2. THEORETICAL BACKGROUND

This section is divided into three major parts. The first part shortly presents the tasks that were used in the present study, namely the episodic memory task (Method of Loci, MOL), the working memory task (N-back), and the sensorimotor task of balancing on a special device, the ankle-disc board. I summarize research on developmental changes in the underlying capacities. The second part discusses cognitive theories on resource allocation in dual-task situations. Different theoretical assumptions about the way in which resources might influence dual-task performance are contrasted. In addition, studies on developmental changes in resources and their influence on dual-task behavior are presented, followed by a subsection on task parameters influencing dual-task performance in general, like for example practice and task difficulty. The third part describes the ecological approach to dual-task research (K.Z.H. Li, Krampe, & Bondar, in press), which enables the researcher to investigate processes related to the theory of selection, optimization, and compensation (SOC; Baltes & Baltes, 1990). The underlying assumption is that dual-task situations are very demanding and can trigger selection processes, which occur when people focus more strongly on one task domain than on the other when performing both tasks concurrently. Empirical evidence for such selection processes stems from studies with young and older adults, which were conducted within the ecological approach to dual-task research. After an overview on cognitive and sensorimotor dual-task studies in children, a first study with 9- and 11- year old children and young adults is presented, which took some of the concerns of the ecological approach into consideration.

2.1 Development of Memory and Balance Performance in Childhood

The present study investigated dual-task situations in the laboratory. However, the aim was to use tasks and task combinations that should have some ecological validity, such that the laboratory findings could be generalized to dual-task situations in everyday life.

Selection of tasks. Two different cognitive tasks were used, namely an episodic memory task and a working memory task. Episodic memory performances and working memory capacity are known to increase during childhood and are therefore interesting in age-comparative studies. Furthermore, the ability to remember episodes and to hold information active in working memory while completing a cognitive task were considered fundamental aspects of many different cognitive tasks in everyday life. Two different cognitive tasks were used because the interference between a cognitive and a sensorimotor task was expected to be due to some general difficulty of performing these two types of tasks concurrently. The resulting patterns of interference were therefore expected to be comparable across different types of cognitive tasks. The sensorimotor task of the present study consisted of balancing on a special device, the ankle-disc board, which required participants to perform constant body movements to stabilize themselves. It might be compared to stabilizing the body's equilibrium while standing on a bus during a bumpy ride.

Selection of study participants. Three different age groups were tested in the present study: 9- and 11-year old children and young adults. No specific predictions were formulated concerning differences between the dual-task performance patterns of 9- and 11-year olds, and the inclusion of two different childhood age groups was mainly exploratory in nature, since differences in the dual-task patterns of these two age groups had been found in a previous study (see Section 2.3.5 for details). Furthermore, participants were selected for participation according to their performances in standardized cognitive tasks. Since the samples of the present study were rather small, with nine participants in each age group, this was done to assure that the samples would be comparably representative for their respective age groups in basic cognitive performances.

The following section presents the tasks used in the study, along with a description of developmental changes during childhood in the underlying capacities.

2.1.1 The Development of Episodic Memory

Wheeler (2001) points out that episodic memory was originally defined

> "as the variety of memory that receives and stores information about temporally dated episodes or single events, and the temporal-spatial relations among them, while semantic memory comprised organized knowledge about the world, including information about words, objects, and events."
> (p. 4715)

According to Wheeler, more recent definitions of episodic memory refer to a neurocognitive system that renders possible the conscious recollection of events as they were previously experienced.

