

REVIEW OF THE LITERATURE

Normal versus Pathological Cognitive Aging

For many years, theoretical concepts have used the differentiation between normal and pathological aging as a heuristic to describe differential patterns of aging in gerontological research (e.g., Rowe & Kahn, 1987). Although the differentiation between normal and pathological aging has proven useful, especially with regard to cognitive aging, it has received considerable criticism. One critical point is that the differentiation between normal and pathological aging may underestimate the influences of biological changes that may alter functioning before a pathological process can be identified (e.g., Fozard et al. 1990). In the following, empirical evidence regarding pathological changes in aging and Alzheimer's disease will be reviewed. On the background of age- and dementia-related processes on a brain level, behavioral changes, specifically changes in the ability structures with age and in Alzheimer's disease, will be discussed.

Pathological Changes in Normal Aging and Alzheimer's Disease

Alzheimer's disease is generally considered a classical example of pathological cognitive aging (Burns et al., 1990; P. Baltes & M. Baltes, 1990). Neuropathological studies of the aging brain have primarily focussed on the loss of neurons, a reduction in size of neuronal populations, and a decrease in overall size within the aging brain. By nature, these studies are limited in the sense that they are designed cross-sectionally. Regarding brain weight, studies indicate a decrease of about 17% from the fifth to the ninth decade (Esiri, 1996). The most obvious change in the aging brain is the accumulation of protein deposits within the neuron. Specifically, it has been shown that neurofibrillary tangles (NFT) and amyloid plaques (AP) increase in number within aging neurons. It is interesting to note that the same pathological features are a

constituent factor for the neuropathological diagnosis of Alzheimer's disease (Figure 1). However, both the amount and the pattern of spread of pathology within neuronal populations may differ in healthy aging (Esiri, 1996). In Alzheimer's disease, these abnormalities within the brain are more severe in the medio-basal temporal cortex and the basal forebrain (Braak & Braak, 1992). Furthermore, it is assumed that the process of accumulation of NFT and AP is accelerated in Alzheimer's disease due to disturbances in cell metabolism. These disturbances have both been related to oxidative stress within cells, and to disruption of biochemical regulators in the synthesis of AP (for review, see Tanzi, 1989).

Figure 1

Neuropathological Changes associated with Alzheimer's disease

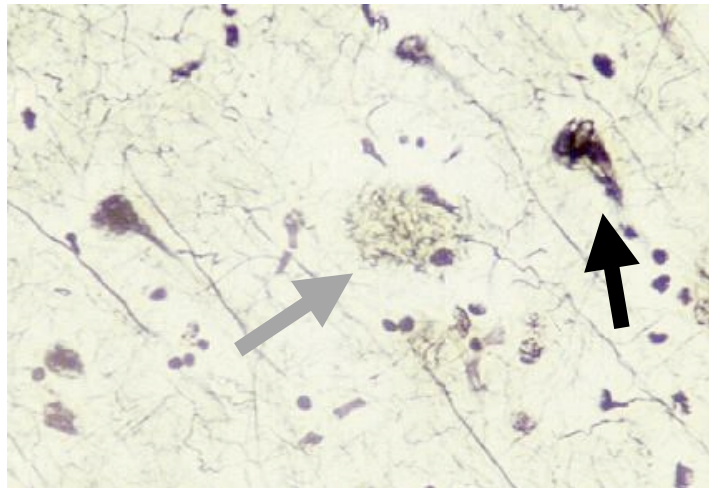


Figure 1. Plaques (gray arrow) and Tangles (black arrow) in a post mortem brain specimen obtained from a patient with clinical Alzheimer's disease.

Aside from changes in cellular structure, changes in neurotransmitter functioning have been discussed in both aging and Alzheimer's disease. Changes in the levels of dopamine, acetylcholine, and serotonin seem to occur in both healthy older adults and in patients with Alzheimer's disease. However, in the case of acetylcholine, a specific process has been proposed in the case of Alzheimer's disease, linking the increase in cellular pathology in the basal forebrain to a decrease in neurotransmitter level in the Basal Nucleus of Meynert (Perry et al., 1978). In addition, it has been proposed that there might be a differential reaction to AP accumulation in normal aging and Alzheimer's disease, suggesting that an inflammation reaction to AP might be a causal factor for the steep cognitive decline associated with Alzheimer's disease (Monsonogo et al., 2001).

A recent study suggested that the delineation between normal and pathological aging on a neuropathological basis could be less sharp than expected (Medical Research Council Cognitive Functions in Ageing Study [MRC CFAS], 2001). In a population-based study of 209 older adults, Ince and colleagues found pathological signs of Alzheimer's disease sufficient to warrant a pathological diagnosis in about 30% of the healthy older adults. All participants underwent regular neuropsychological testing at 1-year intervals prior to death. Plaques (AP) in the neocortex were found in 69% of the healthy older adults and 80% of the clinically diagnosed dementia patients. Tangles (NFT) were found in 34% of the healthy older adults and 61% of the clinically diagnosed dementia patients (MRC CFAS, 2001). These findings suggest an extensive overlap of structural brain changes in healthy and demented older individuals.

However, specific physiological changes that occur only in Alzheimer's disease, such as the inflammatory response to plaques (AP) or the decrease in acetylcholine, may account for differences in behavior between normal and pathological aging. In a neurophysiological study differentiating between the presence of plaques and the presence of an inflammatory response, the

inflammatory response was associated with lower levels of cognitive functioning and with faster decline over time before the onset of Alzheimer's disease (Crystal, et al., 1996). On the background of these theories, structural differences can be expected in cognitive performance between normal aging and Alzheimer's disease.

Ability Structures in Normal Aging and Alzheimer's Disease

On the background pathological theories on aging and Alzheimer's disease, the question arises in how far the ability structures of cognitive performance differ in aging and Alzheimer's disease.

The Two-Component Model of Intelligence

Cognitive performance and intelligence have been broadly categorized in fluid and crystallized intelligence. Fluid intelligence denotes processing that involves the manipulation and interpretation of stimuli, whereas crystallized intelligence reflects the result of learning and acculturation over the lifespan (Cattell & Horn, 1978; Horn, 1989). Fluid intelligence encompasses perceptual speed and the coordination of cognitive operations (e.g., working memory, attention and executive control²). Crystallized intelligence, however, encompasses declarative and procedural memory. It is thus a reflection of knowledge that can be acquired throughout the lifespan, such as verbal knowledge, expert knowledge or reasoning abilities (compare Lindenberger & Reischies, 1999). It has been shown

² In that context, attention and executive function can be seen as complementary and overlapping concepts. Whereas attention refers to the ability to control processing and direct attention by means of a central executive system (CES; Baddeley, 1986; Shallice, 1988), executive function is defined as the ability to plan, schedule, and execute complex goal-directed activities (Lezak, 1983; Duke & Kaszniak, 2000). Neuropsychological tasks that primarily test attention thus require the specification of a goal and an exact instruction, whereas tests of executive function require self-monitoring and the manipulation of stimuli (Perry & Hodges, 1999, p.390).

by numerous authors (Cerella, 1990; Horn & Hofer, 1992; Salthouse, 1991; Schaie, 1996) that fluid intelligence shows a continuous decline from early adulthood onward, whereas crystallized intelligence exhibits a high degree of stability. Such findings have been related to concepts of the biocultural architecture of the lifespan (P. Baltes, 1997). Informed by work on the biology of aging (e.g., Esiri, 1996; Cotman, 1995) it has been argued that fluid intelligence is associated with biological changes within the brain, while crystallized intelligence reflects the influence of cultural factors (such as education) across the lifespan. In that context, biological components of intelligence have been termed mechanics, whereas cultural components have been termed pragmatics (compare P. Baltes, Lindenberger, & Staudinger, 1997).

However, in old age, decline patterns have been described in both the cognitive pragmatics and the cognitive mechanics, although to a different extent. This empirical finding has led to the proposition of a directionality dedifferentiation in old age (P. Baltes & Lindenberger, 1997). The directionality dedifferentiation hypothesis posits that the age gradients for mechanics and pragmatics show similar directions (of decline) in old age, although the gradient for the cognitive mechanics component shows a steeper slope than the gradient for the cognitive pragmatics component. This pattern was also found in cross-sectional data from the Berlin Aging Study (BASE; Lindenberger & Reischies, 1999). The presence or absence of dementia did not influence the slope of the cross-sectional gradients. In the context of this dissertation, it is interesting to note that in Alzheimer's disease, verbal abilities show decline comparably later in the disease process. In a longitudinal analysis of change in cognitive functioning in dementia patients, Christensen and colleagues (Christensen et al., 1999) were able to show significant decline in measures of processing speed, memory, and spatial ability over time. Measures of cognitive pragmatics or cultural knowledge, however, remained relatively stable, even three years after the disease was clinically manifest. These and similar findings (Becker, Bajulaiye,

& Smith, 1992; Fabrigoule et al., 1998; Perry, Watson, & Hodges, 2000) suggest that the influence of cultural factors on cognition prevail even in the face of a cognitive disorder. At the same time, the decline in verbal ability in later stages of the disease suggests that directionality dedifferentiation might be present in Alzheimer's disease to a larger degree as compared to healthy aging.

