) the stimulus was shown. The stimulus presentation was terminated by the response. Subsequent to the subject's response, visual feedback was presented with a delay of 100, 500 or 1500 ms (selected at random). Feedback consisted of the presentation of the words 'GOED' (correct) or 'FOUT' (incorrect) just below the presentation square. On each trial, one stimulus (selected at random) appeared in the square in the middle of the screen. The stimulus required a response with one of two response keys (the 'z' and 'y' keys of the computer keyboard that were operated by the left and right index fingers, respectively). The subject's task was to respond as fast and accurately as possible with the designated response finger. The next trial was started exactly 1 s after the subjects' response. The definition of a correct response on a given trial depended on the specific instruction, which varied from task to task. This was explained in detail to the subject prior to each task. All tasks were practiced before the main session, in a separate practice session that included all tasks. The five tasks were administered in random order, to control for sequence effects.

**Simple Response Time task (SRT)** ■ In the SRT task, whenever a stimulus appeared the subject was required to press the response button as fast as possible with his/her right index finger, regardless of the identity of the stimulus. This task was presented in a block of 40 trials, and was practiced for 20 trials.

**Pure Blocks: Choice Reaction Time Tasks (CRT-1, CRT-2 and CRT-3)** ■ Three highly comparable tasks were administered. The difference between the tasks is the stimulus dimension that was selected for discrimination. In the CRT-1 female faces designated left-hand responses; male faces designated right-hand responses. In the CRT-2 happy faces designated left-hand responses; sad faces right hand responses. In the CRT-3 faces wearing glasses designated left-hand responses; faces without glasses right-hand responses. Each of these three CRT tasks was presented once in a block of 50 trials, and practiced in a block of 20 trials before the main session.

**Switch Blocks: Choice Reaction Time/Task Switch task** ■ The task switch task is the implementation of a three-set task-switch paradigm. The three task sets used are the three choice reaction time tasks that were practiced in the training session. The subjects had to respond to each stimulus using the task-set that was cued before the stimulus appeared. The cue used consisted of two words: “Man-Vrouw” (man-woman) for the CRT-1 task, “Lachen-Niet” (laugh-not) for the CRT-2 task and “Bril-Geen” (glasses-none) for the CRT-3 task. This cue was presented for 500 ms, and was followed by an interval of 33, 166 or 500ms (selected at random) preceding the stimulus. On each trial there was a 50% chance of a switch in rule-set. Therefore about 50% of the trials were preceded by trials of the same task-set, and 50% of the trials were preceded by trials of a different task-set. The task-switch task consisted of 150 trials. An additional 30 administered before the main session served as practice trials.

Care was taken to ensure that all subjects understood the instructions and were able to perform the task. Feedback was given to motivate the subjects to perform as fast and accurately as possible. The tasks were administered in random order, and were separated by short breaks of one to two minutes. A four-minute break followed the second task. The time taken to complete one task block varied between 5 and 11 minutes, depending on the specific task. Total test time was about 45 minutes, including time spent on the break and a short intelligence test.

#### 5.2.4 Data Analysis

**Dependent Measures** ■ Mean RT's on trials that were responded to correctly was the dependent measure in the analysis of variance. All response latencies shorter than 75 ms were discarded (less than 2% of all trials). As there were no trials exceeding four standard deviations of the mean in any of the subjects we decided not to eliminate outliers. The trials of the task-switch task were subdivided into repetitions and alternations. We used a repeated measures design, entering task and trial types as within-subject variables and age-group as between-subject variable. The analyses were carried out using the R statistical package (Ihaka and Gentleman, 1996).

### 5.3 Results

Mean response latencies on the different tasks are shown in Table 5.1 and in Figure 5.1 (left panel). Error proportions are shown in Figure 5.1 (right panel). Mean shift costs and mixing costs are shown in figure 5.2.

Two sets of analyses were performed. The first set of analyses addressed the effects of age-group on mixing costs and switching costs (ANOVA). The second set of analyses examined the effects of age-group on mixing costs and switching costs *given* the response times on the SRT (ANCOVA). In this way we controlled for differences in perceptual and motor speed (using analysis of covariance) by entering SRT performance as a covariate into the ANOVA.