Research on memory development during childhood has shown that increases in performance can be observed for many areas of language-based memory. These improvements are often attributed to the increasing central processing capacity during that age range. However, Case (1985) argues that the total amount of capacity does not change with age, but that the same task requires less resources with developmental age, for example due to increases in the speed of information processing. Another explanation for gains in memory performance with age focuses on the role of memory strategies (e.g., Harnishfeger & Bjorklund, 1990). Within this framework, strategies are defined as potentially conscious, intentional cognitive activities that improve memory performance (Schneider & Büttner, 2002). During encoding, strategies like rehearsal, categorizing, and elaboration can be used. Research on memory strategies in childhood has shown that different and distinguishable stages of strategy use exist in development (Flavell, Friedrichs, & Hoyt, 1970; Miller, 1990; Reese, 1962), and that almost all children use rehearsal and organizing strategies by middle and late childhood (Folds, Footo, Guttentag, & Ornstein, 1990; Kee & Davies, 1988; Kemler & Jusczyk, 1975; Miller, Woody-Ramsey, & Aloise, 1991; Schneider, 2001; Schneider & Sodian, 1997). An important factor in children's strategy acquisition is the amount of mental effort they have to invest to execute a strategy: For a newly learned strategy, this effort is so high that too few additional resources remain to be devoted to the actual retrieval of target information (Bjorklund & Harnishfeger, 1987). Therefore, the initial use of such a strategy might not lead to an actual improvement in recall performance. Only when the newly learned strategy has been practiced repeatedly, improvements in memory performance emerge. Elaboration strategies for encoding are considered to be the most complex, and they are usually observed later in development. Considerable individual differences concerning these strategies are found, and only a minority of adolescents and young adults uses the more complex elaboration strategies spontaneously.

In the present study, episodic memory performance was measured after study participants had been instructed in an elaboration strategy, the Method of Loci (MOL). In the MOL task, participants were instructed to encode series of words by combining them with a list of fixed locations via mental imagery. In addition, a working memory task (N-back) was used in the study, which required monitoring, short-term storage, and scheduled retrieval of digits. The following section describes the development of working memory performance.

2.1.2 The Development of Working Memory

Working memory is conceptualized as a mental workspace consisting of activated memory representations. These representations are available in a temporary buffer for manipulation during cognitive processing. The buffer is often proposed to be limited in its capacity, and there are considerable changes across the lifespan on measures of working memory capacity. Presumably the most influential model of working memory was introduced by Baddeley (1986). In his model, the term working memory refers to a brain system that provides temporary storage and manipulation of information necessary for complex cognitive tasks. According to the model, the working memory system can be divided into three subcomponents: The central executive, which is an attentional-controlling system, and two slave systems, (a) the visuospatial scratchpad, which constructs and preserves visual images, and (b) the phonological loop, a mechanism for the retention of speech-based material. In recent publications, Baddeley (2000) also proposes the existence of a fourth component of the model, the episodic buffer, which is a limited capacity system providing temporary storage of information held in a multimodal code, therefore being capable of integrating information from the subsidiary systems.

Increases in working memory capacity with age can be measured during childhood (e.g., Hitch, Towse, & Hutton, 2001). Case (1995) pointed out that the growth of working memory span across the childhood years can be predicted by improvements in the speed of processing. There is a high correlation of speed measures with increases in span (see also Fry & Hale, 1996). For these improvements in processing speed, some sort of maturational influence is expected to be operative. It might be caused by increasing myelinization, or by more rapid long distance transmission across frontal and posterior lobes, with concurrent reductions in activation spread within these lobes. Waves of dendritic branching and pruning might underlie these changes. A study by Case, Kurland, and Goldberg (1982) investigated the relationship of operational speed and memory span by equating adults and 6-year old children on speed of word repetition through a manipulation of word familiarity. The differences in word span disappeared under these conditions. The authors conclude that the increase in span is not due to an increase in total processing space, but due to basic operations becoming faster and more efficient with age.

The sensorimotor task used in the study consisted of balancing on a special balance device, the ankle-disc board. The following section therefore describes the development of balancing abilities

2.1.3 The Development of Balance Abilities

Balancing, that is maintaining the body's equilibrium under different postural demands, requires the coordination of many body parts. Balance is usually seen as a behavior that emerges from the complex interaction of a number of subsystems, including the sensory systems, the motor system, the musculo-skeletal systems, and a high-level adaptive system with a strong cognitive component (Balasubramaniam & Wing, 2002; Bernstein, 1967; Woollacott, 2000). Concerning age differences in balance abilities, young adults are reported to be superior to children in their balance performance when balance is measured by body sway, which is defined as the constant small deviations from the vertical and their subsequent correction during upright stance (Sheldon, 1963). Children increase their performance on balance tasks with increasing age (DeOreo & Wade, 1971; Figura, Cama, Capranica, Guidetti, & Pulejo, 1991; Wolff, Rose, Jones, Bloch, Oehlert, & Gamble, 1998). Reductions in the sway of their center of pressure during stable stance can be observed, and children become increasingly able to withstand support surface perturbations with increasing developmental age (Roncesvalles, 1998).