Differential Patterns of Cognitive Decline in Age and Alzheimer's Disease

The examination of ability structures in cognitive aging research further revealed an increase in the association between performance within and across cognitive domains with age. That is, with age, both tasks from the cognitive mechanics and tasks from the cognitive pragmatics component of intelligence are strongly correlated within and across components. In the Berlin Aging Study (BASE; P. Baltes & Mayer, 1999), a high intercorrelation was found between measures of perceptual speed, reasoning, memory, knowledge and verbal fluency (Median $r=0.71$, range 0.63-0.73). On a conceptual level, it has been argued that the covariance structure of cognitive abilities shows dedifferentiation with age (covariance dedifferentiation; P. Baltes & Lindenberger, 1997). Interestingly, this pattern was also found across non-cognitive domains. Especially sensorimotor variables, such as vision, hearing and gait, showed high correlations to measures of cognitive abilities (Lindenberger & P. Baltes, 1994). One possible explanation for this correlative pattern is the model of a general, common, cause exhibiting influence across cognitive and sensorimotor domains with age. This line of thinking lead to the proposition of a neurobiological common cause hypothesis, stating that global processes of brain aging could account for the decline observed across domains in older adults (Lindenberger & P. Baltes, 1994).

For many years, Alzheimer's disease was considered a dementia characterized by global cognitive impairment (Alzheimer 1907; Lishman, 1978). In the last decade or so, however, studies have found differential patterns of impairment and preservation of cognitive functioning in Alzheimer's disease,

especially in the extent of visuoconstructional deficits and executive functioning (Becker, Huff, Nebes, & Holland, 1988), remote memory, and dyscalculia (Karlinsky, Madrick, Ridgley, & Berg, 1991). Investigation of the profile of the initial cognitive impairment in Alzheimer's disease has revealed specific components that may account for different subtypes of the disease. For example, Becker and colleagues (Becker et al., 1988) proposed a two-component model of cognitive deficits in Alzheimer's disease, differentiating between an amnesic and a dysexecutive syndrome. These results are based on a component analysis of 71 patients suffering from Alzheimer's disease and 89 normal controls. In the first component, which is referred to as the secondary memory or amnesic syndrome component, test performance loaded high (+/- .74 to +/- .84) on tasks such as Story Recall, Figure Recall, Verbal Pairs, and Face-Name Pairs. The second component, referred to as dysexecutive syndrome, showed high loadings on Forward Digit Span, Reaction Time, and Word Fluency (+/- .70 to +/- .83; Becker, 1988). Further research in dementia patients showed that these findings are well replicable and prove to be a good heuristic to differentiate subtypes (deficits in memory versus deficits in executive function) in Alzheimer's disease, especially in the insidious stages (Becker, et al., 1992; Salthouse & Becker, 1998). In addition, there is growing evidence that executive dysfunction is a reliable predictor of later onset of dementia (Fabrigoule et al., 1998). Sliwinski and Hofer (1998) reported similar findings for processing speed.

On the basis of these findings, data from the Berlin Aging Study (BASE) were explored in order to investigate whether there is indeed an additional differentiation between processing speed (or executive control) and memory functioning in dementia patients. Results showed that correlations between processing speed and memory functions were higher in the healthy older adults than in the dementia patients (for healthy older adults, $r = .53$, $p < .001$; for dementia patients, $r = .36$, $p < .001$). Interaction analysis revealed that this numerical difference in the correlative pattern was significant (for the

interaction term $\beta = -0.165$, $SE = 0.021$, $p < 0.001$; that is, the correlation was actually lower in the dementia patients as compared to healthy older adults; compare Figure 2).³

Figure 2
Cognitive Speed as a Function of Memory Performance
in Older Adults with and without Dementia

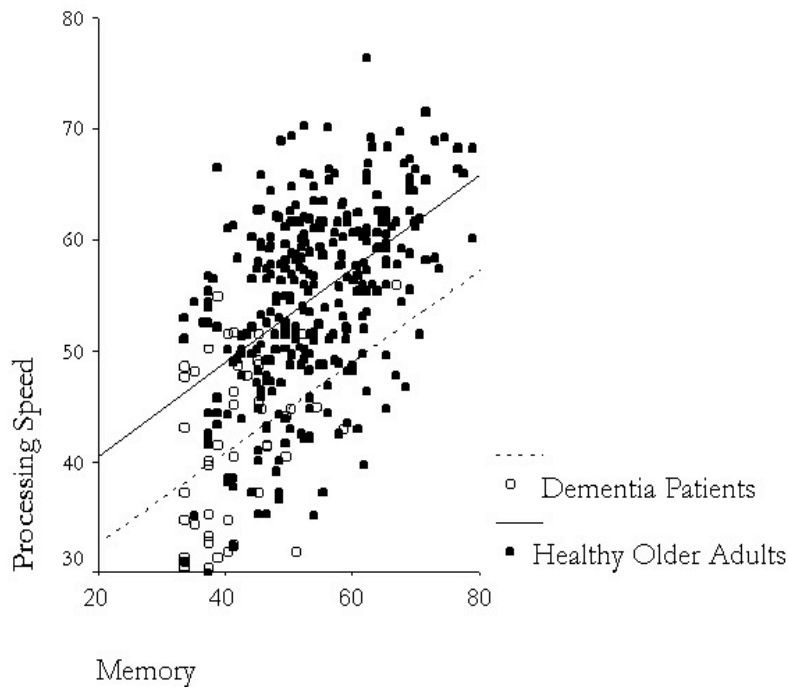


Figure 2. Data from the Berlin Aging Study (BASE; $N = 408$, aged 70 to 101 years; P. Baltes & Mayer, 1999). Speed reflects a composite of Digits Symbol Substitution, Digit Letter, and Identical Pictures. Memory reflects a composite of Task Recall, Memory for Story, and Paired Associate Learning. Dementia patients ($N = 109$) are depicted in open, healthy older adults ($N = 408$) in solid squares.

³ Thanks to Florian Schmiedek for letting me work with his data.

Consistent with the two-component model of memory and executive dysfunction in Alzheimer's disease (Becker, 1988), this finding points to a local differentiation between working memory and processing speed in patients with dementia. Thus, behavioral results support the notion of a qualitative difference between normal aging and dementia.

Summary: Different Pathophysiology, Different Ability Structures

The structural neuropathological evidence discussed in this section suggests a continuum from normal to pathological aging in the underlying structural brain changes. However, pathophysiological theories show additional pathological changes in Alzheimer's disease beyond brain structure. Specifically, theories on inflammatory responses (Crystal et al., 1996) or reductions in acetylcholine in Alzheimer's disease (Perry et al., 1978) point to a specific differentiation between normal and pathological aging.

On a behavioral level, in old age, the direction of decline in fluid and crystallized intelligence components converges. There is, however, evidence that cognitive pragmatics are more strongly preserved in aging, and, albeit to a lesser degree, in Alzheimer's disease. With regard to the structure within cognitive domains, and across cognitive and sensorimotor domains, there is evidence for a dedifferentiation of covariance in aging. However, in Alzheimer's disease, several studies suggest an additional (local) differentiation between memory and processing speed or executive control.

The existence of a dysexecutive syndrome in Alzheimer's disease has been related to pathophysiological changes in the disease. Specifically, Perry and Hodges (1999) have argued that changes in attention and executive control are related to changes in the neurotransmitter acetylcholine in brains of Alzheimer's disease patients (compare Perry et al., 1978). One of the strongest variables differentiating normal older adults from Alzheimer's disease patients is dual-task performance, the simultaneous performance of two tasks (Baddeley, 1986). On a theoretical level, the differences in dual-task performance could be ascribed to

changes in attention and executive functioning, which are in turn related to changes in acetylcholine in patients with Alzheimer's disease (Becker, 1988; Perry & Hodges, 1999; Perry et al., 1978). In the following section, models of dual-task performance and empirical evidence from studies on normal aging and Alzheimer's disease will be discussed.

Dual-Task in Age and Alzheimer's disease

In the previous section, it has been shown that differences in processing speed and executive function are a strong indicator for structural differentiation in Alzheimer's disease, as opposed to structural dedifferentiation in normal aging. Both processing speed and executive control have been related to the simultaneous performance of two tasks, i.e., dual-task performance. For processing speed, significant decreases have been reported in Alzheimer's disease patients (Nebes & Brady, 1992). From the study of patients suffering from Alzheimer's disease, Baddeley and colleagues (Baddeley et al., 1986) proposed dual-task as a means of exploring a subset of working memory that is related to frontal lobe functioning, the central executive system (Baddeley, 1992; Baddeley, 1986). It has been suggested that the decline in performance in a given task when adding a secondary task may be one of the strongest variables differentiating between normal and pathological cognitive aging on a behavioral level (Baddeley, 1986). Conflicting models have provided explanations for the differential performance decrement in dual-task in aging and Alzheimer's disease. In the following, these concepts will be reviewed with special emphasis on Alzheimer's disease.