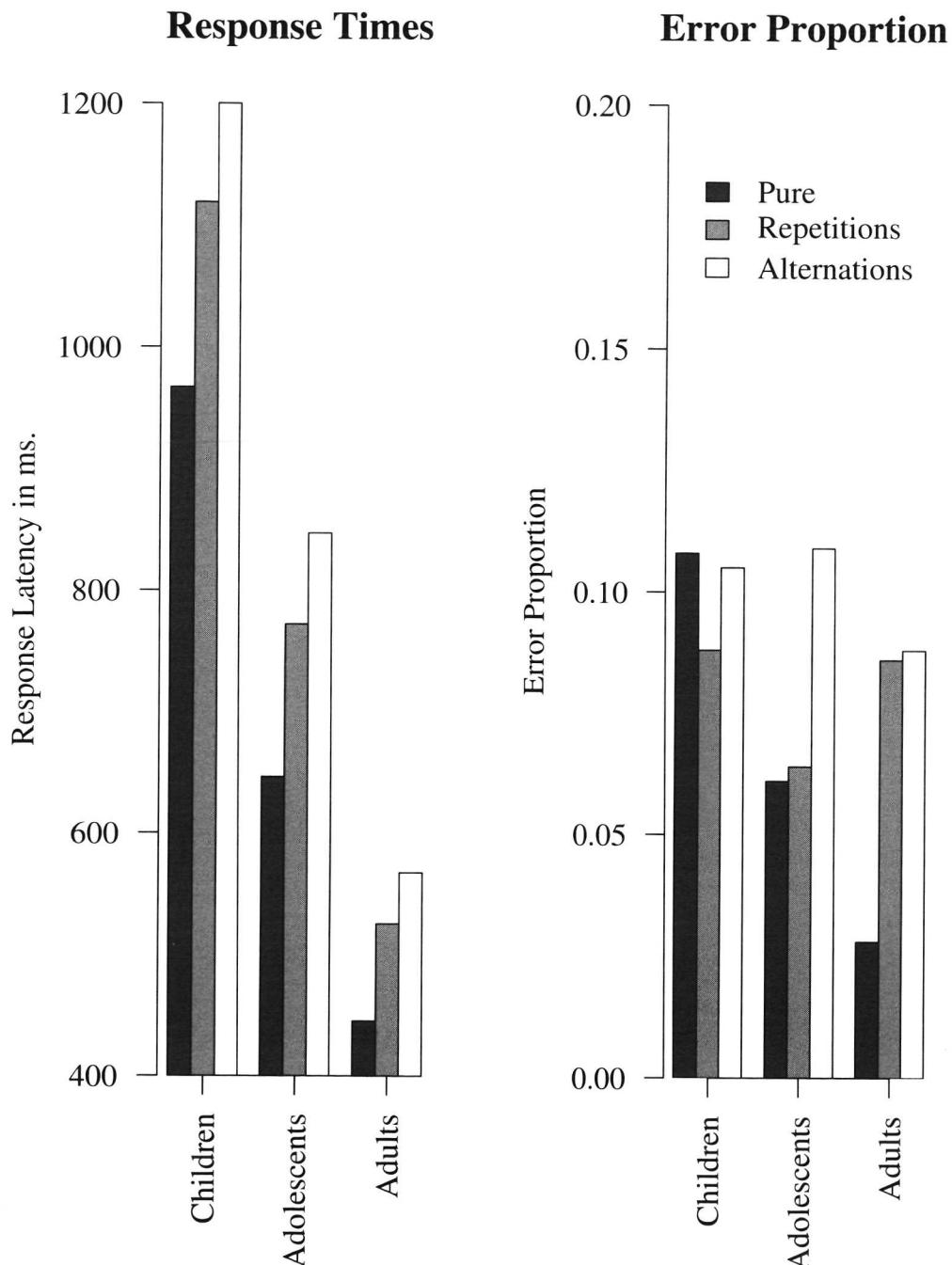


Figure 5.1: Response Latencies and Error Proportions for both the switch tasks and the pure blocks (see text for the descriptions of the tasks).

**Table 5.1: Response Latencies for both the switch tasks and the pure blocks. The Simple Response task is a identity-independent response measure. Pure Blocks are simple choice reaction time tasks varying in perceptual difficulty. On the task-switch task these three choice reaction time tasks were mixed (see text for the descriptions of the tasks).**

Age-Group	Repetitions		Alternations	
Simple Response:	mean	sd	mean	sd
Children	477	(116)		
Adolescents	354	(108)		
Adults	271	( 65)		
Pure Blocks:				
Children	976	(200)		
Adolescents	646	(157)		
Adults	445	( 55)		
Switch Blocks:				
Children	1119	(123)	1305	(147)
Adolescents	772	(190)	847	(202)
Adults	525	(107)	567	(139)

### 5.3.1 Analysis of Variance

**Shift costs ■** Both shift costs and mixing costs are shown in Figure 5.2. Mean response latency on correct responses on the task-switch task were entered into an ANOVA with Age Group as between-subjects factor and Trial Type (repetitions versus alternations) as a within-subjects factor. This analysis of variance revealed a significant effect of Age Group ( $F(2,44) = 73.3, p < .001$ ), Trial Type ( $F(1,44) = 74.8, p < .001$ ) and an Age Group  $\times$  Trial Type interaction ( $F(2,44) = 12.5, p < .001$ ). The within subject ANOVA on error proportions showed no significant effect for Age Group ( $F(2,44) = 3.0, p > .1$ ), no effect for Trial Type ( $F(1,44) = .46, p > .1$ ) and no Age Group  $\times$  Trial Type interaction ( $F(2,44) = 2.37, p > .1$ ).

**Mixing costs ■** We also entered the repetitive trials in the task switch setting together with the pure block latencies in an ANOVA to test mixing costs. The ANOVA model included Age Group as a between-subject factor, and Task Type (pure versus mixed) as within-subjects factor. For the response latencies this ANOVA showed significant effects of Age Group ( $F(2,44) = 79.8, p < .001$ ), a significant Task Type effect ( $F(1,44) = 41.8, p < .001$ ) but no significant interaction between these factors ( $F(2,44) = .96, p > .1^1$ ). In the ANOVA on error proportions, only the Task Type factor showed a significant effect ( $F(1,44) =$

<sup>1</sup> Post-hoc analyses showed the effect size to be negligible. Hays'  $\omega^2$  for mixing cost in this study is extremely small: The partial  $W_\alpha^2 = -0.0017$ .  $W_\alpha^2$  can take on negative values, because it is estimated ( $\omega_\alpha^2$  is estimated by  $W_\alpha^2 = \frac{2 \times (F-1)}{2 \times (F-1) + N}$ ). Hays'  $\omega^2$  cannot assume negative values, but it is clear that the effect is negligible.

8.17,  $p < .01$ ), but the Age Group effect and the interaction between age and task were not significant ( $F(2,44) = 1.79, p > .1$  and  $F(2,44) = 2.8, p > .05$ , respectively). The trend towards an interaction as well as the main effect of Task Type were found to go in the same direction as the corresponding effects on response latencies, thus discarding an explanation in terms of speed/accuracy trade-off.

### 5.3.2 Analysis of Covariance

The analyses above were repeated with the response times of the individual subjects on the SRT task as a covariate. This analysis tests the variance on the response times of the experimental conditions that is not shared with the SRT. Again, Age Group was entered as a between-subjects factor, and Task Type or Trial Type as within-subject factor. The mean response times on the SRT are presented in Table 5.1 and differed by Group: Older groups are faster than younger groups ( $F(2,42) = 14.7, p < .01$ ).

**Shift costs** ■ This analysis of covariance showed a significant Age Group ( $F(2,41) = 33.83, p < .001$ ), Trial Type ( $F(1,41) = 81.01, p < .001$ ), and Age Group  $\times$  Trial Type interaction ( $F(2,41) = 4.06, p < .05$ ), that were independent of the SRT performance.

**Mixing costs** ■ Although no Age Group  $\times$  Task Type interaction was found using ANOVA, we also performed an analysis of covariance on the mixing cost data. Both the Age Group effect ( $F(2,41) = 38.3, p < .001$ ), and the Type effect ( $F(1,41) = 39.51, p < .001$ ) remained significant. The interaction between these main effects was (not surprisingly) not significant ( $F(2,41) = .37, p > .1$ ).

## 5.4 Discussion

**Development of Switching Speed** ■ The main goal of this study was to gain insight into developmental changes in set-switching abilities. Using the task-switch paradigm we hoped to identify the processes that are relevant in developmental trends in the efficiency of cognitive functions as involved in switching sets. To reduce the amount of irrelevant variance between tasks the stimulus material and the response mappings were identical between tasks.

The approach we took to identify component processes in task switching is similar to that taken by Fagot (1995). Fagot distinguishes three experimental conditions: Pure blocks, repetitive trials in a switch setting and alternating trials in a switch setting. The difference between the response latencies in single task performance and latencies in alternating trials is termed 'switching costs', and reflects the conjunction of two components. The first of these components is mixing cost, the reflection of the decay in performance resulting from keeping multiple task sets in working memory, or 'the mere relevance of several tasks rather than a single task' (Meiran and Gotler, 2001, page 167). The second component is shift costs, associated with processes that detach previously correct stimulus-response rules from working memory (inhibition), working memory processes, and task-set activation processes (the reconfiguration of stimulus-response rules).