Woollacott and Shumway-Cook (1990) distinguish between two types of models to describe the neural basis for developing posture and movement control in children: the reflex-hierarchical model and systems models. According to the *reflex-hierarchical model*, the central nervous system (CNS) is organized as a strictly vertical hierarchy. Primitive reflexes are controlled at the spinal cord level and more elaborated reflexes by the brain stem. The righting reactions, which are reactions responsible for maintaining alignment to gravity and for keeping body parts in alignment after rotation, are controlled at a slightly higher CNS level, the midbrain. According to that model, the cortex controls the equilibrium reactions, which are the body's responses to tilting of the support surface (Chandler, Andrews, & Swanson, 1980; Weiss, 1938). Concerning the development of balancing abilities, proponents of the reflex-hierarchical model assume that the control of movement moves from the reflexive to the voluntary state with maturation.

The *systems model*, on the other hand, views the body as a mechanical system that is subject to gravity and inertial forces (Bernstein, 1967). According to that model, the same motor programs can cause different movements, depending on the position of the body. Central concepts within the systems model are "synergies", which are defined as muscles acting as a unit. Since the nervous system has to control and coordinate many joints as part of a single movement, synergies help to organize these behavioral patterns. Movement always stems from the interaction of a complex assembly of systems and subsystems, and balance is controlled by multiple neural and mechanical components. Development of balancing abilities within the systems framework is expected to be rate-limited and constrained by the maturation of the slowest critical component.

Woollacott and Shumway-Cook (1990) further point out that different strategies are available to keep the center of body mass over the base of support: the ankle strategy (movement of the ankles), the hip strategy (movement of the hip), and the suspensory strategy (lowering the point of gravity), and that the efficiency of a particular strategy depends on factors like height and muscle response time. Due to these constraints, the hip strategy is rarely observed in young children. Thelen (2000) points out that the dynamics systems perspective clearly dominates the current research on motor development.

Hay and Redon (1999) investigated the differential influence of feedforward and feedback control on postural development. *Feedback postural control* is the only strategy available for maintaining balance when subjects are coping with unpredictable externally generated postural disturbances, whereas *feedforward control* clearly operates when the disturbance is directly generated by own movements (e.g., during arm raising or gait). The authors report that feedforward control becomes more efficient when children grow up, but that it does not show a monotonic pattern of development. In their study, 6- to 8-year olds showed an overcontrol of posture, while older children and adults could tolerate imbalance better. Feedback control seems to change little with development. Kirshenbaum, Riach, and Starkes (2001) also stress the non-linearity in aspects of children's postural development. With longitudinal data, the authors showed that children initially did not relax stability limits, and that they then entered a period of exploration, relaxing the tight restrictions. Coordination of control is therefore discovered by experimentation. That is,

> "to learn and improve skill, one must be constantly testing the limits to discover which available strategy works at any given time." (p. 429)

Shumway-Cook and Woollacott (1985) investigated the role of inter-sensory conflict for the development of postural control. According to the authors, the balance system depends on visual, vestibular, and support surface-somatosensory inputs. Whereas adults resolve inter-sensory conflict by suppressing inputs not congruent with the vestibular reference, children can sway and fall due to misleading visual information. Their system still relies heavily on visual-vestibular inputs in the control of posture, possibly because the information from ankles and feet (somatosensory input) has not been calibrated and fine-tuned yet. With development, somatosensory input increases in importance, and mature postural control (including the ability to resolve inter-sensory conflict) can be observed by the age of 7 to 10. Accordingly, Wolff, Rose, Jones, Bloch, Oehlert, and Gamble (1998) report that the performance on different balance measures improves when the tasks are performed with eyes open versus eyes closed. Studying children's performance on a moving platform, Woollacott and Shumway-Cook (1990) measured increases in neuromuscular response organization with age and experience. Younger children often reacted slower and more variable, and they showed more antagonist muscle coactivation and larger sway amplitudes. Peeters, Breslau, Mol, and Caberg (1984) found that body weight and height have no direct influence on the computed parameters when age is controlled for.