The General Resource Model

Based upon the empirical finding that, with age, performance in several tasks declines, research has aimed at identifying general factors that may account for decline patterns across domains. One such account is the model of general resource decline with age (Craik & Salthouse, 2000). Craik and Salthouse propose the existence of general age-related cognitive inefficiencies, that can be related to a decline in general resources, specifically, the "energy to fuel mental processes" (Craik & Salthouse, 2000, p.691). Performance in a given task is thus dependent upon the amount of mental effort or cognitive resources needed. The more a given task requires the initiation or coordination of cognitive processes,

the more resources should be required. Examples of such processing components are retrieval (Craik & Masani, 1969), the inhibition of irrelevant information (Zacks & Hasher, 1997), and the scheduling of information (Mayr & Kliegl, 1993). As cognitive resources decline with age, age-related decrements are predicted by this model for a variety of tasks (for review, see Craik & Jennings, 1986). Two main accounts can be identified that follow these assumptions: models of general slowing (Salthouse, 2000), and models of attentional resources (Norman & Bobrow, 1975).

The processing speed hypothesis can be viewed as an extension of the general resource account (Salthouse, 2000). It has been shown across numerous tasks that the effects of age on reaction time can well be described by a linear function (Cerella, 1994; Hale & Myerson, 1996). This phenomenon has led to the notion of a general slowing in processing speed that may account for age-related differences on a general level (Salthouse, 1996). Thus, from the perspective of a general slowing account, it might well be that age- or disease-related changes in dual-task performance can be related to a decrease in processing speed in a given task in the first place. It has been repeatedly shown that older adults are about 1.6 times slower in a simple reaction time task when compared to young adults (e.g., Cerella, 1994; Cerella, 1985; Hale, et al., 1987; Salthouse, 1985). If the increase in latency were sufficient to explain dual-processing declines with age, further slowing should be expected in Alzheimer's disease, where dual-task decrements show a further increase (e.g., Baddeley, 1986; Nebes, Huff, & Brady, 1989). Indeed, earlier work has shown that dementia patients, when compared to healthy older adults, show a general slowing in central processing speed of about 1.9 (Nebes, et al., 1989). Based upon models of general slowing, researchers have argued that decline in dual-task performance may merely be a function of processing speed, rather than a specific dysfunction of working memory (compare Verhaeghen, Steitz, Sliwinski, & Cerella, 2001).

From an attentional resources perspective, in the dual-task paradigm, resource losses can be deduced from the relative performance decrement when comparing single and dual-task performance for a given task. There are two central models aiming at the explanation of dual-task performance and performance decrements in dual-task in that context. The model of limited central capacity predicts that performance decreases with the capacity limitations of a central resource pool (Kahneman et al., 1973). Thus, tasks that are resource demanding will lead to a decrement in dual-task performance in both tasks, whereas less resource demanding tasks will lead to little or no decrement in dual-task performance. Capacity denotes the amount of available resources in a single pool. The interaction between performance and resources is described by a performance-resource-function (Norman & Borbrow, 1975), indicating that, with increasing resource demands, the amount of resources available shrinks, thus leading to a decrease in dual-task performance. The model of multiple resource pools, as implemented by Wickens and Kessel (1980) assumes that there are different resource pools depending on task structure. Three dimensions of task structure are proposed in the model. The dimensions of task structure include processing, differentiating between perceptual-cognitive activity and response processes, the perceptual modality, differentiating between visual and auditory input, and the codes of information processing, differentiating between verbal and spatial forms of response operations (Wickens & Kessel, 1980). In general, the model of multiple resource pools predicts that structurally dissimilar tasks use different resource pools and that structurally similar tasks use the same resource pools.

Concepts of Working Memory

Concepts of working memory dysfunction within dual-processing have proposed a specific deficit in attentional control, rather than a general decrease in cognitive resources (e.g., Baddeley, 1992). Working memory has been shown to decline with age (Morris, Gick, & Craik, 1988), especially in dual-task situations

(Gick, Craik & Morris, 1988). One feature of this decline seems to be specific age-associated losses when the manipulation of information within working memory is involved in a task (Dobbs & Rule, 1989). In Alzheimer's disease, numerous studies have shown a distinct decline in working memory performance (for review, see Morris, 1996). The evidence that, both in age and in Alzheimer's disease, decrements are observed when two tasks are performed simultaneously has led to a model of working memory that incorporates the specific ability to divide attention between two tasks. Based on a model by Shallice (1988), this line of thinking follows the notion that changes in the ability to divide attention are associated with a subcomponent of working memory, the central executive system (CES) (Baddeley, 1986). The central executive is proposed to have a general, integratory component, and several subsystems, termed slave systems that refer to specific functions, such as the phonological or visuospatial loop. The central executive in Baddeley's model coordinates mental activity between, for example, phonological and visuospatial domains of working memory. The basic assumption is that the central executive is a processing unit with limited capacity. Declines in working memory, which can be observed in aging in a variety of tasks (for review, see Verhaeghen, Marcoen, & Goessens, 1993), could thus be a reflection of limited capacity in the central executive. Thus, when information has to be processed simultaneously in two or more subsystems of working memory, the capacity of the central executive is the limiting factor (Baddeley, 1986). Based on the study of Alzheimer's disease and frontal lobe patients, Baddeley and colleagues were able to show a specific deficit in Alzheimer's disease when combining two tasks, and subsequent work (Baddeley et al., 1991) showed that this deficit became more pronounced in the course of the disease. There is evidence that dual-task performance allows for a differentiation between normal aging and Alzheimer's disease (Baddeley, 1986).

An extension of the working memory model proposed by Baddeley has been offered by Cowan (1988). The theory is based on the assumption that the

focus of attention and the working memory component involved in attention have to be distinct. This assumption is based on two empirical findings. First, the number of items that can be retained in the focus of attention is obviously smaller than the number of items that can be stored in working memory (Baddeley, 1986). Second, the focus of attention can be activated unconsciously, as unmasked priming experiments suggest (Balota, 1983). Following this distinction, Cowan (1988) postulated a model of information processing, in which the central executive directs attention and controls voluntary focussing. The focus of attention is seen as embedded within the attention component of working memory. Different sensory modalities (such as the visuospatial loop in Baddeley's model (Baddeley, 1986) are proposed not to be unique entities of the working memory component, but are rather seen as being activated in an initial sensory storage phase lasting only several milliseconds.

From lesion studies, it is known that the simultaneous performance of two tasks is a function that relies in part on the integrity of a specific part of the brain, the frontal lobes, and, more specifically, the dorsolateral prefrontal cortex (DLPFC; Shimamura, 1995). A variety of functions linked to the simultaneous performance of two tasks has been attributed to the DLPFC, among them executive functioning and attention (Goldman-Rakic, 1994). In Alzheimer's disease, one causal pathological pathway discussed is the reduction in acetylcholine projections to the prefrontal cortex due to neuronal loss (Perry et al., 1978).⁴ On a behavioral level, functional deficits have been reported in

⁴ There are, however, conflicting neuropsychological theories on the central executive deficit in early Alzheimer's disease. Morris (1994) proposed alternative explanations to the frontal lobe dysfunction hypothesis, stating that the CES might be an emergent property of different association lesions. This line of research has coined the term "disconnection syndrome" for the study of Alzheimer's disease (Morris, 1994). However, it has received considerably less attention in the past years.

planning, working memory and attention in Alzheimer's disease (for review, see Duke & Kaszniak, 2000).

A model integrating these behavioral and neurophysiological findings has been proposed by Fuster, Diamond, and Goldman-Rakic (Diamond, 1990; Fuster, 1989; Goldman-Rakic, 1994). The proposition is that a central, integrative component of functioning that is associated with the frontal lobes declines with age. The key feature of this component is the ability to integrate provisional memory, prospective memory, interference control, and inhibition of prepotent responses (Goldman-Rakic, 1994). Such a model would include functions ascribed to the central executive as proposed by Baddeley (1986), but at the same time go beyond such a model by including specific integrative functions of attention in planning and sequencing.

Methodological Controversies in Dual-Task Research

Theoretical accounts of the performance decrements observed in dual-task with age and in Alzheimer's disease provide conflicting, but at the same time converging insights for the study of dual-task performance. The implications of the processing speed hypothesis (Salthouse, 2000), that is, that the number of processing steps leads to a decline in performance, converges with the limited capacity model of working memory as proposed by Shallice (1988). The proposition that only interrelated tasks will lead to dual-task costs (Wickens, 1998) may be reflected in the notion of a visuospatial and a phonological loop from the working memory model offered by Baddeley (1986). The notion of a central executive system overlaps with the notion of a specific lesion in the prefrontal cortex (Diamond, 1990).

