OVERALL DISCUSSION

Overview

The aim of this study was to investigate adaptive resource allocation in aging and Alzheimer's disease while performing a cognitive and a sensorimotor task simultaneously (i.e., dual-task performance). The central research question asked whether an adaptive prioritization of tasks critical to survival in a dual-task situation is preserved in Alzheimer's disease. Specifically, it was investigated whether patients suffering from Alzheimer's disease adaptively prioritize balance performance, which is considered critical to survival in old age, over cognition when the balance task is made more difficult. The argument was made that in Alzheimer's disease, as compared to normal aging, adaptive prioritization can be present despite a specific dual-task performance decrement, and independent of cognitive resources.

In line with predictions, differential dual-task decrements were found in cognition when adding a balance task. Decrements were larger in older adults as compared to young adults. When the balance task was made more difficult, dual-task decrements in cognition increased disproportionally in Alzheimer's patients, as qualified by a significant group by difficulty interaction.

Dual-task decrements in balance when adding a cognitive task increased from young to older adults to Alzheimer's patients on a stable platform. However, on a moving platform, dual-task decrements decreased in older adults and more so in Alzheimer's patients, indicating that with increasing difficulty of the balance task, dual-task decrements decrease in older adults and Alzheimer's patients. This result speaks to a prioritization of balance over cognition in older adults and Alzheimer's patients in a dual-task context. In further analyses, it could be shown that the pattern of prioritization was specific to Alzheimer's disease, as revealed by a group by domain by difficulty interaction.

In Experiment 2, it was shown that both the amount and pattern of dual-task decrements did not differ between older adults high and older adults low in

performance on a fluid intelligence task, but differed significantly in Alzheimer's patients. Correlational analyses further showed an effect of dementia status on dual-task performance beyond the level of performance in the Digit Symbol Substitution task on both cognition and balance.

The central finding of the present study is that, when performing a balance and a cognitive task simultaneously, Alzheimer's patients prioritized balance over cognition when the task was made more difficult. The pattern of prioritization was present despite large dual-task performance decrements in Alzheimer's disease patients. This pattern of prioritization implies that effects of adaptive processes have considerable influence on dual-task performance in Alzheimer's disease.

Possible limitations and qualifications of the results of *Experiment 1* and *Experiment 2* were discussed at some length in the respective *Discussion* sections. Here, the results of the present study are discussed in the context of models of dual-task performance and theories of normal and pathological aging.

Dual-Task Performance in Aging and Alzheimer's Disease

The results of this study have some implications for concepts of dual-task performance. First, implications for general resource models on dual-task performance are discussed. Specifically, it will be argued that the amount of dual-task costs found in this study speaks to a specific deficit in dual-processing in Alzheimer's disease. At the same time, however, effects of task difficulty emerged. These effects are discussed with respect to adaptive prioritization processes in aging and Alzheimer's disease. Potential causes for the preservation of such adaptive prioritization in Alzheimer's disease are discussed with respect to models from the cognitive neurosciences and learning theory.

Limitations of a General Resource Model of Dual-Task Performance

Models of general resources or processing speed imply the notion that cognitive systems operate in the same way, but at different rates of processing or with

different amounts of resources available. A model of dual-task performance based on such findings would expect proportional, additive decrements when performing two tasks simultaneously. The results of this study, however, showed disproportional performance decrements in dual-task in older adults and Alzheimer's patients independent of the amount of cognitive resources available.

One way to explain such a pattern of results from the perspective of a general resource model would be that both tasks share resources to a large extent, thus leading to a multiplicative, rather than merely additive decrement when performed in combination (compare Verhaeghen et al., 2002). However, such a model would predict a linear relation between the amount of cognitive resources available and the overall dual-task decrements, be they proportional or disproportional (Cerella, 1990; Salthouse, 2000). In the case of Alzheimer's patients two findings speak against this model. First, the emergence of a significant task by group interaction on proportional dual-task costs between older adults (and likewise, older adults low on cognitive resources), and Alzheimer's patients. Second, the finding that the relation between cognitive resources (as measured with a fluid intelligence task) and dual-task performance was qualified by an interaction with the presence or absence of dementia.