Taken together, children's improvements in balance performance with increasing age are probably caused by their increased sophistication in the use of different balance strategies. With advancing age, information from different sources can be integrated more easily. Maturational changes and increased experience with the tasks and the constraints of their bodies both contribute to children's performance gains.

After having described the development of basic capacities that underlie task performances of the current study, the following section presents theories on resource allocation processes in dual-task situations.

2.2 Cognitive Theories on Resource Allocation

What happens when people have to perform two tasks simultaneously? Why should such a situation be problematic at all? In the history of dual-task research, many of the dual-task situations required that participants performed two cognitive tasks simultaneously, for example an auditory matching task and a reaction-time task (e.g., Birch, 1978). However, one of the tasks could also involve a sensorimotor component, like maximum speed finger tapping. Many studies referred to one of the tasks as the primary task, and to the other task as the secondary task. In a dual-task situation, participants were then instructed to perform the primary task at a pre-specified performance level while concurrently performing the secondary task (Guttentag, 1989a). Performance decrements on the secondary task were presumed to index the resource demands of primary-task performance. In his overview article on age differences in dual-task performance, Guttentag (1989a) points out that this logic allows for individual differences in resource demands even if there are no differences in primary task performance under single-task conditions. However, some of the more recent studies on dual-task performance (K.Z.H. Li, Lindenberger, Freund, & Baltes, 2001; Lindenberger, Marsiske, & Baltes, 2000) do not distinguish between primary and secondary task, but instruct participants to keep the performance level of both tasks as high as possible.

The concept of *resources* is often used to explain dual-task performance decrements. Wickens (1991) mentions the underlying assumption that

> "…the human operator has a limited capacity for processing resources that may be allocated to task performance. Two tasks demand more resources than one, therefore, timesharing can lead to a situation in which one or both have fewer resources than required, and hence, performance on one or both may deteriorate (…). As we try harder at a task, we invest more mental effort into its

> performance, and performance will often, though not invariably, improve. In this sense, resources are the mental effort that is invested to improve performance." (p. 4)

In the literature, resources are nor a uniformly defined concept. In Guttentag's (1989a) overview article, resources are defined as general information processing abilities, for example cognitive speed, working memory capacity, or attention span. This definition takes into consideration that the dual-task studies cited in the article always included at least one cognitive task. Wickens (1984, 1991) defines resources as physiologically-based energetics systems, and argues that they can be operationalized as physically identifiable factors like pupil dilation and changes in the blood flow to different areas of the brain. Furthermore, Wickens (1984) points out that there is considerable conceptual overlap with other concepts like capacity, attention, and effort. Navon (1984) defines resources as "any internal input essential for processing (…) that is available in quantities that are limited at any point in time." This definition explicitly allows for a pool of different processing resources instead of a unique, general purpose unit or structure (Kahneman, 1973).

In their often-cited 1979 article, Navon and Gopher suggest multiple resources instead of one single resource. They describe the human system as rather complicated with many units, channels, and facilities, each with its own capacity. Multiple, somewhat independent resource pools are proposed, which could be a function of (a) different modalities of stimulus input (visual vs. auditory), (b) processes operating on different internal representation codes (e.g., visual vs. verbal), (c) different response modes (manual vs. verbal), and (d) processing in different cerebral hemispheres (Friedman, Polson, Dafoe, & Gaskill, 1982; Hiscock & Kinsbourne, 1978; see also Wickens, 1984). Therefore, some resources can be used by both tasks, or by just one of them, and there can be limitations in the trade-off between certain tasks. Under that assumption, the choice of tasks is crucial in determining the degree of overlap in the need of specific resources.