However, there is an ongoing methodological controversy as to whether the dual-processing deficit seen in Alzheimer's disease reflects a specific dysfunction in attention and executive control (Perry and Hodges, 1999; Baddeley, 1992) or whether performance decrements in dual-task can be

explained by a general age-related decrease in processing speed, which is pronounced in Alzheimer's disease (Salthouse, 2000).

Recent experimental work has added further evidence for the existence of a specific deficit in executive control in Alzheimer's disease (Baddeley et al., 2001) by showing qualitatively different patterns of impairment in a series of experiments using attentional tasks in older adults and Alzheimer's patients. On the other hand, a recent meta-analysis on dual-processing in older adults has shown additive effects of age on dual-task performance, consistent with the notion of a general, age-related factor (Verhaeghen et al., 2002). While most experimental studies investigating dual-processing in older adults and patients with Alzheimer's disease have used techniques of analysis of variance, searching for task by group dissociations, researchers in the field of cognitive aging have often employed regression analytic techniques to separate effects of general slowing from specific effects of task processing. Both approaches have received considerable criticism (compare Verhaeghen, 2000; Perfect and Maylor, 2000).

With regards to results from experimental studies, it has been argued that the presence of age (or dementia) by task complexity interactions alone cannot be interpreted as clear evidence for specific processing deficits. Despite strong empirical findings, on a theoretical level, alternative explanations for the dual-processing deficit in Alzheimer disease can not be fully ruled out, at least for latency data. For instance, it could well be that the deficits observed in dual-task in Alzheimer's patients simply reflect a decline in basic processing speed (Salthouse, 2000). Indeed, earlier work has shown that dementia patients, when compared to healthy older adults, show slowing in central processing speed of about 1.9 (Nebes & Brady, 1992). Dual-task costs are typically calculated by subtracting dual-task performance from single-task performance. If, however, performance of the two groups is related by a close-to-multiplicative function (e.g., latency of Alzheimer's patients equals about 1.9 times latency in healthy older adults), this might lead to spurious conclusions of group differences in

dual-task performance. The central argument is that complexity effects that are already present at baseline could drive the age (or dementia) by task interaction. It has been shown that, due to general slowing, for example, age (or dementia) by task interactions may disappear after controlling for baseline performance (e.g., by using logarithmic transformations or proportionate change parameters; Salthouse and Somberg, 1982).

The alternative methodology proposed by many researchers in the field of cognitive aging is to employ a regression analytic approach, controlling for baseline performance (Salthouse, 2000; Cerella, 1985; Verhaeghen et al., 2002). This approach mainly employs Brinley analysis (Brinley, 1965). Following a model of general slowing (Cerella, 1985), dual-task performance is regressed on single-task performance (a so-called state-trace analysis). The critical statistical test is then whether the slope of this function is equal to 1 or larger than 1. Slopes equal to 1 would indicate additive decrements from single- to dual-task performance, while slopes greater than 1 would indicate multiplicative performance decrements, which would in turn be indicative of additional processing deficits in a given group (compare Verhaeghen et al., 2001). This correlational approach has received considerable criticism in the past (Baddeley et al., 2001; Lindenberger and Pötter, 1998; Perfect and Maylor, 2000; Perfect, 1984). The key argument of this criticism is that the magnitude of the correlation between age (or dementia status) and a given task performance can substantially confound estimates of the amount of age-related variance in a second task (Perfect and Maylor, 2000). If the correlation between single- and dual-task performance was high (in the literature, these correlations tend to be above .70; compare Verhaeghen et al., 2002), and if only a small proportion of that correlation was related to age (or dementia), the magnitude of the variance due to interindividual differences (above 49%) would decrease the power to detect specific effects of age (or dementia). In addition, the magnitude of the correlation between age (or dementia) and, say, single-task performance would

have an effect on the slope in the Brinley analysis. Specifically, small correlations would, as shown in a path analysis model by Lindenberger and Pötter (1998), lead to the conclusion that dual-task performance is dependent upon single-task performance, irrespective of age, while large correlations would lead to the opposite conclusion.

An alternative way of examining the relation between single- and dual-task as a function of dementia status has been introduced by Kinsbourne (1975). In order to control for baseline performance and at the same time test for disproportional effects of age (or dementia), Kinsbourne proposes to employ a proportional metric of dual-task performance according to equation 1:

$$DTC = [(Single\ Task - Dual\ Task) / Single\ Task] * 100 \quad (1),$$

where DTC represents the proportional dual-task cost metric, and Single and Dual Task reflect performance in the given conditions.

This approach follows the assumption that tasks from different domains tax shared resources in a dual-task context, thus leading to proportional age (or dementia) differences. A number of studies have in fact shown proportional dual-task costs under certain task conditions in older adults (e.g., Korteling, 1993; Ribeaupierre and Ludwig, 2000; Salthouse et al., 1996) and dementia patients (e.g., Baddeley, 1986; Baddeley et al., 1991; Baddeley et al., 2001). As Lindenberger points out, disproportional dual-task effects can be expected when tasks share stimulus modality, when sequencing and coordination between tasks is necessary, and third, when one task in itself taxes cognitive control processes to a high degree (Lindenberger et al., 2000).

A second reason for computing dual-task costs in a proportional metric is of relevance. Only rarely have researchers succeeded in equating performance between young adults, older adults and Alzheimer's patients. Potentially, two methodological approaches are possible. First, participants could be equated in

performance using a series of training sessions in a testing-the-limits paradigm (compare Kliegl, Smith, & P. Baltes, 1989). Alternatively, it has been proposed to use simple tasks of working memory in order to equate performance (e.g., Baddeley, 1986). While such a strategy has shown successful results, it does not allow for complexity manipulations, since more complex tasks would lead to differences in baseline performance. A proportional metric of dual-task performance, however, can account for specific features of the tasks used in combination (such as interrelatedness of modalities or different demands on cognitive control), while at the same time controlling for differences in baseline performance. The argument upon which the metric is based is thus a theoretical, rather than a statistical one. However, an additional statistical benefit of this way of analysis deserves mention. Proportional dual-task costs, e.g., expressed as percentages, allow for a direct comparison across conditions and task domains (Li et al., 2001).

In the following section, this methodological approach will be applied in a meta-analytic review of dual-task performance in aging and Alzheimer's disease.

Dual-Task Performance in Alzheimer's Disease: A Meta-Analysis

In this section, a meta-analytic review of the literature on dual-task performance in Alzheimer's disease as compared to dual-task performance in normal aging will be presented. Given the emphasis on working memory and executive control on dual-task performance in Alzheimer's disease (e.g., Baddeley, 1992), this relation will be of specific interest in the present analyses. Three questions guided this analysis. First, is there a dual-task deficit associated with Alzheimer disease, over and beyond the effects of baseline performance? Second, is there a dual-task deficit associated with working memory and executive control tasks, over and beyond the effects of baseline performance? Third, is this possible dual-task deficit in older adults and Alzheimer's patients associated with working memory and executive control tasks, or is it independent of the content of the primary task?

Method

Studies were collected using PsycINFO and Medline electronic databases, through personal contacts, and by checking references found in the articles thus retrieved. The search was concluded in July 2001. Inclusion criteria were: (a) the study contained experiments in which a comparison was made between age groups, namely older adults (with a mean age of 60 years and older) versus Alzheimer's patients (with a mean age of 60 years and older); and (b) the study compared either latencies or accuracy or both under dual-task conditions with the corresponding measure in single-task performance. Thirteen studies were found that matched the inclusion criteria for this analysis.

The complete data set for latency data is shown in Appendix A, Table 1; the complete data set for accuracy data is shown in Appendix A, Table 2. In total, these studies yielded 21 different conditions for latency, and 34 conditions for accuracy data. Exploratory analysis showed that the latency data from the Filoteo et al. (1992) study were outliers, in the sense that these latencies were

situated at three or more interquartile ranges from the mean. Therefore, this study was excluded from further analyses, leaving a truncated data set of 19 conditions ($k = 19$) for the latency data.

For both latency and accuracy data, proportional dual-task costs were computed for each condition. For the latency data, dual-task costs were computed following equation 2:

$$\text{DTC} = ((\text{RT dual} - \text{RT single}) / \text{RT single}) * 100 \quad (2),$$

where DTC reflects proportional dual-task costs, RT single and RT dual reflect reaction time under single- and dual-task conditions, respectively. For the accuracy data, proportional dual-task costs were computed following equation 3:

$$\text{DTC} = ((\text{ACC single} - \text{ACC dual}) / \text{ACC single}) * 100 \quad (3),$$

where DTC reflects proportional dual-task costs, ACC single and ACC dual reflect accuracy under single- and dual-task conditions, respectively.