These findings are in line with a model of a specific deficit in dual-task performance in Alzheimer's disease, as proposed by Baddeley (1992). Baddeley's working memory model of dual-task performance implies a specific deficit in executive control in patients suffering from Alzheimer's disease. However, this model was specified for tasks within working memory. The overadditive effects found in this study may thus reflect differential processes outside working memory, or both within and outside working memory. On the level of task characteristics, it can be argued that both the N-Back as well as the balance task used in this study presumably tax the visuospatial sketchpad within working memory. In a prior study by Maylor and colleagues (Maylor, Allison, & Wing, 2001), it was shown that the simultaneous performance of a balance task and a

visuospatial task lead to significant dual-task decrements in older adults. On a psychometric level of analysis, one could argue that the increase in the correlational association between sensorimotor and cognitive variables with age (Lindenberger & P. Baltes, 1994) reflects a similar process, the permeation of cognition with sensorimotor processes, which in the case of a specific deficit in executive control would in turn lead to overadditive effects.

In sum, the overadditive dual-task costs found in this study suggest that the specific deficit in executive control in patients with Alzheimer's disease may play a role in the simultaneous performance of a balance and a cognitive task. The central executive system within a working memory model as proposed by Baddeley is thus generalizable to balance performance. However, despite large dual-task performance decrements in balance, a specific pattern of prioritization emerged in patients with Alzheimer's disease.

Adaptive Prioritization of Balance in Dual-Task Performance

Over and above the amount of dual-task decrements, this study found a differential pattern of dual-task costs between healthy older adults and Alzheimer's patients. Specifically, as the balance task became more difficult, Alzheimer's patients' dual-task costs increased in cognition and decreased in balance, indicating a prioritization of balance. Thus, the results of this study suggest an influence of adaptive processes on dual-task performance in Alzheimer's disease, despite large dual-task performance decrements, and independent of cognitive resources.

Although - as predicted by models of central executive dysfunction - the amount of dual-task costs in cognition increased disproportionally in patients with Alzheimer's disease, the pattern of dual-task costs is similar to that found in a prior study on dual-task performance in a cognitive and a sensorimotor task in older adults (Li et al., 2001). In line with theories of successful aging, this pattern indicates that patients with Alzheimer's disease, at least in the early stage of the disease, tend to select one task over another in a multitask context.

From a bio-behavioral perspective, this result can be interpreted within the framework of the theory of selection, optimization, and compensation (P. Baltes & M. Baltes, 1990) as a tendency to selectively prioritize the task critical to survival (in this case, balance). The tendency to prioritize one task over another can be seen as a loss-based selection, i.e., when at the limits of resources, persons need to select one task over another. Specifically, the earlier findings by Li and colleagues on walking in healthy older adults (Li et al., 2001) emerged when older adults were tested at the limits of performance, i.e. after a series of 23 sessions of adaptive training in walking and cognition. In this study, the prioritization of balance in older adults showed numerically, but did not reach statistical significance, indicating that performance limits had not been taxed in the older adults. However, in the Alzheimer's patients, a clear prioritization pattern emerged as the balance task was made more difficult.

In order to account for the prioritization pattern found in this study, the allocation process of resources needs to be considered (compare Schneider & Pichora-Fuller, 2000). One process involved in the allocation of resources is the concept of a central executive system (Baddeley, 1986; Goldman-Rakic, 1994). Reallocation of resources, however, seems to be a function of task complexity. When task demands are high and both tasks share the same resources, reallocation of resources comes into play (Schneider & Pichora-Fuller, 2000). In the following, the prioritization pattern found in this study will be discussed with reference to neuroscience models of resource allocation. Then, the role of learning processes in the prioritization of balance over cognition will be discussed from a developmental perspective.