The resource concept has been criticized fundamentally by Brainerd and Reyna (1989). The authors refer to studies on children's memory development and dual-task costs, arguing that various assumptions that underlie a resource model are not met. In some of these studies, age-invariance in memory and age-reductions in dual-task deficits are found, while others report age improvements in memory and invariance in dual-task deficits. Brainerd and Reyna suggest that *output-interference* is the driving force underlying these data patterns. They argue that in dual-task situations with memory and finger tapping, fundamentally independent control processes are used for the two tasks. Only the output (noise, cross-talk) that is generated by these systems leads to dual-task interference. According to that account, the organization of internal activity is parallel, and only that of overt behavior is serial, leading to so-called output *bottlenecks*.

The position of Brainerd and Reyna (1989) has evoked criticism by various dual-task researchers (Bjorklund & Harnishfeger, 1989; Guttentag, 1989b; Howe & Rabinowitz, 1989). Chapman (1989) argues that it is not necessary to choose between the two models. Instead, the specific conditions under which one model is more appropriate than the other should be investigated.

Pashler (1994) proposed a different version of the bottleneck model, which does not refer to the outputs (or responses) of concurrent processes, but to a central bottleneck instead. For two tasks which both require manual reactions to different stimuli, Pashler reports data on the psychological refractory period effect. In the experimental settings used in his studies, a first stimulus precedes the second stimulus, and reaction times are recorded to each. Typically, the second reaction is slowed as the interval between the tasks is reduced. This indicates that the second response cannot be produced until a certain time after the first response. Pashler interprets this effect as evidence for a stubborn bottleneck encompassing the process of choosing actions and probably memory retrieval in general. He points out that other limitations associated with task preparation, sensory-perceptual processes, and timing can generate additional and distinct forms of interference. The central bottleneck seems to be a structural instead of a strategic phenomenon (Ruthruff, Pashler, & Klaassen, 2001).

The EPIC (Executive-Processes/ Interactive-Control) architecture suggested by Meyer and Kieras (1997a, 1997b) does not assume a response-selection bottleneck, but proposes a cognitive processor that can select responses and do other procedural operations simultaneously for multiple concurrent tasks. According to that model, interference occurring during the execution of two tasks is mainly due to sensorimotor constraints.

Taken together, there are two main theoretical accounts for interference in dual-task situations, the resource account and the bottleneck account. Proponents of both of these accounts have added further subdivisions to these basic models, for example by proposing the existence of a pool of separable resources instead of a unitary one (Navon & Gopher, 1979), or by placing the bottleneck at the level of central processing (Pashler, 1994) versus at the level of response output (Brainerd & Reyna, 1989).

2.2.1 Developmental Considerations Regarding Dual-Task Performance

Do the two main theoretical accounts on dual-task performance make any statement on developmental changes in the processes underlying dual-task performance? For the resource theory, Brainerd and Reyna discuss different scenarios in their 1989 article. One possible assumption is that the total supply of resources does not vary with age. What changes with development are the resource requirements of the tasks: Specific tasks need fewer resources in older than in younger children, and dual task interference decreases with age (Case, 1985). However, the resource account also offers the possibility that there might be multiple resources in the human processing system. Following this line of reasoning, it is conceivable that specialized resource stocks develop independently of each other. Brainerd and Reyna (1989) state that the empirical evidence for that assumption is quite strong. For example, there is data showing that children's ability to solve information-processing problems and their ability to maintain problem-relevant information in short-term memory are often stochastically independent from each other (Brainerd & Kingma, 1984, 1985), and that such abilities often follow independent developmental trajectories.

The output-interference account, on the other hand, explains developmental trends in dual-task performance with age changes in the susceptibility to such interference.[1] Neither the bottleneck model by Pashler (1995) nor the EPIC model by Meyer and Kieras (1997a) offer any reference to developmental changes in their underlying processes.