In order to test whether proportional dual-task costs are different between older adults and Alzheimer's patients, and between task conditions in which a working memory task was included or not, a 2 (Presence versus absence of dementia) by 2 (Presence versus absence of a working memory task) analysis of variance (ANOVA) on dual-task costs, taken together for accuracy and latency data, was computed. While significant differences between older adults and Alzheimer's patients would be consistent with overproportional dual-task costs in Alzheimer's disease, an analogous interpretation would be applicable to differences with respect to the presence or absence of a working memory task.

Results

Figure 3 shows the mean proportional dual-task costs in older adults and Alzheimer's patients in the presence or absence of a working memory task.

Figure 3

Dual-Task Costs as a Function of Dementia Status and Involvement of a Working Memory Task

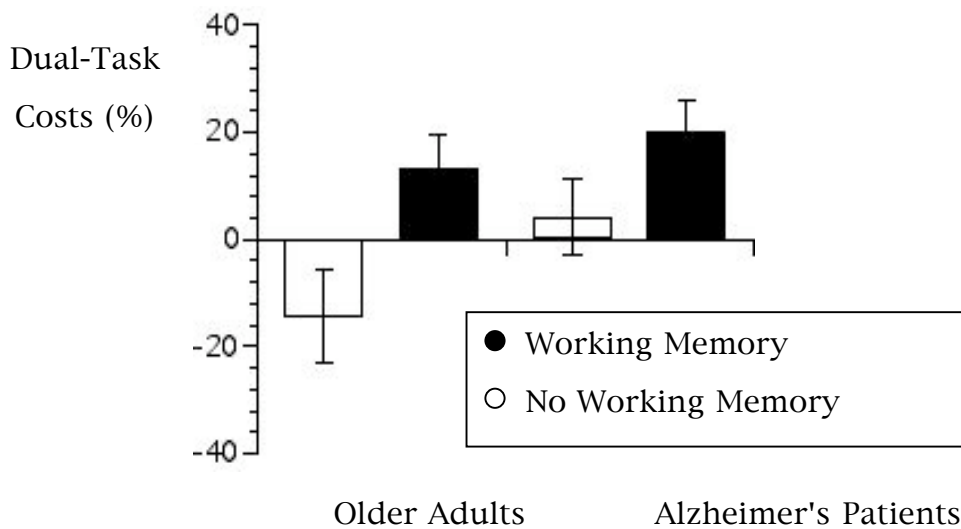


Figure 3. Proportional dual-task costs as a function of dementia status and inclusion of a working memory task. Results from a meta-analysis of 13 experimental studies on dual-task performance in Alzheimer's disease. Error bars reflect standard deviations.

In the ANOVA, a main effect of dementia ($F(1, 100) = 18.92, p < .001$), a main effect of whether or not a working memory task was included ($F(1, 100) = 18.92, p < .001$), and an interaction of the two factors ($F(2, 100) = 4.24, p < .05$) emerged. Closer scrutiny revealed that the interaction between working memory and dementia was mainly due to the fact that the experiments not including a

working memory task lead to dual-task costs significantly below zero (i.e., facilitation effects) in older adults ($t(23) = 3.70, p < .001$) and failed to produce dual-task costs significantly different from zero in Alzheimer's patients ($t(23) = 1.35, p = .19$). However, in task conditions including a working memory task, proportional dual-task costs were significantly larger in Alzheimer's patients as compared to older adults ($t(56) = 2.20, p < .05$).

Specifically, Alzheimer's patients, on average, accrued about 20% dual-task costs, while older adults, on average, accrued about 13% dual-task costs when a working memory task was included.

Discussion

Three questions guided this meta-analysis. First, whether there is a specific dual-task deficit associated with Alzheimer's disease, over and beyond the effects of disease-related slowing. Second, whether this possible dual-task deficit in Alzheimer's patients takes a different form from the dual-task deficit found in healthy older adults. Third, whether this possible dual-task deficit in Alzheimer's patients is related to working memory functioning, as claimed in the literature.

With regard to the question whether Alzheimer's patients have a specific deficit in dual-task performance, over and beyond the dual-task deficit suffered by healthy older adults, the answer turns out to be affirmative. Considered at the level of proportional dual-task costs, we indeed find a specific effect in Alzheimer's disease. Given that proportional dual-task costs take baseline performance into account, the main effect of dementia status on dual-task costs suggests an overproportional performance decrement in Alzheimer's patients as compared to older adults, indicating a specific deficit in dual-task performance in these patients.

The second question concerned the influence of working memory tasks on the dual-task effect. Results show that dual-task costs in task combinations including a working memory task were larger as compared to task combinations without a working memory task.

The third and final question asked whether proportional dual-task decrements are larger in Alzheimer's patients as compared to older adults when a working memory task is added. The interpretation of this result is somewhat difficult, since the interaction between working memory task inclusion and dementia status found in this meta-analysis was mainly due to the fact that older adults had significant facilitation effects in those studies where no working memory task was included. These data, however, all originate from one single study in which linguistic abilities were tested. Thus, it may well be that the level of task difficulty was too low to produce dual-task effects in this study. When the results of those studies including a working memory task are considered, however, proportional dual-task costs are larger in Alzheimer's patients as compared to healthy older adults, suggesting that the specific deficit in dual-processing found in these patients is related to working memory functions.

These findings are in line with the literature on executive dysfunction in dual-task performance (Baddeley et al., 2001; Baddeley et al., 1991; Baddeley et al., 1986), suggesting that working memory involvement indeed is a component of the dual-processing deficit observed in Alzheimer's disease. On a theoretical level, these findings imply that the delineation between normal and pathological aging could be qualitative, rather than quantitative, in nature. The behavioral data analyzed in this meta-analysis suggest that Alzheimer's disease yields dual-task effects that are qualitatively different from those found in normal aging.

Some words of caution are in order. First, even after almost two decades of dual-task research in Alzheimer disease, the number of data sets available for meta-analysis is relatively small. Since there is only a small number of studies, every study weighs heavily on the final result (most notably in the case of the Waters & Caplan, 1997, study, which contributes half of the latency estimates). Third, there was most probably a positive selection bias in the present studies with regard to dementia severity (in that usually only mildly demented patients

participated), and with regard to the age of the patients (in that usually young-old patients were selected).

Despite these limitations, the results clearly show that Alzheimer's patients accrue larger dual-task costs than healthy older adults. These dual-task costs are overproportional in demented older adults, as compared to healthy older adults, and exacerbated by the presence of a working memory task. The results speak to a specific effect of working memory on dual-task in aging and Alzheimer's disease. The results are thus in line with models of dual-task performance proposing that tasks that are highly interrelated are a necessary condition for the emergence of disproportional dual-task performance decrements. In the following section, such effects of task characteristics will be discussed with special reference to the combination of a cognitive and a sensorimotor task. The central research question in this study, specifically, whether adaptive processes show an influence on dual-task performance in Alzheimer's disease, will be introduced, following the notion of balance as a task critical to survival in older adults.

Adaptive Resource Allocation in Aging and Alzheimer's Disease:

The Role of Balance Performance

For the purpose of the present study, balance performance is of interest for two main reasons. First, there is growing evidence for a strong connection between sensorimotor and cognitive functions with age (e.g., P. Baltes & Lindenberger, 1994). It can be assumed that a cognitive and a sensorimotor task, such as balance performance, are interrelated, require an integrated system (compare Schneider & Pichora-Fuller, 2000), and are thus sensitive to dual-task performance.

Second, a recent study on dual-task performance in a cognitive and a sensorimotor task has suggested an influence of task difficulty on dual-task performance (Li et al., 2001). Specifically, it was shown that older adults prioritize walking over cognition in a dual-task context. Under the assumption that walking is considered a task of higher age-saliency (i.e., has a critical value for survival in old age) the results from this study have been interpreted as an adaptive process within the framework of selection, optimization, and compensation (P. Baltes & M. Baltes, 1990). On a micro-analytical level, this concept implies that biological losses in age and Alzheimer's disease may be contrasted with an increasing tendency to prioritize critical tasks (loss-based selection; compare Freund, Li, & P. Baltes, 1990). Such effects of adaptive processes may have a considerable influence on dual-task performance with age. It has however, not yet been investigated whether such processes are present in Alzheimer's disease. In the following sections, these two premises will be introduced presenting empirical evidence and theoretical implications.

Cognition and Sensorimotor Performance with Age: A Strong Connection

Recent research suggests a strong connection between cognitive and sensorimotor variables with age (e.g., Anstey et al., 1997; Anstey et al., 1993; P.

Baltes & Lindenberger, 1997). Specifically, it has been shown that, with age, measures of general cognitive ability are strongly related to vision, hearing, and simple measures of gait and balance (Lindenberger & P. Baltes, 1994). Furthermore, several experimental studies have indicated an effect of sensorimotor functioning on balance performance with age (e.g., Stelmach & Worringham, 1985).