Neuroscience Models of Prioritization

In the field of cognitive neurosciences, reallocation of resources has been conceptualized as increased neural activation in cortical areas that are not primarily ascribed to a given task. Reallocation of resources has been shown both with increasing task complexity (Just, Carpenter, & Hemphill, 1996) and

with age (Reuter-Lorenz et al., 2000). Several neuroimaging studies on dual-task and resource allocation have investigated the notion of a specific process of allocating resources (Bunge, Klingberg, Jacobsen, & Gabrieli, 2000; D'Esposito, Detere, Alsop, & Shin, 1995; Klingberg, 1998). However, conflicting results have been reported.

D'Esposito and colleagues combined a memory span task with a suppression task and were able to show a specific activation in the dorsolateral prefrontal cortex under dual-task conditions (D'Esposito et al., 1995). For the present study, this model would imply a specific module of resource allocation, consistent with the notion of a central executive. However, this central executive is thought to decline in Alzheimer's disease (see Baddeley, 1992). Consequently, the prioritization pattern found in Alzheimer's patients in this study is unlikely to be due to resource allocation in a central executive module within working memory.

Gabrieli and colleagues, on the contrary, report increases in cortical activation areas related to both primary tasks when combining the two tasks. They combined a reading and a short-term memory task. While reading alone, as well as memory alone, showed increased activation in the parietal and prefrontal lobes, dual-task did not result in an increase in activation in any additional region. The authors conclude that an increase in activation in those areas that are related to the primary tasks might reflect a resource model of dual-task, leading to increases in activation when two tasks are combined (Bunge et al., 2000). From this perspective, reallocation of resources requires sizeable resources in both primary tasks, that can additionally be recruited in a dual-task situation. This assumption is unlikely for three reasons. First, Alzheimer's patients are assumed to have few resources, especially in the cognitive domain, to begin with. Second, the prioritization pattern found in this study was stable beyond the effect of cognitive resources, as shown in Experiment 2. Third, earlier studies have shown such a prioritization pattern in healthy older adults at the

limits of performance, i.e., at the limits of resources (Li et al., 2001). Thus, it seems that this pattern of prioritization is likely to emerge at the limits of performance, when resources are sparse.

Antecedents of Prioritization

From a developmental perspective, the question arises whether the adaptive pattern of prioritization found in patients suffering from Alzheimer's disease is grounded in a learning process that occurs over time. Specifically, one may argue that Alzheimer's patients, given the existence of a specific deficit in dual-processing, are forced to prioritize one task over another early in the disease process, possibly even in a preclinical stage. Such resource allocation could have been learned prior to the emergence of the clinical disorder. On a theoretical level, two modes of learning may play a role in this context: Avoidance and discriminative learning (see March, 1996; Papini, 2002).

Avoidance learning would imply the appreciation of a stimulus, coupled with the representation of a given behavior to avoid an unpleasant stimulus (Solomon, Sullivan, Nichols, & Kiernan, 1979). As recent empirical evidence has shown, avoidance, but also risk aversive behavior can be seen as a consequence of accumulated experience rather than a specific human trait (March, 1996). For an interpretation of the results of the present study, one could argue that due to unpleasant experiences when combining a cognitive and a balance task in everyday activities, older adults, and more so patients with Alzheimer's disease, learn to prioritize balance in order to avoid a risky situation that may go along with some degree of instability, or a risk of falling. However, it is debatable whether avoidance behavior can be learned in Alzheimer's patients over a period of time, given an specific deficit in episodic memory. Such deficits in episodic memory could lead to a decreased ability to learn avoidance behavior over a longer period in time (Papini, 2002).