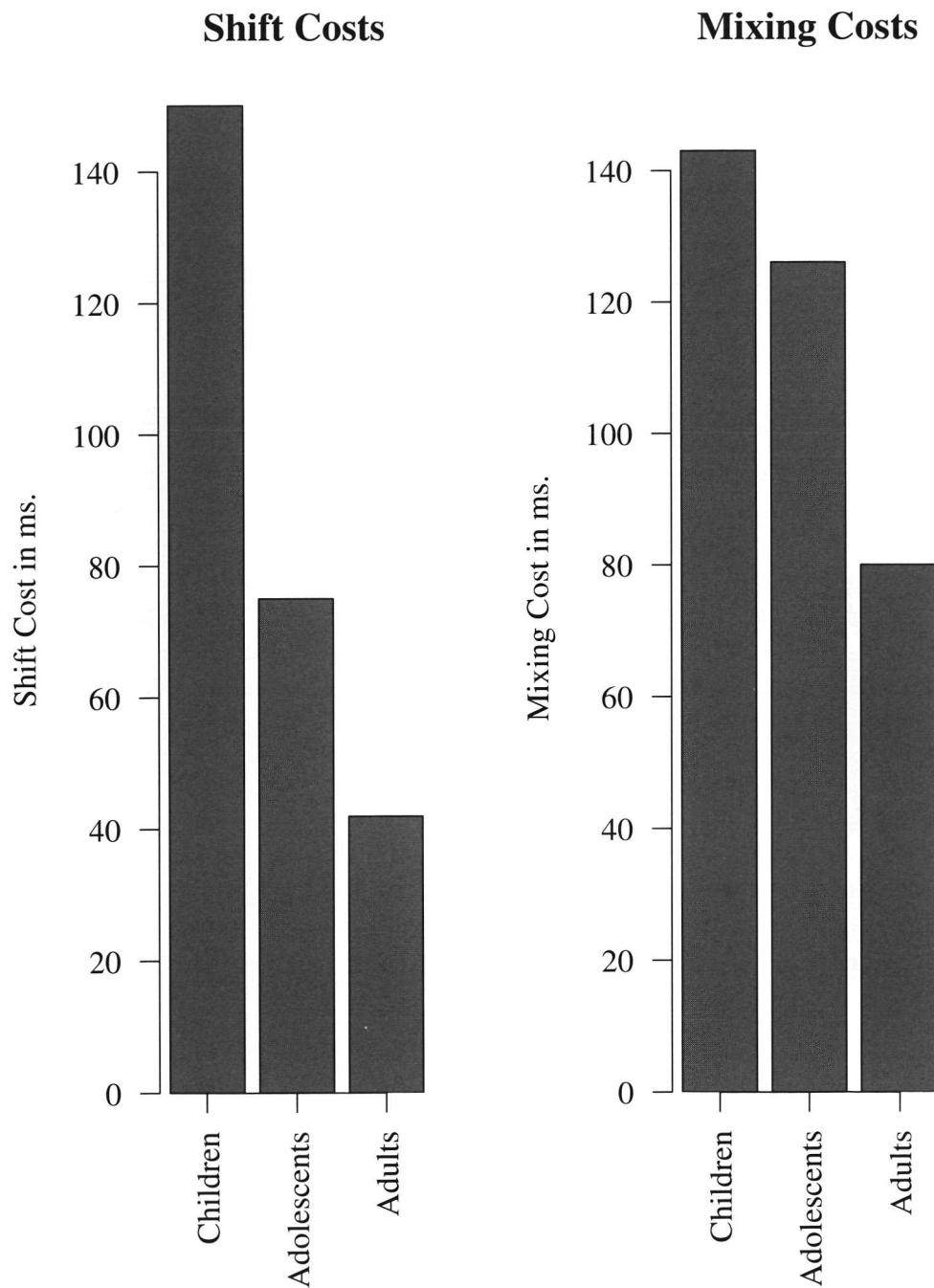


Figure 5.2: *Shift Costs* are latency differences between repetitive trials and alternating trials in mixed blocks. *Mixing costs* are latency differences between repetitive trials in the mixed blocks and the pure blocks.

The main finding of the present study is that the ability to reconfigure the cognitive system when switching from one set to another is disproportionately inefficient in childhood. In contrast, the ability to effectively maintain and coordinate multiple task sets during task switching does not seem to undergo disproportional development. Interestingly, this result is the opposite of the pattern of results observed at the other end of the life span by Mayr (2001), who performed an aging study using a cued (three set) task shift paradigm. Mayr conducted two experiments to investigate the role of several cognitive processes on age-related differences in task-shift performance. In his first experiment he found substantial mixing costs (global costs) and smaller shift costs (local costs), thus replicating the findings of Kray and Lindenberger (2000). Focusing on the influence of so-called backward inhibition of no-longer-relevant task sets, Mayr suggested that this process is utilized by older adults, possibly to compensate for difficulties with the activation and maintenance of the currently relevant set. In the second experiment he replicated this finding, and was able to relate age-related differences in mixing costs (global costs) to situations with stimulus ambiguity and full response-set overlap. Mayr suggested that mixing costs can be attributed to age-related difficulties in set-updating, a process that is thought to reset the internal control, and which is relevant only in the task-shift environment. Both conditions (stimulus ambiguity and response-set overlap) which are found relevant for the occurrence of disproportional mixing costs in the aging population, are present in our study. However, the developmental trends in mixing costs were not found to approach statistically significant. The present results thus indicate that children are not detrimentally affected in set-updating. In an aging study using the task set described in this article (Span et al., 2001b), we did find significant age effects on mixing costs in older adults. This suggests that task-specific properties are unlikely to be responsible for the absence of mixing costs in the present study.

**Mixing Costs ■** In the current paper, mixing costs were defined as latency differences between repetitions in pure blocks and mixed blocks. Mixing cost appear to be proportional between age-groups. Although care has to be taken to account for null-findings, the effect size was negligible. Therefore we conclude that the absence of a significant interaction between age-group and the mixing costs is not due to small sample size, resulting in lack of power of the tests.

As mentioned, mixing cost can be viewed as reflecting the sub-optimal preparation of the task set (or set-updating) in mixed blocks. The context of a mixed block results in uncertainty about the upcoming task. In the Cepeda et al. (2001) study, children were found to show little evidence of rapid decay of task-set activation, as they did not benefit from a prolonged RCI. The conclusion of Cepeda et al. (2001) that preparatory processes become efficient earlier in life than inhibitory processes, is corroborated by the results of the present study. Using the cued task-switch paradigm in an aged population Kray et al. (in press) found that general switching cost, defined as latency differences between pure blocks and switch blocks, were confined to switch trials. This suggests that age effects on mixing costs in their study were non-significant, in agreement with the present findings. In contrast to these findings, Meiran and Gotler (2001) argue that mixing costs (again, in the aging population

and using a cued switching paradigm) are about equal in size to shift costs ( $\eta^2 = .30$  vs.  $\eta^2 = .36$ ).