Figure 4

Balance as a Complex Multimodal System

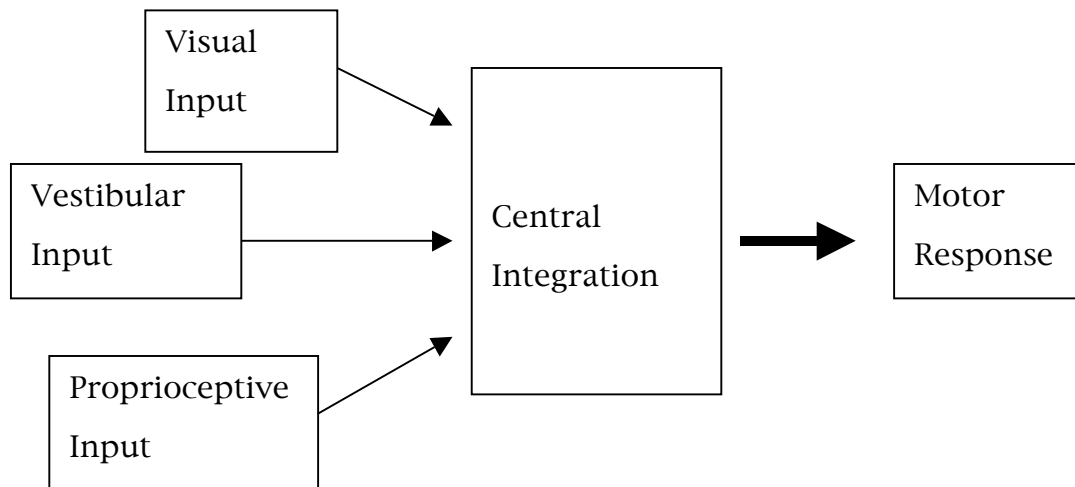


Figure 4. In the balance system, information from different modalities is integrated to form a controlled motor response. Adapted from: Wolfson, 1991.

Balance is a complex multimodal system that uses segmental and long-loop co-ordination reflexes and central integratory processes, and maintains body equilibrium during movement and correction of environmental changes in order to achieve postural stability (Figure 4; compare Wolfson, 1991). In classical research, balance control has been defined as the ability to maintain the body's center of mass within individual stability limits. However, more recent

approaches have argued for an integrated systems definition of balance control, incorporating levels of cognitive and sensory functioning and extrinsic environmental factors (compare Woollacott, 1996).

Vision is critical to the perception of motion and spatial orientation (Stoffregen, 1985). The vestibular system contributes to triggering postural responses after a sudden change of balance (Horak, Shupert, Dietz, & Horstmann, 1994). Proprioceptive feedback from joints and muscles is considered the primary effector of long-loop reflexes in the control of reactions to sudden perturbations of the balance system (Horak et al., 1994). Vibratory sensation is critical for the perception of stimulation at the ankle joint, indicating that age-related decreases in vibratory sensation might contribute to declines in balance control (Woollacott, 1996). Balance performance relies to a large extent not only on motor, but also sensory functioning. Both motor and sensory functions decrease with age, and perhaps more so in Alzheimer's disease (Fozard, 1990). The need to integrate sensory and motor functions on a central level indicates that differential patterns of decline in age and Alzheimer's disease could be due to changes in sensory function, motor functioning, central integratory processes, or a combination thereof.

In the context of the Berlin Aging Study (BASE), a strong correlation between sensorimotor and cognitive variables emerged. Measures of visual and auditory acuity explained 52% of the unique and age-shared variance in general intelligence (Lindenberger & P. Baltes, 1994). Specifically, there were moderate positive correlations between measures of general intelligence and vision ($r = .57$), hearing ($r = .51$), and simple measures of postural control like the Romberg test ($r = .59$). This finding is in line with propositions that age-related changes in sensory functioning might reflect changes in the central nervous system (e.g., Fozard, 1990; Rabbitt & Maylor, 1991). Baltes and Lindenberger (1997) suggest that such findings indicate that walking is increasingly in need for attention with

age. The authors conclude that a common mechanism (brain aging) drives age-related change in both sensorimotor and cognitive domains.

Recent experimental research is in support of that notion. Prior research on postural control has shown postural disturbance to be associated with experimental changes in sensory input in age, supporting the hypothesis of a central integratory problem (for review, see Brown and Wollacott, 1998). More refined design, however, showed that a decrease in sensory information and a decrease in cognitive performance may lead to an increase in attentional demands (Teasdale et al., 1992). Maylor, Allison, and Wing (2001) showed a performance decrement while performing a cognitive task relying on the visuospatial sketchpad of working memory with aging, and Brown and colleagues (Brown, Shumway-Cook, & Woollacott, 1999) reported increased attentional demands for balance performance in older adults. In a study combining walking and a memory task in the dual-task paradigm, Lindenberger and colleagues further explored the connection between cognition and sensorimotor performance in an experimental setting. They were able to show that with advancing age, participants showed greater performance decrements in cognition when walking concurrently (Lindenberger et al., 2000).

Consistent with these findings in older adults, recent research suggests an influence of sensory organization and attention on balance in Alzheimer's disease. Chong and colleagues (Chong, Horak, Frank, & Kaye, 1999) reported a decreased ability to suppress incongruent visual stimuli in Alzheimer's disease, which manifested in a twofold increase in the incidence of falls in Alzheimer's disease as compared to Parkinson's disease and healthy older controls (Chong et al., 1999). In a study investigating the combination of walking and a verbal fluency task, Camicioli and colleagues (Camicioli et al., 1997) showed a specific deficit in Alzheimer's disease while performing two tasks simultaneously. When presented with a verbal fluency task while walking, Alzheimer's patients markedly slowed down walking speed. They concluded that the decline in

walking speed in Alzheimer's disease could be due to impairment in working memory functioning (Camicioli et al., 1997). Specifically, based upon theoretical models by Baddeley (1986), they proposed that in addition to a decrease in attentional resources, there might be a specific deficit in Alzheimer's disease in allocating these resources, referred to as executive control deficit. That is, not only the amount of resources, but also the time-dependent scheduling of responses and the coordination of the two tasks (executive control) may be impaired in Alzheimer's disease. Since these functions are attributed to the frontal lobes in the neuropsychological literature (compare Goldman-Rakic, 1994), this finding is consistent with neuroimaging data that suggest that a decrease in frontal lobe function may account for postural disturbance in Alzheimer's disease (Nakamura, et al., 1997). Thus, deficits in executive functioning in Alzheimer's disease may account for specific deficits in gait and balance.

In sum, theoretical accounts for the dual-task deficit observed when combining a sensorimotor and a cognitive task differ to some extent in cognitive aging research and neuropsychology. Cognitive aging research has focussed on the amount of cognitive resources available (cognitive load hypothesis; Kinsbourne, 1987; Lindenberger & P. Baltes, 1994). In the neuropsychological literature, deficits in the ability to allocate resources have been emphasized, especially for the case of Alzheimer's disease (Baddeley, 1986; Camicioli et al., 1997; Perry & Hodges, 1999). Beyond the effects of aging and Alzheimer's disease, however, effects of task characteristics have recently received considerable attention with regards to dual-task performance in cognitive and sensorimotor tasks.

Balance as a Task Critical for Survival in Age

Falls are the primary etiology of accidental deaths in persons over the age of 65 years. The mortality rate for falls increases with age. One-third of the people over 65 living in the community and two-thirds of nursing home residents fall

each year (Fuller, 2000). In Alzheimer's disease, there is a threefold risk for falls and injuries as compared to non-demented older adults (Buchner & Larson, 1987; Wilking, Dowling, & Heeren, 1990). From an ecological validity perspective, securely maintaining an upright stance is an essential component of independent living and functioning. Various everyday tasks illustrate the necessity of a functional postural control system, e.g. dressing, walking stairs, reaching for a book on a shelf, going shopping or for a walk (compare Brown & Woollacott, 1998). In the Berlin Aging Study (BASE), it has been shown that variables of balance and gait show a significant association with functional competence ($r = .66$), positive affect ($r = .29$), and social network size ($r = .33$). These findings again underline the central impact of sensorimotor changes with age to broad domains, such as everyday activities, well-being, and social interactions (Marsiske, Klumb & M. Baltes, 1997).

These remarks underline the importance and ecological validity of balance tasks in older adults and patients with Alzheimer's disease. Based upon the metatheory of selection, optimization, and compensation (SOC; P. Baltes & M. Baltes, 1990), experimental researchers have further examined the strong connection between sensorimotor and cognitive functioning with special emphasis on task-difficulty. Given a simple everyday example, such as standing on a crowded bus while reading a paper. If older adults need more cognitive resources to maintain an upright stance, it should be adaptive to select stable posture over reading the paper, since maintaining upright stance can be considered a task critical for survival in older adults.