Empirical evidence. In an overview article, Guttentag (1989a) has summarized research on children and dual tasks. In many of the studies reviewed in the article, maximum speed finger tapping was used as the secondary task, and the primary tasks were distinct cognitive tasks like rhyme recitation (Hiscock & Kinsbourne, 1978), memory rehearsal (Guttentag, 1984), or transitive reasoning (Halford, Mayberry, & Bain, 1986). In most cases, the amount of secondary task interference declined with age. Older children tended to show superior performance on the primary task and lower dual-task costs on the secondary task. These age differences in dual-task costs have often been interpreted as reflecting age differences in the resource demands of the primary task. The older children get, the fewer of their mental resources have to be invested into a particular task. However, Guttentag (1989a) questions the assumption that the secondary-task costs provide a valid index of the resource demands of the primary task. He refers to the notion of multiple, independent resource pools

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[1] However, Brainerd and Reyna (1989) remain rather unspecific on that topic.

proposed by Navon and Gopher (1979) and to the output-interference model by Brainerd and Reyna (1979) to discuss alternative interpretations of the data.

The following section describes the influence of several aspects of the tasks on dual-task performance.

2.2.2 Task Parameters Influencing Dual-Task Performance

In a book chapter on common problems of dual-task methodology, Diane Damos (1991) gives an overview of different task parameters potentially influencing dual-task performance patterns. First of all, the *choice of task* is often crucial. However, the dual-task situations described by Damos usually consist of a combination of two cognitive tasks that have to be performed concurrently. In the study reported here, a cognitive task was combined with a sensorimotor task, and many of the constraints (e.g., increases in dual-task interference due to the usage of identical response modalities) are therefore irrelevant. In addition, it is important to be aware of the influence of *practice* (see also Fisk & Rogers, 1991; Lintern & Wickens, 1991). Dual-task performance should be assessed when participants have reached a stable performance level in the single-task condition. If that is not the case, practice effects can blur the results of the dual-task testing phase. Single- and dual-task practice do not always lead to the same performance improvements, and it is an empirical question which type of practice improves dual-task performance most efficiently for certain task combinations. Furthermore, the effect of *task feedback* should not be underestimated. Damos argues that participants in dual-task studies should receive feedback about their performance in each of the tasks after every trial. By instruction, they are either encouraged to keep the performance as high as possible in both tasks or to focus more strongly on one task than on the other. In any case, participants need the feedback to be able to adjust their performance according to instruction.

Wickens (1984, 1991) discusses the influence of *task difficulty* on dual-task performance. The topic of task difficulty is related to that of practice, because well-practiced tasks also become easier. Resource theories would assume that a more difficult task requires more resources than an easy one. Therefore, increasing the difficulty of one task should lead to more pronounced performance decrements in the dual-task situation if the two tasks share some (or all) processing resources. Systematic variation of task difficulty for the two component tasks in dual-task studies should therefore produce data patterns that either support or contradict the basic assumptions of resource theories.

According to a lifespan approach, children and old adults might differ from young adults in their patterns of resource investment into two distinct task domains. The model of selection, optimization, and compensation (SOC model; Baltes & Baltes, 1990) offers a framework for interpreting performance trade-offs and age differences therein in specific dual-task situations. I present the SOC model in the following section.

2.3 The Ecological Approach to Dual-Task Research: Implications Derived From the Selection, Optimization, and Compensation (SOC) Model