**Shift Costs ■** Shift costs were defined as latency differences between alternations and repetitions within mixed blocks. Shift costs differed between age groups, with the largest shift costs found in the youngest group. These results are in agreement with the Cepeda et al. (2001) study. In their study switching costs are calculated by subtracting pure-block latencies from mixed-block latencies. Using a set of two tasks (deciding whether the number 1 or the number 3 was presented, or whether 1 or 3 numbers were presented on the computer screen), they observed that switching cost displayed a U-shaped function across the life span. Although they did not contrast young age-group performance to adult performance, they report an interaction between age-group and switching costs, with switching cost being largest in young children (aged 7–9) and older adults (aged 60+). Mean response latencies and standard errors for pure blocks and mixed blocks (repetitions and alternations) are comparable to the means and standard errors in the present study. Cepeda et al. conclude that inhibitory processes in set-shifting become efficient later in life compared to preparatory processes. This conclusion is consistent with observations using other paradigms like the Stroop task (e.g., Comalli Jr. et al., 1962) and the stopping task (e.g., Ridderinkhof et al., 1999; Williams et al., 1999).

To test the age-related effects on switching speed against effects on basic perceptual and motor speed, the response times on a simple reaction task were entered as a covariate into the analyses. Age effects on shift costs appear to be at least partly separable from age effects on perceptual and motor speed: the interaction between age group and trial type remained significant. This effect is consistent with previous findings using this task set in an aged population. In Span et al. (2001b) we also found a dissociation between basic speed (in this case measured by pure block performance) and set switching.

In conclusion, shift costs appear to be influenced more by increasing age than are mixing costs. The age-modulated gains in speed of switching is at least partially independent of basic perceptual and motor speed development. These results seem to point to an inhibitory deficit in children (e.g., Bjorklund and Kipp-Harnishfeger, 1990; Dempster, 1992, 1993; van der Molen, 2000) to provide an account for the slower response times found in the switching condition as compared to non-switching conditions.



# SUMMARY AND CONCLUSIONS

The primary objective of the research presented in this thesis is to further the understanding of the lifespan trends in the efficiency of executive control. In the introduction of this thesis executive functions are defined as functions that are responsible for the organization and management of more specialized cognitive processes. These functions are involved in error monitoring, interference control, task-set reconfiguration and context updating (e.g., Meyer and Kieras, 1997; Norman and Shallice, 1986; Shallice, 1994). Executive functions, or cognitive control functions, are relevant to the capacity of the cognitive system to monitor the environment and modify behavior accordingly. The starting point of our interest in executive functions was the Wisconsin Card Sorting Test (WCST). Aspects of the WCST are identified that are especially relevant for the presence of age-related differences in adaptive behaviour. To this end several tasks that share meaningful characteristics with the WCST were employed.

## 6.1 Summary

In general, there is consensus that, in neuro-anatomical terms the process of aging is modular. In Chapter 1 evidence is summarized for the hierarchical nature of brain development and aging. Phillips and Della Sala (1998) reviewed literature on cognitive aging and suggested that only functions associated with dorsolateral prefrontal regions are impaired with age, while orbitofrontal areas are not. This suggests that the hierarchical development is characteristic of prefrontal areas of the brain too. Tucker et al. (1995) outlines some anatomical evidence for the 'dual evolutionary origins of the frontal cortex', taken as evidence for differential trends in the development of both the dorsolateral and the orbitofrontal areas of the prefrontal cortex.

The global speed hypothesis and the specific loss hypothesis have provided new perspectives on research concerning age-related differences in the speed of cognitive processes. The study presented in Chapter 2 addressed these hypotheses in a simple empirical study. We assessed the extent to which age exerts an independent influence on the efficiency of executive control after the age-related covariance with global processing speed is partialled out. This is achieved by means of a MANCOVA with mean response times on each non-executive task entered as covariates. This analysis revealed a mixed pattern of results. In children, partialing out global speed was found to remove the differences with adolescents in each of the executive function tasks. This suggests that global processing speed was the primary factor underlying developmental changes in the efficiency of information process-

ing, regardless of the involvement of executive control functions. In contrast, in the older adults, substantial residual differences with young adults remained in each of the executive function tasks after controlling for global processing speed. Thus, executive control may be viewed as a fundamental factor underlying the effects of aging on the efficiency of cognitive processing, independent of aging effects on global processing speed.

The discrepancy between the results at the opposite ends of the life span attests to the sensitivity of the covariance analysis to both the global speed and executive control factors. Insensitivity of the method to any of these factors would have resulted in patterns of results going in similar directions for development and aging, which is clearly contradicted by the present outcome. When assessing age-related changes in the speed of cognitive processes, the present MANCOVA approach should be preferred over regression techniques like Brinley analysis. We tested the regression model more directly by means of structural equation modelling (SEM). The model presented in Figure 2.2 provides an adequate description of the response latency data from each age group. Adolescents and young adults differ neither in the basic perceptual and motor speed (SP) factor nor in the executive control (EF) factor; by the age of 15, the efficiency of information processing has approached that of young adults, regardless of the type of task included in this study. Children differ from adolescents, but only in the SP factor; removing the EF factor from the model did not result in a poorer model fit. As with the MANCOVA results, this outcome suggests that global processing speed was the primary factor underlying developmental changes in the efficiency of information processing, regardless of the involvement of executive control functions. Young and older adults differed not only in the SP factor but also in the EF factor; removing the EF factor from the model resulted in a considerable deterioration of the model fit. This outcome suggests that both global processing speed and executive control are important and independent factors contributing to the effects of aging on the efficiency of cognitive processing. In development, only the SP factor seems to be contributing to the efficiency of cognitive processing.

Card sorting tasks like the Wisconsin Card Sorting Test (WCST) are quite complex and efficient performance in such tasks involves many different cognitive operations. One approach to establish in greater detail why older adults and frontal patients experience difficulties in endogenous adaptive control in these tasks, is to decompose the WCST into component processes. In Chapter 3 of this thesis this problem is addressed in two steps. First, it was investigated whether older adults' performance benefited from the presentation of explicit cues that tell them to shift to another sorting rule. If explicit cueing facilitates older adults performance such that they persevered less frequently in previously correct categorization rules, this would suggest that age-related differences in adaptive control processes are accounted for by deficits in performance monitoring rather than in rule-induction or set-shifting abilities. Young and older adults were administered cued and non-cued versions of a dimensional shift task bearing resemblance to the WCST. From the consistent finding that older adults were unable to capitalize on specific (compared to non-specific) shift cues it was inferred that, instead of performance monitoring or rule induction, the basic set-shifting ability is the major factor responsible for the increased tendency to

persevere with increasing age.

This set-shifting factor was measured in a more experimentally controlled setting in the latter part of this thesis (Chapters 4 and 5). Stuss et al. (1995) proposed that the task-shift paradigm is more suitable to the investigation of cognitive flexibility than card sorting. They suggested that the task switching paradigm may provide an experimental analogue of the WCST demands, which include switching ability, flexibility and inhibition. This paradigm was utilized in Chapter 4 of this thesis. In a group of subjects, ranging in age from young adolescence to senescence, the task-switching paradigm is used to investigate the cognitive efficiency of shifting behaviour. Age is considered to be the mediating factor in this efficiency. The main finding of this chapter is the dissociation of the type of function that best describes the age-related changes in response speed in pure blocks and in a task-shift setting. Pure blocks are best described using a simple linear function, but both the repetitive trials and the alternating trials in the task-shift setting are better described by an exponential function. We thus demonstrated that age trends in the efficiency of adaptive control abilities become progressively more pronounced at the more extreme part of the adult life span. This finding is by no means new (see e.g., Cerella and Hale, 1994), but here we were able to identify a dissociation between simple choice response time tasks and cognitive flexibility.