These propositions have been operationalized in a recent experimental study by Li and colleagues (Li et al., 2001). In a series of 25 sessions, task-difficulty in a sensorimotor task (walking) was continuously manipulated by adding obstacles on a walking track. Young adults and older adults were tested in a dual-task paradigm, performing a memory task simultaneously while walking. Results showed an increase in dual-task costs in cognition together with

a decrease in dual-task costs in walking with increasing number of obstacles in older adults. This finding has been interpreted as a specific tendency in older adults to prioritize walking over cognition with increasing difficulty of the walking task (Li et al., 2001).

These results point to the influence of task difficulty and adaptive processes on dual-task performance with age. Such adaptive processes have been described in the framework of selection, optimization, and compensation (P. Baltes & M. Baltes, 1990). In this framework, selection is defined as the choice, specification and pursuit of goals or tasks from different domains. The simultaneous performance of two tasks has been conceptualized as a laboratory analogue of situations in which multiple goals have to be coordinated (Freund et al., 1999). Given that the specific dual-task context is one in which resources are being restricted due to the simultaneous performance of two tasks, the argument is made that the selective prioritization of one task over another is a reflection of loss-based selection as introduced by the framework of SOC. On a micro-analytical level, this concept implies that biological losses in age and Alzheimer's disease may be contrasted with an increasing need for adaptive processes (compare Freund, Li, & P. Baltes, 1990)⁵.

Several research findings across different domains have been provided to support the importance of both selection and optimization for successful

⁵ From a behavioral sciences perspective, biological and cultural factors have been integrated in an ontogenetic perspective by Baltes (P. Baltes, 1997). Based upon the notion of incompleteness of human development (compare the notion of a "Mängelwesen"; Gehlen, 1940) the role of cultural and biological factors on human development is conceptualized as an interplay between evolutionary and ontogenetic factors, proposing a distinct architecture of this interplay across the lifespan. Specifically, with advancing age, the evolutionary (biological) mechanisms of selection show decreasing effects, which might be exemplified by the existence of age-associated diseases, such as Alzheimer's or Parkinson's disease.

cognitive aging in healthy older adults (for an overview, see P. Baltes et al., 1999). In Alzheimer's disease, SOC processes might be disturbed due to a general loss in brain functioning. In the conception of their theoretical framework, P. Baltes and M. Baltes (1990) differentiate between normal and pathological aging, and their propositions denote that SOC processes need to be placed into the context of normal and pathological aging. In pathological aging, and especially in Alzheimer's disease, there is a significant loss of resources in the course of the disease. Thus, external resources, or compensatory procedures might be of extreme relevance in this disease group. Bäckman (1992) described a set of propositions needed to develop effective training procedures in Alzheimer's disease. Among them are the reliance on preserved skills (selection), extensive training (optimization), the involvement of caregivers (compensatory shift from internal to external resources) and a strong support in transfer situations (compensation through external resources). Applying such basic assumptions to dual-task research, the following premises can be made. First, dual-task performance reflects situations of restricted resources. The selection of one task over another in dual-task contexts can thus be seen as an operationalization of an adaptive process, specifically, loss-based selection (compare Freund et al., 1999). On that background, the question arises whether such adaptive processes are also present in Alzheimer's disease.

Summary

The combination of a cognitive and a sensorimotor task promises some insight with respect to models of dual-task performance in aging and Alzheimer's disease and with respect to the conception of adaptive processes and the influence of task difficulty on dual-task performance in older adults and Alzheimer's disease patients. In the following section, the basic premises put forth in this review will be integrated and the research questions and predictions of the present work will be specified.

Outline of the Present Study

The purpose of this study was to investigate the simultaneous performance of a cognitive task and a balance task in young adults, older adults, and Alzheimer's patients. Given this framework, three central questions emerged from the reviewed empirical evidence and theoretical background. First, whether there is a specific deficit in dual-task performance in Alzheimer's disease. Second, whether patients with Alzheimer's disease prioritize balance over cognition in a dual-task context when balance is made more difficult. Third, whether these effects are specific to Alzheimer's disease beyond the effect of cognitive resources.

The first question was motivated on the background of theories of normal versus pathological aging and concepts of dual-task performance. The connection between cognition and sensorimotor functioning has been subject to some theorizing, including the proposition that with age, cognitive resources are more and more needed for sensorimotor behavior. While this has been shown in older adults (Lindenberger et al., 2000), literature on Alzheimer's disease suggests that patients suffering from this disease show a qualitatively different pattern of performance decrements as compared to older adults when combining two tasks (Baddeley, 1986). This difference seems to be exaggerated when adding a working memory task (compare *Dual-Task Performance in Alzheimer's disease: A meta-analysis*, this volume). One question is whether these qualitative decrements also occur when combining a cognitive and an everyday sensorimotor task such as maintaining a stable posture, i.e. whether they generalize to behaviors close to everyday activities. A simple operationalization is that quantitative differences show additive, i.e., main effects, whereas qualitative differences show overadditive, i.e., interaction effects (compare Verhaeghen et al., 2002).

The second question was motivated by prior research investigating loss-based selection from the framework of SOC within a dual-task paradigm. It is

assumed that the prioritization of one task over another reflects loss-based selection as introduced by the metatheory of selection, optimization and compensation (compare Freund et al., 1999). Differential manipulations of task-difficulty in the balance task were used in order to assess changes in the relative pattern of dual-task costs between cognition and sensorimotor performance as a function of the adaptive value of a given task domain (compare Li et al., 2001). Specifically, this allowed for a comparison of the amount of dual-task costs for the cognitive domain with those for the sensorimotor domain. The study was divided up into a first and a second experiment.

The specific aim of the first experiment was to investigate whether patients suffering from Alzheimer's disease prioritize balance over cognition in a dual-task situation despite larger dual-task performance decrements in both domains. Participants were healthy young and older adults and patients suffering from Alzheimer's disease. Prior to the dual-task assessment, participants were trained in the cognitive task and both cognitive and balance performance was assessed.

The third question, whether the dual-task effects observed were specific to Alzheimer's disease or a function of the amount of cognitive resources available, was approached in a second experiment. The specific aim of the second experiment was to investigate whether the pattern of dual-task performance expected in Alzheimer's patients in Experiment 1 differs from the pattern observed in older adults low on cognitive resources. To that end, older adults low on cognitive resources were selected from a larger screening sample. These participants completed the exact same procedure as in Experiment 1.

Tasks Used in this Study

The combination of tasks from the cognitive and the sensorimotor domain was chosen for three reasons. First, both cognitive and sensorimotor functioning show a significant relation to everyday life in older adults (Marsiske et al., 1997). It can thus be assumed that the combination of the two tasks has some ecological

validity. Second, balance performance can be seen as a highly age-salient task critical for survival. The third reason was a methodological one. If one aims at examining the role of cognitive resources or specific cognitive functions in normal and pathological aging on dual-task performance, it seems vital to examine domains that are highly interrelated and thus allow the expectation of significant dual-task performance decrements.

Cognitive Task

One paradigm that measures the monitoring, short-term storage, inhibition and scheduled retrieval of stimuli within working memory is N-Back (Dobbs & Rule, 1989; Smith & Jonides, 1999). The task offers different conditions that allow for testing different aspects of attention and working memory. The principle paradigm comprises the monitoring of a list of digits. In the 0-Back condition, participants are asked to read out the digit that is currently presented. This condition tests monitoring or sustained attention, but does not require short-term storage of the digits presented. In the 1-Back condition, participants are asked to read out the digit that was presented one before the currently presented digit. Thus, the digits have to be read and voiced at a specific point in time, at which the next digit is presented and has to be stored. The 1-Back condition is assumed to test monitoring and response scheduling. In the 2-Back condition, participants are asked to read out the digit that was presented two before the currently presented digit. Thus, the digits have to be read, stored in short term memory, and voiced at a specific point in time, at which the next digit is presented and has to be stored. In addition, participants have to inhibit currently irrelevant information, and, while keeping one digit stored, add another digit to working memory, which again has to be voiced at a different point in time. Thus, the 2-Back condition tests sustained attention and further properties related to working memory, such as inhibiting currently irrelevant information and coding representations in working memory for time of appearance within a sequence of digits. Furthermore, in the 2-Back condition,

there seems to be an involvement of spatial memory (Smith & Jonides, 1999). Neuroimaging studies have revealed different cortical areas involved in this task. For example, verbal 0-Back tasks have been shown to activate the left posterior parietal cortex (BA 40), whereas verbal 1- and 2-Back tasks have shown to activate Broca's area, the premotor cortex (BA 6), and three frontal sites (Broca's area, BA 44, and BA 6) (for review, see Smith & Jonides, 1999). These findings imply that the N-Back task allows testing for attention and working memory functions across verbal and spatial domains.

Balance Task

The measurement of balance disorders and sway has been standardized by means of dynamic posturography. This method allows testing for deviations of the center of body pressure (COP) while standing. The COP is a projection of the body's center of gravity on the ground level an individual is standing on. Measurement platforms have been developed that contain sensors allowing for measurement of the force applied to the surface and the center of body pressure for every given point in time. The dependent variable is the area covered by the center of body pressure movement over time (area of center of pressure movement). Thus, the amount of sway during a given trial (area of COP movement) can be measured.