One basic assumption in lifespan psychology is that development in every stage of life includes gains and losses (Baltes, 1987; Baltes, Lindenberger, & Staudinger, 1998). In the case of cognitive development, for example, the developmental trajectory for many basic abilities follows an inverted U-shaped function over the lifespan, with increases in performance during childhood and decreases in performance during aging (e.g., S.-C. Li, Lindenberger, Hommel, Aschersleben, Prinz, & Baltes, 2004). Nevertheless, performance in specific domains of functioning can already decrease during childhood, for example when a task is not performed regularly any longer, and performance deteriorates as a consequence of lack of practice. A specific example would be the knowledge of Latin vocabulary in a 12-year old who has started taking Latin classes as a school subject at the age of 10. If that child decides to choose another language class (e.g., French) instead of Latin at the age of 12, and does not practice Latin vocabulary any longer, the knowledge of Latin words will have declined when the child reaches the age of 14, despite of an overall increase of basic cognitive abilities. On the other end of the lifespan, in old age, performance increases can be observed in specific abilities if older adults invest time and effort into a new task domain. Singer, Lindenberger and Baltes (2003) showed that old adults between 75 and 101 years of age could still improve their memory performance when being instructed in a memory technique, although memory performance in general is known to decline substantially in that age range, along with many other basic cognitive abilities (Bäckman, Small, Wahlin, & Larsson, 2000; Lindenberger & Baltes, 1997). These examples show that the level of performance in specific task domains or areas of functioning at any age depends on the investment of resources into that domain.

The model of selection, optimization, and compensation (SOC) proposed by Paul B. Baltes and Margret M. Baltes (1990) describes three fundamental processes that enable successful development and adaptation across the lifespan (Baltes, 1987; Freund & Baltes, 2000; Marsiske, Lang, Baltes, & Baltes, 1995). One underlying assumption is that individuals aim to maximize gains and minimize losses during ontogenetic development. The SOC model does not only describe how individuals manage to flexibly pursue their goals by successfully using their resources at a given point in time, but also how they can generate and develop new resources by the adaptive application of selection, optimization, and compensation processes.

Selection is the first of the three processes. It refers to the selection, elaboration, and commitment to a subset of possible alternative life-trajectories, goals, or functional domains. Since the pool of available options usually exceeds the internal and external resources that people have access to, the process of selection helps to narrow down the range of alternatives. It enables the individual to focus on specific domains of functioning and selectively invest into these chosen domains, instead of diffusing one's energy in many diverse areas. The process of selection can further be divided into the categories of elective selection and loss-based selection. *Elective selection* refers to situations in which many different options are available in principle, and the choice between them is not driven by losses. For example, the 14-year old teenager from the example mentioned above might be able to choose whether he or she wants to learn French, Spanish or Italian as a school subject. *Loss-based selection*, on the other hand, comes into play if the maintenance of a given level of functioning in a specific goal-domain is threatened. For example, a 70-year old long-distance runner might experience increasing problems with his knees while running, and he might therefore stop engaging in that sport.[2] Loss-based selection describes processes of focusing on the most important goal, of reconstructing the goal hierarchy, of adapting to modified standards, and of searching for new goals. It is therefore important for successful development in the face of decreasing resources, because resources that are freed by disengaging from one domain of functioning can be invested into alternative goals. It is especially useful when means for compensation are not available or would be too costly (Freund & Baltes, 2002).

The second process, *optimization*, refers to situations in which means are applied to achieve optimal functioning or desired outcomes, and resources are allocated and refined in order to reach a certain goal. For example, the teenager who has chosen to learn Spanish might invest a lot of his daily study time into this new subject, in order to profit as much as possible from the Spanish lessons at school, and to be able to have a conversation in Spanish during his next summer holiday. The research on expertise indicates that the acquisition of

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[2] Instead, he might decide to go swimming, because this sport does not harm the knees as much, and is not as physically demanding.

expert performance always requires a large amount of deliberate practice (Ericsson, Krampe, & Tesch-Römer, 1993; Krampe & Baltes, 2003), which is a form of resource investment.

The third process necessary for successful development according to the SOC model is *compensation*. This process is relevant in the management of loss, because it describes the substitution of means or use of alternative means to maintain a given level of functioning. For example, declines in sensory or sensorimotor systems in old age often lead to compensatory behaviors. The reduction of vision can be compensated for by using glasses, or the increasing instability of gait can be compensated for by using a walking stick. It is important to note that compensation refers to the means used to maintain a given level of functioning or to achieve a goal, whereas the process of selection refers to the selection of or disengagement from goals.