Using covariance analysis, the effect of development on cognitive flexibility is also investigated using the task-switch paradigm in Chapter 5. Several measures of set-switching costs were calculated and attributed to different cognitive processes. *Switching costs* refer to latency differences between pure and mixed blocks. Switching costs are a composite of *shift costs* and *mixing costs*. Shift costs are expressed in the latency differences between repetitions and alternations in the mixed blocks. Mixing costs are represented by latency differences between pure blocks and repetitions in mixed blocks. To test the age-related effects on switching speed against effects on basic perceptual and motor speed, the response times on a simple reaction task were entered as a covariate into the analyses. Age effects on shift costs appear to be partly separable from age effects on perceptual and motor speed: the interaction between age group and trial type remained significant. Shift costs appear to be influenced more by increasing age than are mixing costs. The age-modulated gains in speed of switching is at least partially independent of basic perceptual and motor speed development. These results are attributed to an inhibitory deficit in children in Chapter 5 (e.g., Bjorklund and Kipp-Harnishfeger, 1990; Dempster, 1992, 1993; van der Molen, 2000). This finding is consistent with the recent developmental literature on developmental trends in task-shifting (Cepeda et al., 2001). In the study of Cepeda et al., children did not benefit from a longer Response-Cue Interval associated with inhibition of the previously performed task. Children benefited as much as older adults from a prolonged Cue-Target interval, associated with preparation processes.

## 6.2 Discussion

Several similarities and discrepancies between developmental and aging speed trends were found. In Chapter 2 of this thesis a direct test of the global speed versus the specific loss hypothesis was conducted. The results showed a marked difference between the developmental and the aging data. Where the results of older adults showed a large influence of a latent 'executive processing' variable, in young subjects the response latencies could be described exhaustively using only a latent 'global speed' variable. In this chapter a set of tasks that are known to rely on executive-control processes were used. In Figure 2.6 the contribution of general speed and executive function to the mean response latencies is shown. Older adults showed disproportional slowing on all of the response selection, response inhibition, working memory and adaptive control tasks. Clearly, in the youngest children latency differences are unrelated to task-type (simple versus executive). A similar discrepancy is found in Chapters 4 and 5, where task-shifting performance showed qualitatively different patterns of age-related speed differences for older adults (Chapter 4) and children (Chapter 5). In older adults, a marked difference in performance is found in a comparison of single task performance with mixed block performance. In children, however, the performance decrease is observed when comparing switch trials in a switch block with repetitions in a switch block. No significant developmental performance differences are found when comparing repetitions in a switch block with single block performance. The age-related effect in the older adults should therefore be attributed to different cognitive functions than in children. In the next paragraphs the nature of these functions will be inferred.

**Lifespan trends in cognitive flexibility** ■ One of the puzzling results of this thesis is the discrepancy between the behavioral patterns of children and seniors. The frontal lobe hypothesis (e.g., Ardila and Rosselli, 1989; Dempster, 1992, 1993; Dempster and Brainerd, 1995; Diamond, 1990; Pennington, 1994; Stuss, 1992; Welsh et al., 1991; West, 1996; Whelihan and Lesher, 1985) predicts process-specific speed differences that originate in neurobiological differences between children, seniors and young adults. Tasks that are susceptible to age-related differences are thought to draw on functions located in the prefrontal cortex (PFC). This brain area is the last area to reach adult levels of maturation, and is the first in old age to show detrimental structural changes. We will propose two hypothesis to account for the differential findings of our studies.

**Differentiation and dedifferentiation** ■ A major issue in cognitive aging and development is the question of structure and development-associated changes in structure. The best-known model involves a change in the structure of cognitive efficiency toward differentiation in early life followed in late adulthood by the reverse process of dedifferentiation (e.g., Baltes et al., 1999; Li and Lindenberger, 1999). This hypothesis is based on the assumption that changes in cognitive efficiency reflect limitations imposed by a set of biological (e.g., Spearman, 1927) and/or environmental constraints (e.g., Baltes et al., 1999). Li and Lindenberger (1999) propose the dopamine (DA) model as an explanatory model for the

differentiation/dedifferentiation of cognitive abilities during aging and development. The importance of DA in normal functioning of the brain's inhibitory system can be seen in patients with Parkinson's Disease. Here, symptoms of tremor, akinesia (complete or partial loss of muscle movement), and rigidity emerge after the death of dopaminergic neurons in the brain. Simply put, the deficit in DA results in excessive inhibition. While it may be simplistic to suggest that disinhibition in children represents a type of 'reverse Parkinson's', some evidence makes this possibility worth considering. Its concentration in cerebrospinal fluid (the fluid cushion protecting the brain and spinal cord) peaks at about the age of two and declines fairly rapidly over the next dozen years. Inhibition of cortically mediated behaviour is through projections via the striatum, to the globus pallidus, which dampens the inhibitory projection to the subthalamic nuclei. This results in an inhibition of the thalamus. Primary neurotransmitters in this pathway are glutamate,  $\gamma$ -aminobutyric acid (GABA), and DA, which modulates this system (Casey et al., 2001, 2000). Optimal levels of DA are a prerequisite for efficient functioning of this pathway.

When applied to lifespan development, the differentiation/dedifferentiation hypothesis predicts that the prominence of the general factor decreases during childhood as a function of brain maturation and domain-specific knowledge acquisition, remains relatively stable throughout adolescence, adulthood, and early old age, but increases again late in life. In later life, system-general constraints such as biological brain aging regain importance (Baltes et al., 1999; Li and Lindenberger, 1999; Lindenberger et al., 1999). One possibility for the high degree of homogeneity of cognitive functions in childhood and senescence is developmental change in the brain that affects all cognitive functions similarly.

The response times of young children in our research show high levels of homogeneity between tasks. The differentiation of functions into domain specific (or automated) functions is apparent in adolescents and adults (see e.g., Figure 2.6). In older adults, no evidence for dedifferentiation can be demonstrated. Possibly, system-general constraints such as biological brain aging can cause differential, domain specific slowing during senescence. DA turnover is largest in the PFC. In contrast to young children, older adults show low concentrations of DA in the cerebrospinal fluid. It is not unlikely that the effect of this DA deficiency is more pronounced in tasks that rely on the PFC. The dedifferentiation would then be domain specific, showing more homogeneity *within* executive control functions and *within* general cognitive processes.

**Qualitative differences in task performance ■** Age-related differences in processing speed are often assumed to be quantitative in nature (e.g., Ridderinkhof and van der Stelt, 2000). That is, all the cognitive functions engaged by a given task are assumed to differ only in their efficiency and speed of execution (the Invariant Structure assumption). If processing stages differ between age groups, such that this task would be performed *qualitatively* different between groups, then one could easily misidentify the nature of such age-related changes in processing speed when focusing on quantitative changes rather than structural differences. To identify qualitative differences in the performance of the tasks used in this thesis, we will turn to the literature on electrophysiological differences between age groups

on executive tasks.