Stable platforms have been used in a variety of studies, and sensory and visual input have been manipulated in standardized protocols using posturographic procedures (for review, see Barin, 1992). While standing on stable grounds can be seen as a largely automatized task that has been trained over a lifelong period, standing on a moving surface is assumed to increase the need of compensatory and adaptive behavior. Although such movements can be automatized over time, even subtle tilts at low frequencies are assumed to increase sway significantly (for review, see Woollacott, 1998). Thus, the difficulty of the balance task was manipulated by introducing a balance

condition that did not induce the risk of instability and a difficult condition that went along with some induction of sway (compare Li et al., 2001).

Design

In this study, two general manipulations were included in the design. First, single-task performance (of working memory and balance) versus dual-task performance (combining the two tasks). In order to control for effects of verbalization and monitoring of stimuli, the single-task balance condition included one condition in which participants monitor and verbalize stimuli only (0-Back) while performing the balance task.

Figure 5
Design of Task Factors

		Stable Platform	Moving Platform
0-Back		Single	Single
1-Back	Single	Dual	Dual
2-Back	Single	Dual	Dual

Figure 5. The complexity of the N-Back task was manipulated by the lag of responses (1 versus 2). The complexity of the Balance task was manipulated by introducing an easy (stable) platform condition, and a difficult (moving) condition. All conditions were assessed in both single- and dual-task. In order to control for effects of verbalization and stimulus presentation, single-task conditions in balance included the verbalization of stimuli (0-Back).

Second, within each domain, there was a complexity manipulation. In the working memory task, there were two tasks measuring monitoring, scheduling (1-Back), and inhibition within working memory (2-Back). The difficulty of the

balance task was continuously manipulated by introducing a balance condition that did not induce the risk of instability (standing as stable as possible on firm grounds) and a difficult condition that went along with some induction of sway (standing as stable as possible on moving grounds). The design is graphically shown in Figure 5.

Research Predictions

Predictions 1 to 4 listed below referred to experiment 1. Predictions 1 to 3 referred to the analysis of group differences between young adults, older adults, and patients with Alzheimer's disease in dual-task performance in a cognitive and a balance task. Specifically, the first set of predictions (*Predictions 1*) referred to dual-task performance in cognition and the second (*Predictions 2*) to dual-task performance in balance in the three groups, introducing a complexity manipulation in the balance task (stable versus moving platform). In the third set of predictions (*Predictions 3*) the question whether older adults and patients with Alzheimer's disease prioritize balance over cognition in a dual-task situation was addressed. A comparative analysis of dual-task performance across domains (cognition versus balance), introducing a complexity manipulation in the balance task (stable versus moving platform), in young adults, older adults, and patients with Alzheimer's disease, was used to operationalize prioritization.

Predictions 4 and 5 listed below referred to Experiment 2, comparing healthy older adults, older adults low on cognitive resources and patients with Alzheimer's disease. The main aim of this experiment was to assess the effect of cognitive resources in healthy older adults and patients with Alzheimer's disease. The fourth set of predictions (*Predictions 4*), in analogy to third set of predictions (*Predictions 3*), referred to the comparative analysis of dual-task performance in cognition and balance, now in older adults, older adults low on cognitive resources, and patients with Alzheimer's disease. The fifth set of predictions (*Predictions 5*) referred to the correlational analysis of dual-task performance as a function of cognitive resources and dementia status.

Performance decrements in cognition when adding the balance task

Theoretical foundations of dual-task performance and empirical evidence in older adults and patients suffering from Alzheimer's disease motivated the first set of predictions (compare *Dual-Task in Aging and Alzheimer's Disease*). The connection between cognitive and sensorimotor performance in old age has been subject to some theorizing, including the proposition that with age, cognitive resources are more and more needed for motor behavior (e.g., P. Baltes & Lindenberger, 1997). The literature on Alzheimer's disease suggests that patients suffering from this disease might have a qualitatively different pattern of performance decrements when combining two tasks (e.g., Baddeley et al., 2001). In both experiments, participants performed cognitive tasks (1-Back and 2-Back) and a balance task under two complexity conditions (stable versus moving platform) both in isolation (single-task) and concurrently (dual-task). Dual-Task performance was measured by computing dual-task costs, the relative performance decrement from single- to dual-task performance. The complexity manipulation in the balance task was introduced in order to manipulate task-difficulty in a task critical to survival in older adults.

It was predicted that performance decrements in cognition would increase when the balance task was made more difficult. Age-related decrements in dual-task performance in cognition were expected, which were predicted to be exaggerated in Alzheimer's disease (compare Lindenberger et al., 2000; Camicioli et al., 1997).

Predictions 1 (Performance decrements in cognition when adding the balance task):

- a) Main effect of platform condition on dual-task performance in cognition.*
- b) Main effect of age on dual-task performance in cognition.*
- c) Main effect of dementia status on dual-task performance in cognition.*

d) Dementia Status by platform condition interaction on dual-task performance in cognition.

Performance decrements in balance when adding the cognitive task

The predictions regarding dual-task performance in the balance task, too, followed general models of dual-task performance in aging and Alzheimer's disease. However, effects of task difficulty on adaptive behavior needed to be considered (compare Li et al., 2001). Specifically, based upon the assumption that standing on a moving platform is a task of high difficulty and critical to survival in older adults, thus reinforcing adaptive behavior, a decrease in dual-task costs (i.e., an improvement in dual-task performance in balance) was expected in older adults from stable to moving platform conditions. In patients with Alzheimer's disease, a similar pattern would indicate the presence of adaptive processes despite large dual-task performance decrements.

Predictions 2 (Performance decrements in balance when adding the cognitive task):

- a) Main effect of platform condition on dual-task performance in balance.*
- b) Main effect of age on dual-task performance in balance*
- c) Main effect of dementia status on dual-task performance in balance.*
- d) Dementia Status by platform condition interaction on dual-task performance in balance.*

Prioritization of balance over cognition in dual-task

Following the notion of an effect of adaptive processes on dual-task performance in a cognitive and a sensorimotor task (compare Li et al., 2001), the prioritization of one task over another was the focus of the next set of predictions. Specifically, it was predicted that dual-task costs in cognition increase, while dual-task costs in balance decrease with increasing task difficulty

in the balance task. Following the notion of a specific deficit in dual-task performance in Alzheimer's disease, it was expected that this pattern of prioritization was exaggerated in the presence of the disease. These predictions were tested by comparing dual-task performance (measured as dual-task costs) across both task domains (i.e., cognition versus balance).

Predictions 3 (Dual-Task performance decrements in both task domains):

- a) Main effect of age on dual-task performance.*
- b) Main effect of dementia status on dual-task performance.*
- c) Main effect of platform condition in older adults and patients with Alzheimer's disease.*
- d) Interaction between platform condition and task domain (balance versus cognition) in older adults and patients with Alzheimer's disease.*
- e) Interaction between dementia status, platform condition, and task domain (balance versus cognition).*

Influence of cognitive status versus dementia status on dual-task performance

The fourth and fifth sets of predictions were based on the question whether performance decrements and pattern of dual-task costs are specific to patients suffering from Alzheimer's disease, or whether they simply reflect a decrease in the amount of cognitive resources available. In order to delineate the nature of these decrements, in Experiment 2, healthy older adults and healthy older adults with low cognitive resources were compared to Alzheimer's patients. Given that the prioritization of balance was expected to be a function of the dual-task deficit specific to Alzheimer's disease, rather than related to the amount of cognitive resources available, differential patterns were expected. Thus, the difference between dual-task costs for balance and working memory was predicted to be overadditive in Alzheimer's patients as compared to older adults

low on cognitive resources. These predictions were formulated in analogy to the third set of predictions (*Predictions 3*).

Predictions 4 (Dual-Task performance decrements in both task domains in older adults, older adults low on cognitive resources, and Alzheimer's patients):

- a) Main effect of dementia status on dual-task performance.*
- b) Main effect of platform condition.*
- c) Interaction between platform condition and task domain (balance versus cognition).*
- d) Interaction between dementia status, platform condition, and task domain (balance versus cognition).*

The fifth set of predictions referred to the correlational analysis of dual-task performance as a function of cognitive status and dementia status. On a correlational level, dual-task performance was predicted to be dependent upon single-task performance in both normal and pathological cognitive aging. Additional variance was predicted to be explained by the presence or absence of dementia beyond the level of cognitive performance.

Predictions 5 (Dual-Task performance decrements in both task domains as a function of single-task performance in older adults, older adults low on cognitive resources, and Alzheimer's patients):

- a) Dual-Task performance increases as a function of single-task performance.*
- b) Beyond the effects of single-task performance, dual-task performance decreases as a function of dementia status.*