A recent example for a learning process that may be independent of such episodic representation is the case of conjunctive discrimination learning

(O'Reilly & Rudy, 2001). In a computational neural network approach, the authors were able to show that rapid discriminative learning requires episodic cues and intact hippocampal function. However, long-term discriminative learning could also occur independent of hippocampal function. An example of such a learning process would be a cortical learning process that involves the extraction of general, invariant features of a given situation, but not the representation of a specific experience. Over longer time course, such learning could also occur in the case of balance and cognition. From a generally unpleasant experience (instability) older adults and patients with Alzheimer's disease could learn to prioritize balance in order not to feel unstable (see O'Reilly & Rudy, 2001). Such theoretical assumptions receive empirical support from studies showing an increased tendency to stop walking while talking in dementia patients and patients at risk of falls (Lundin-Olsson, Nyberg, & Gustafson, 1997). On a general level, this theoretical approach would imply that the prioritization of balance could have been learned and automatized prior to the emergence of clinical dementia. Likewise, it could well be that this process in older adults reflects a specific overlearned behavior that emerges in situations when resources are sparse. Within the framework of the theory of SOC (P. Baltes & M. Baltes, 1990) such behavior can be interpreted as a tendency to selectively prioritize the task critical to survival (in this case, balance). The tendency to prioritize one task over another can be seen as a loss-based selection, i.e., when at the limits of resources, persons need to select one task over another.

Summary

With regard to models of dual-task performance, two central points from this study add to the picture.

First, with regard to the pattern of prioritization, it can be noted that in Alzheimer's disease, a behavioral pattern consistent with models of successful aging, specifically, the notion of loss-based selection in the framework of SOC, is present. This pattern can be related to learning theories, calling for further

research on effects of task characteristics on dual-task performance employing both behavioral and neuroscience methods. On a general level, these results imply that adaptive processes, specifically, loss-based selection, are preserved in early Alzheimer's disease through earlier processes of automatization.

Second, the amount of dual-task costs found in older adults and Alzheimer's patients in this study suggests that a general resource model of dual-task performance is limited in the sense that additional factors, such as working memory functions and executive control, play a role in dual-task performance between a cognitive and a balance task in normal and pathological cognitive aging.

In the following, implications for models of normal and pathological aging as well as implications for the early prediction of dementia will be discussed.

Implication for Models on Normal and Pathological Aging

In the literature review, recent neuropathological work was reported that showed that the pathological changes observed in Alzheimer's disease may also occur in healthy older adults, albeit to a lesser degree, and possibly in a different quality (MRC CFAS, 2001). While the results of this study are in line with theories of executive functions and specific deficits in Alzheimer's disease (Baddeley, 1986), an additional phenomenon (the prioritization of balance in Alzheimer's patients) was observed that can be interpreted within the framework of behavioral theories of successful aging and theories of resource allocation in the cognitive neurosciences alike. Two consequences for theoretical and empirical work on the distinction between normal and pathological aging will be discussed here. First, the potential role of these findings for the early prediction of dementia on a behavioral level, and second, the general implications for neuropsychological theories on normal and pathological cognitive aging.

Potential Implications for the Early Diagnosis of Alzheimer's Disease

Given that the prioritization of balance found in this study reflects a function of Alzheimer's disease for an individual in both a neuropsychological (i.e., the need to allocate resources within the brain) and a behavioral (i.e., the need to select one task over another in a situation where task demands for a given individual are high; loss-based selection) perspective, the question arises how sensitive the measurement of such a behavior would be for the early prediction of dementia.

Aside from cognitive ability levels, it would be interesting to see whether the pattern of prioritization reflects changes in the transition phase to dementia, and would thus enable to determine which individuals will eventually develop dementia and which will not. It could be that the behavioral pattern (i.e., the prioritization of one task over another) reflects a more sensitive measure of later dementia than the level of performance. From the perspective of this study, it would seem vital to follow the older adults and especially the older adults low on cognitive resources over a longer period of time in order to determine the potential development of dementia in these persons. This hypothesis lends further support from Experiment 2 of this study, which indicates that the pattern of prioritization may be independent of cognitive status in healthy older adults, but rather a function of the absence or presence of dementia. Following this line of thinking, the hypothesis would be that those participants who showed a pattern of prioritization on an individual level should have a higher risk for subsequent dementia.