The ERN (Error-Related Negativity) is an ERP component that is associated with performance monitoring. It is usually observed on trials that are characterized by response conflicts, or even an overt, incorrect response. A central factor in the occurrence of the ERN and performance monitoring is the DA system (e.g., Holroyd and Coles, *in press*; Nieuwenhuis, 2001). In patients with PFC damage, the ERN is apparent not only on the incorrect responses, but also on trials that are responded to correctly (Gehring and Knight, 2000). Given that ERN activity is a manifestation of performance monitoring in the EEG, this finding implies that in prefrontal patients, performance monitoring is activated even when the task does not require it. Generalizing this finding, we can speculate that for frontally impaired patients, executive control manifests itself on trials that do not require executive control in normals.

Young children may manifest the same phenomenon. The PFC of children is not fully matured, and young children appear to show performance deficits similar to frontal lesions on some clinical tests. Children could be utilizing executive control functions on tasks that do not require executive control in young adults. This would lead to diminished performance on even simple response time tasks that resemble diminished performance on executive function tasks. These simple tasks then require the intact functioning of structures mediating cognitive control, i.e. the PFC and the DA system. When we analyze the data of young children according to Model 2.2, the latent EF factor would not be separable from the latent SP factor, as all tasks require executive control. If the speculative hypothesis expressed above were true, the variance of the EF factor would be (largely) shared with the variance of the SP factor. The SP factor would in reality be a combined SP/EF factor.

In Chapter 5 we were unable to identify differential age-related changes in the speed of processing between pure blocks and repetitions in shift blocks. This could be due to the involvement of executive control functions in pure block performance. The finding that repetitions and alternations within task-shift blocks does show differential developmental patterns is by no means contradictory to the 'simple-executive' hypothesis. It is possible that children show specific, disproportional slowing on the task-set reconfiguration, leading to shift costs that are not attributable to the general 'SP/EF' factor.

How could we test this idea? First, it would be useful to show that children display ERN activity on correct trials, like patients with a prefrontal deficit. This is the most direct test of the hypothesis expressed above. An indirect test that would serve as convergent evidence could be implemented by testing patients with a prefrontal deficit using the tasks described in Chapter 2. In these patients, we would predict a pattern of results similar to the results found for the child group in this chapter: a one factor model describing the response latencies for all tasks.

### 6.3 Conclusions

The central question that is addressed in the four empirical chapters of this thesis is whether executive control functions show differential age-related differences in processing efficiency. In these chapters different statistical analysis techniques were used to identify differential patterns of development and aging when comparing tasks that rely in lesser or greater extent on executive control functions. In all chapters the special role executive control functions play in development and aging is demonstrated. Age-related changes in the efficiency of cognitive processes are investigated from a neurocognitive viewpoint. It is demonstrated that age-related changes in brain structure have implications for the response latencies in tasks that rely in these structures. These results are presented here as convergent evidence for the neurocognitive change hypothesis presented in Chapter 1. This hypothesis predicts specific age-related differences for tasks that rely on executive control functions (presumed to rely on prefrontal brain structures). An important addition to this hypothesis is made, when observing the differences in the pattern of age-related change between young children and seniors. The locus of the age-related changes in efficiency is shown to be different for children and seniors. Although, on a broad level, there are similarities between the age-related changes in brain structure in the young and old, it appears that the effect of these changes is qualitatively different between both ends of the life-span. These differences are thought to originate in: 1) Qualitative differences in the performance on 'non-executive' tasks, and/or 2) Biological constraints on a more specific level, e.g., the role of DA in the inhibitory mechanisms.



## **SAMENVATTING**

Een van de makkelijkst te repliceren effecten in de cognitieve psychologie is dat de reactiesnelheid bij het volwassen worden toeneemt en weer afneemt bij het ouder worden. Dit consistente patroon wordt geobserveerd bij allerlei verschillende snelheidstaken, van de eenvoudigste druk-zo-snel-als-je-kan-taken tot taken die zeer complexe cognitieve vaardigheden vereisen zoals mentale rotatietaken. Het feit dat dit effect op zoveel verschillende taken wordt gevonden, wordt vaak aangehaald om aan te tonen dat er *een globaal mechanisme* aan ten grondslag ligt. Kail and Salthouse (1994) formuleerden de *kloksnelheidmetafoor*, afgeleid van de populaire vergelijking tussen de hersenen en computers. De kloksnelheid van de hersenen zou worden beïnvloed door leeftijd en daardoor zouden alle elementen waaruit een taak bestaat op eenzelfde, gegeneraliseerde wijze beïnvloed worden. De relatieve duur van elk van de processen wordt echter constant verondersteld, omdat dezelfde elementen ten grondslag liggen aan de taak, ongeacht de leeftijd van de proefpersoon die hem uitvoert.

In dit proefschrift is getracht de invloed van leeftijd op executieve controleprocessen te verduidelijken. In de inleiding worden executieve controleprocessen gedefinieerd als functies die verantwoordelijk zijn voor de organisatie en het controleren van meer gespecialiseerde cognitieve processen. Deze functies zijn bijvoorbeeld betrokken bij het detecteren van fouten, het onderdrukken van afleidende, niet relevante input, het prepareren voor een nieuw uit te voeren taak en het integreren van de context bij de evaluatie van een stimulus. Executieve functies, of cognitieve controefuncties, zijn belangrijk voor een persoon bij het aanpassen van het gedrag aan wisselende taakomstandigheden. De oorsprong van onze interesse in executieve processen ligt bij de Wisconsin Card Sorting Test (WCST). Deze test wordt gebruikt om mensen met hersenletsel te diagnostiseren. Mensen die een letsel hebben aan een specifiek gedeelte van de hersenen (prefrontaal) hebben erg veel moeite deze taak uit te voeren. Met name de executieve controleprocessen worden verondersteld aangetast te zijn bij deze patiëntengroep. Kinderen en ouderen blijken echter ook slechter te scoren op deze taak dan jonge volwassenen. Wij hebben geprobeerd aspecten van deze taak te identificeren die relevant zijn voor de leeftijdgerelateerde verschillen in flexibel gedrag. Hiervoor zijn verschillende taken geconstrueerd die inhoudelijke overeenkomsten hebben met de WCST.

Er bestaat brede consensus over het feit dat neuro-anatomisch gezien het verouderingsproces modulair verloopt. In hoofdstuk 1 staat een overzicht van recente literatuur over het hierarchische patroon dat hersenontwikkeling en hersenveroudering kenmerkt. Phillips

and Della Sala (1998) hebben een review geschreven over de veroudering van het brein en concludeerden dat alleen functies die dorsolateraal prefrontaal gelocaliseerd zijn langzamer worden uitgevoerd als men ouder wordt. Orbitofrontale gebieden blijken relatief gespaard. Dit wijst erop dat zelfs binnen de prefrontale cortex een hierarchisch patroon bestaat in de ontwikkeling. Tucker et al. (1995) beschrijven anatomische veranderingen die duiden op 'dual evolutionary origins of the frontal cortex', hetgeen wijst op differentiële trends in de ontwikkeling van de dorsolaterale en de orbitofrontale gebieden binnen de prefrontale cortex.

Zoals gezegd bestaan er twee tegengestelde theoriën over leeftijdgerelateerde vertraging. De eerste wordt de "global speed hypothesis" genoemd en is gebaseerd op de kloksnelheidmetafoor. De tweede wordt de "specific loss hypothesis" genoemd en gaat uit van modulaire, functieafhankelijke vertraging. Beiden hebben nieuwe inzichten opgeleverd over de aard van de leeftijdgerelateerde snelheidsveranderingen binnen het cognitieve systeem. In hoofdstuk 2 worden deze twee theoriën getoetst in één enklevoudige empirische studie. In deze studie wordt bekeken of leeftijd invloed heeft op de snelheid waarmee proefpersonen complexe, executieve controletaken uitvoeren, als we de snelheid waarmee eenvoudige taken worden uitgevoerd uitpataliseren. Dit wordt bewerkstelligd met behulp van MANCOVA, met de gemiddelde reactiesnelheid op de executieve controletaken als afhankelijke variabele en de reactiesnelheid op eenvoudige taken als covariaat. Deze analyse laat een gedifferentieerd patroon zien: Bij kinderen blijkt de reactietijd op complexe taken volledig te verklaren uit de snelheid waarmee ze eenvoudige taken uitvoeren, maar bij ouderen blijkt een groot deel van de vertraging op complexe taken onafhankelijk van de snelheid op simpele taken te zijn. Bij kinderen lijkt er dus inderdaad één enklevoudige factor te zijn die de vertraging tot gevolg heeft (kloksnelheid), bij ouderen lijkt een meer gedifferentieerd patroon aanwezig. Bij onze oudere proefpersonen blijken executieve controlefuncties meer vertraagd dan zou kunnen worden verondersteld op basis van eenvoudige taken.

Het differentiële patroon van de vertraging tussen kinderen en ouderen geeft aan dat de gebruikte methode gevoelig is voor globale en specifieke verouderingstrends. Als MANCOVA niet het onderscheidend vermogen zou bezitten om een van de beide hypothesen te verwerpen, zou voor beide groepen dezelfde conclusie moeten worden getrokken. Dit is hier dus niet het geval; MANCOVA blijkt onderscheid te kunnen maken tussen de globale en de specifieke leeftijdgerelateerde snelheidsveranderingen. In hoofdstuk 2 wordt aangetoond dat deze variantieanalytische procedure de voorkeur geniet boven regressiemethoden zoals *Brinley Analyse*. We hebben de reactietijden van onze proefpersonen direct getest met behulp van een model, waarin we zowel globale als specifieke vertraging hebben kunnen modelleren en toetsen. Dit model staat afgebeeld in figuur 2.2 en blijkt de reactietijden van alle groepen goed te beschrijven. Adolescenten en jong-volwassenen blijken niet van elkaar te verschillen op perceptuele en motorsnelheid, noch op de executieve controlesnelheid; op vijftien jarige leeftijd heeft de efficiëntie van de informatieverwerking het niveau van jong-volwassenen bereikt. Kinderen onder de vijftien jaar verschillen alleen op perceptuele en motorsnelheid van adolescenten en jong-volwassenen. Zoals we al bij de MANCOVA-resultaten signaleerden, wijzen deze resultaten op één globale factor die

de leeftijdgerelateerde verandering in snelheid van informatieverwerking kan verklaren: een kloksnelheidverandering. Ouderen verschillen niet alleen op deze globale snelheidsindicator van jong-volwassenen en adolescenten, maar bovendien ook nog op de executieve controle.

De Wisconsin Card Sorting Test (WCST) is een complexe taak die veel verschillende cognitieve functies veronderstelt. Om vast te stellen waarom ouderen en kinderen meer moeite hebben met het uitvoeren van deze en soortgelijke taken werd deze taak opgesplitst in functionele componenten. In hoofdstuk 3 van dit proefschrift is dit nader bekeken. We hebben onderzocht of ouderen beter presteren op de taak als specifieke cues aangeven dat er gewisseld moet worden tussen de te gebruiken sorteerregels. Als ouderen minder perseveratieve fouten zouden maken als gevolg van het aanbieden van deze specifieke aanwijzingen, zou dat erop wijzen dat leeftijdgerelateerde verschillen in snelheid zouden worden verklaard door problemen van ouderen met de evaluatie van het eigen gedrag en niet door het wisselen van de taak zelf of het activeren van andere sorteerregels. De resultaten laten echter zien dat ouderen geen baat hebben bij deze cue. We concludeerden hieruit dat met name het wisselen van sorteerregels bij ouderen gecompromitteerd lijkt te zijn. De oorsprong van de mindere prestatie van ouderen op deze taak wordt verondersteld gerelateerd te zijn aan het wisselen tussen taakinstructies zelf.

Dit taakwisselen is in een meer experimenteel gecontroleerde wijze onderzocht in de latere hoofdstukken van dit proefschrift (hoofdstukken 4 en 5). Stuss et al. (1995) hebben al voorgesteld dat het taakwissel-paradigma beter geschikt is voor onderzoek naar cognitive flexibiliteit dan sorteertaken. Zij stelden vast dat taakwissel-taken een beroep doen op de relevante aspecten van sorteertaken, onder andere regelwisselingen, flexibiliteit en inhibitie. Het taakwissel-paradigma is gebruikt in hoofdstuk 4 van dit proefschrift. Bij een groep proefpersonen, in leeftijd variërend van jong volwassen en bejaard, is een taakwissel-taak afgenumen om zo de efficiëntie van het taakwisselen te onderzoeken. We gaan ervan uit dat leeftijd een mediërende factor is in deze efficiëntie. De belangrijkste uitkomst van deze studie is dat we de invloed van leeftijd op blokken waarin niet en blokken waarin wel gewisseld moet worden van elkaar verschilt. In blokken waar niet gewisseld moet worden tussen verschillende taken bestaat er een lineair verband tussen leeftijd en reactiesnelheid. In blokken met wisselingen blijkt het verband exponentieel. Dit laatste geldt zowel voor de trials waarin wel als de trials waarin niet gewisseld moest worden. Op deze wijze hebben we aangetoond dat het effect van leeftijd bij het ouder worden steeds groter wordt voor taken waar adaptieve controle bij vereist is. Dit is al eerder gevonden in de literatuur (bv. Cerella and Hale, 1994), maar wij waren in staat een dissociatie aan te tonen tussen simpele reactietijdentaken en taken die cognitieve flexibiliteit veronderstellen.