Implications for Models of Normal and Pathological Aging

Regarding the implications for theories on normal and pathological aging, a distinction has to be made between two central findings of this study. With respect to the amount of dual-task costs in normal and pathological cognitive aging, the results of this study fit nicely into theories of working memory and executive functioning (Baddeley, 1992). The overproportional increase in dual-

task costs from young to older adults to Alzheimer's patients suggests a specific deficit in executive functions in Alzheimer's patients.

The pattern of prioritization found in this study indicates that Alzheimer's patients do not merely fail to multitask, but prioritize one task over another. Specifically, Alzheimer's patients selected balance over cognition, and it seems reasonable to assume that this pattern may be due to the saliency of the task, i.e., the fact that balance can be seen as a task critical for survival. This finding can be interpreted beyond theories of executive control within working memory (Baddeley, 1992), since the amount of dual-task costs and the pattern could indeed reflect different processes. While performing two task simultaneously leads to a steeper performance decrement in Alzheimer's patients, the pattern of performance decrements has earlier been reported in normal cognitive aging research (Li et al., 2001).

From a bio-behavioral perspective, behavioral processes of selection can be seen as consequences of individual levels of biological functioning in that a given person with a specific level of biological change in old age may be pressed to select behaviors that are critical to her. In that context, biological declines observed in pathological cognitive aging, be they qualitatively or quantitatively different from normal cognitive aging, could induce different patterns of behavior in a multitask situation. Thus, in line with earlier theoretical and empirical work in Alzheimer's disease (Bäckman, 1992; M. Baltes, Kühl, Gutzmann, & Sowarka, 1995), the pattern of prioritization found in this study indicates that the theory of selection, optimization, and compensation is applicable to behavioral patterns observed in pathological cognitive aging, in this case Alzheimer's disease. This view is consistent with a disease model of Alzheimer's disease, in which the accumulation of pathology within the brain would - as a quantitative process - leads to a transition to a qualitatively different process (the disease). However, the transition process seems to be subject to additional accelerating and decelerating factors. From the specific

results of this study, one could argue that adaptive processes, i.e., the selection of one task over another, do play a role in the disease process. In turn, it could also be that the degree of pathology influences the need to engage in adaptive processes during the disease.

Outlook

This study investigated the simultaneous performance of a cognitive task (N-Back) and a sensorimotor task (balance performance on a stable and a moving platform) in normal (healthy older adults) and pathological (Alzheimer's patients) cognitive aging.

The results of this study call for further research. An unsettled issue is, for example, the specificity of the prioritization pattern with respect to task characteristics. Further research is needed to investigate whether such patterns also emerge in task which are not as critical to survival as balance performance. Tasks that are less salient and less fear-evoking than balance performance should be investigated on that account. In addition, a critical question is whether the differential pattern between older adults low on cognitive resources and Alzheimer's patients found in this study has some predictive value for the later onset of dementia. Longitudinal research and experiments with high-risk groups for developing dementia need to be conducted to answer such questions.

On a general level, the results of this study may stimulate biomedical and neuropsychological research to investigate correlations between brain functioning and behavior that go beyond performance levels in a given paradigm. Although performance declines may be present in many forms of pathological brain changes, it seems vital to investigate how people with different brains organize their limited behavioral repertoire, be it in a conscious or unconscious manner[18]. Such research could open new perspectives in the

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[18] The issue of conscious versus unconscious allocation of resources reflects current debates in behaviorism and neo-cognitive science (Bargh & Ferguson, 2000). Although it

fields of psychiatry and neurology, but likewise integrate behavioral and biological research in the quest for phenomena that moderate brain-behavior correlations and may add to the explanation of variability often observed in the study of pathological changes in humans.

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seems extremely fruitful to explore such issues experimentally, this question was beyond the scope of this research.