Ook in hoofdstuk 5 is het taakwissel-paradigma gebruikt. Hier hebben we covarianteanalyse gebruikt om de leeftijdgerelateerde vertraging van het taakwisselen te vergelijken met de leeftijdgerelateerde vertraging in enkelvoudige taken, nu bij kinderen. We hebben verschillende afhankelijke maten van het taakwisselen berekend en deze geatribueerd aan verschillende, onderscheidbare cognitieve processen. *Switching costs* zijn de verschillen in reactiesnelheid tussen enkelvoudige blokken en taakwissel-blokken. Ze zijn op te delen in *shift costs* en *mixing costs*. Shift costs zijn de reactietijdverschillen

tussen trials in taakwissel-blokken waarin wél of juist niet gewisseld moest worden. Mixing costs zijn reactietijdverschillen tussen pure blokken, en die trials uit een taakwissel-blok, waarop ook niet gewisseld hoeft te worden. Om de leeftijdgerelateerde effecten op wisselsnelheid te testen tegen perceptuele- en motorsnelheid, werd de snelheid op een simpele reactietijdenaak als covariaat opgevoerd in de analyse. De leeftijdseffecten op shift costs blijken deels te onderscheiden van deze perceptuele- en motorsnelheid; de interactie tussen leeftijdsgroep en het type trial bleef significant na de controle op 'basissnelheid'. Shift costs lijken meer door leeftijd beïnvloed dan mixing costs. De leeftijdgerelateerde vertraging van kinderen in taakwissel-taken is deels onafhankelijk van de ontwikkeling van perceptuele en motorvaardigheden. Wij wijten deze resultaten aan een onderontwikkeld inhibitoir apparaat in hoofdstuk 5 (zie ook Bjorklund and Kipp-Harnishfeger, 1990; Dempster, 1992, 1993; van der Molen, 2000). Deze resultaten zijn in overeenstemming met de literatuur over leeftijdseffecten op taakwissel-taken (Cepeda et al., 2001). In het onderzoek van Cepeda et al., bleken kinderen geen baat te hebben bij het langer maken van de tijd tussen twee trials. Dit wordt geassocieerd met de tijd die de vorige trial krijgt om uit te doven (als gevolg van inhibitie). Kinderen hadden net zoveel baat als jong-volwassenen bij een verlenging van de tijd tussen de cue en de stimulus, geassocieerd met preparatieprocessen.

## Conclusie

De centrale vraag die wordt beantwoord in dit proefschrift is of executieve controlefuncties een onderscheidbare ontwikkeling doormaken gedurende het ouder worden, zowel bij kinderen als bij ouderen (life-span). In de individuele empirische hoofdstukken wordt deze vraag met behulp van verschillende statistische technieken aangepakt. Het gebruik van deze technieken is noodzakelijk om vast te kunnen stellen of executieve controleprocessen een andere ontwikkeling doormaken dan andere (perceptuele- en motor) processen. In alle hoofdstukken is de speciale rol van de executieve processen vastgesteld en is het onderscheidende vermogen van de verschillende gebruikte technieken beschreven. We hebben de leeftijdsgerelateerde veranderingen in de snelheid van informatieverwerking bekeken vanuit een neurocognitief uitgangspunt. We hebben kunnen aantonen dat leeftijdgerelateerde veranderingen in het centrale zenuwstelsel van belang zijn voor de snelheid waarmee functies die hierin geïmplementeerd zijn worden uitgevoerd. De resultaten van de onderzoeken die in dit proefschrift zijn gedocumenteerd kunnen worden gezien als convergerend bewijs voor de *specific loss* hypothese zoals die is geformuleerd in hoofdstuk 1. Deze hypothese voorspelt specifieke leeftijdsgerelateerde snelheidsveranderingen bij taken die een beroep doen op executieve controlefuncties (die in de literatuur in het prefrontale gedeelte van de hersenen worden verondersteld). Een belangrijk nieuw element in deze hypothese die wordt toegevoegd in de hier beschreven onderzoeken is het geobserveerde verschil in reactietijdpatronen van kinderen en ouderen. Het aangrijppingspunt van de leeftijdsgerelateerde snelheidsveranderingen is verschillend voor kinderen en ouderen. Hoewel er oppervlakkig gezien overeenkomsten zijn in de leeftijdsgerelateerde veranderingen binnen het centrale zenuwstelsel van kinderen en bejaarden, blijkt het effect van deze veranderingen

kwalitatief verschillend te zijn voor deze groepen afzonderlijk.

Deze verschillen kunnen worden verklaard door kwalitatieve verschillen bij het uitvoeren van enkelvoudige taken, die bij kinderen wellicht ook een beroep doen op executieve controleprocessen, en bij ouderen autonoom kunnen worden uitgevoerd en/of biologische verschillen op een meer specifiek niveau, bv. de rol van dopamine in de inhiboire mechanismen.



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## **DANKWOORD**

Hoewel er slechts één naam op de omslag van dit proefschrift staat, is het ondenkbaar dat het zou zijn afgerond zonder de hulp van een grote groep mensen. Op de eerste plaats wil ik mijn promotor, Maurits van der Molen, bedanken voor het schrijven van het oorspronkelijke onderzoeksvoorstel en de concrete aanwijzingen en feedback op de stukken die ik hem heb voorgelegd. Co-promotor Richard Ridderinkhof wil ik bedanken voor de begeleiding en voor zijn scherpe feedback. Hij wist altijd tijd vrij te maken als ik met een inhoudelijk en/of praktisch probleem zat.

Mijn leescommissie wil ik bedanken voor de snelle beoordeling van het proefschrift. Het manuscript is hen aangeleverd in de drukke decembermaand, toch wisten zij het snel te lezen en (positief) te beoordelen.

Conor Dolan's inspirerende persoonlijke colleges over 'structural equation modeling' hebben significant bijgedragen aan het academische niveau van dit proefschrift ( $p < .001$ ).

Ad, Annematt, Atie, Bert, Brenda, Cor, Ellen, Eric, Eveline, Han, Hans, Hilde, Ingmar, Lourens, Louis, Maartje, Margot, Peter, Raoul, Riek, Sander: mijn collega's. Jullie worden bedankt!

Rena en Wery hebben het grootste gedeelte van mijn aanstelling een kamer met me gedeeld. Ik wil hen bedanken voor het gezellige karakter van onze samenwerking en het geduld dat nodig is om voor langere tijd met mij een ruimte te delen.

Durk en Eric-Jan zijn mij voorgegaan. Beiden zijn naar de USA gegaan om de wetenschap verder te kunnen dienen. Samen sci-fi of voetbal kijken met een pilsje en macaroni of een nachtje programmeren schept toch een band...

Rena en John bedankt voor het paranimphen.

Mijn vader, moeder, stiefmoeder, schoonvader en schoonmoeder, broer, zus, schoonzussen en schoonbroers: Nico, Riet, Joke, Peter, Jannie, Paul, Liesbeth, Anneloes, Petra, Louis en Zeljko bedank voor alle onvoorwaardelijke morele steun.

Harriëtte bedankt voor alle steun, thuis en op het werk. Het is misschien een open deur, maar zonder jouw steun had ik niet genoeg over gehad om zoveel te kunnen investeren in een proefschrift. Milan: bedankt voor je glimlach (al is dat maar een evolutionair trucje).