In the context of dual-task research, SOC processes can come into play if one considers the dual-task situation as a situation in which limited resources have to be invested into different task domains. The process of selection is considered to be especially important in this context, since it guides the resource investment into one or the other task domain. For example, if an older adult is confronted with a situation in which he has to cross a lively street while concurrently being engaged in a conversation, he or she might select the sensorimotor task of crossing the street and refrain from the conversation until the other side is reached. Similarly, a child confronted with the same situation might also select the task of crossing the street and stop talking for a while. This can be interpreted as an adaptive behavior, because there are dangers of not paying enough attention to the cars passing by, and neglecting this task domain might lead to severe consequences.

In this example, the selection is an example of loss-based selection, because keeping up the conversation while concurrently crossing the street would overtax the resources of an older adult or a child, and the two tasks cannot be performed concurrently without performance reductions. Selection processes might become especially relevant if the laboratory tasks mimic everyday situations, in which a sensorimotor task is often performed concurrently with a cognitive task (e.g., when walking to the subway while concurrently rehearsing the shopping list, or when standing on the subway train while concurrently reading the news on a flash screen). Furthermore, performance trade-offs occurring due to selection processes can only be detected if the dual-task performance patterns for both task domains are investigated and compared to each other. The manipulation of task difficulty, for example by adjusting task parameters individually, guarantees that each participant is challenged by the concurrent performance of the two tasks. Resource limitations come into play, and selection processes are increasingly likely to be measured.

If performance trade-offs are measured in a dual-task situation, an interesting question is whether people can influence these trade-off patterns deliberately. In other words, if instructed to focus more strongly on one task domain than on the other, can they shift their attention according to this instruction, and reverse the pattern of performance trade-offs, or do they continue to show the same pattern, with one task showing more pronounced performance decrements than the other task? Using differential-emphasis instructions in a dual-task situation therefore offers the possibility to empirically distinguish between the processes of loss-based and elective selection. If participants are able to shift their attention according to instruction, the trade-off pattern that has occurred under the "neutral" condition (when they are instructed to try to keep up the performance of both task domains as well as possible) is more likely to be caused by elective selection. However, if there is no shift in the trade-off pattern, it is probably caused by loss-based selection. Note that these selection processes do not have to be conscious, and participants might not be able to report them verbally, although their performance shows a clear trade-off pattern.

The ecological approach to dual-task research. In order to summarize the implications of the SOC model for dual-task studies, K.Z.H. Li, Krampe, and Bondar (in press) recently suggested an ecological approach to dual-task research, by taking considerations about the ecological validity of the tasks, the task difficulty, and participant's control over resource allocation into account. The ecological approach includes four methodological concerns that distinguish it from previous research, namely

> " (1) the use of laboratory tasks that mimic everyday processing demands in multi-tasking; (2) the comparison of coordination costs and their interrelation for all tasks involved; (3) a systematic variation of task difficulties that challenge individuals' potentials at an age-appropriate or individual level (adaptive testing, testing-the-limits approach); and (4) the use of manipulations that challenge participants' control over their resource allocation operations." (K.Z.H. Li, Krampe, & Bondar, *in press*)

The first concern is related to the notion of *ecological validity*. In the dual-task studies reported above, this consideration has usually not been taken into account (see K.Z.H. Li et al., 2001 and Lindenberger et al., 2000 for notable exceptions). Participants were often confronted with dual-task situations that were rather artificial and that do not occur in everyday life, for example when reciting animal names while concurrently tapping their fingers at maximum speed (Hiscock & Kinsbourne, 1978), or when working on a transitive reasoning task while concurrently performing a color recall task (Halford, Maybery, & Bain, 1986). The present study used a sensorimotor task that is relevant in everyday life, namely keeping an upright posture on a rather unstable surface. Similar sensorimotor behaviors might be necessary if one is standing on a bus or on a subway train. The dual-task phase of the study required that participants performed an additional cognitive task concurrently, which could either be a working memory task or an episodic memory task. This laboratory situation might be similar to an everyday situation in which a 9-year-old boy is standing on a moving bus while concurrently trying to learn a list of English vocabulary.

The second concern of the ecological approach argues that *dual-task performance patterns* should be observed *for every task* involved. This is an alternative to the approach of most dual-task studies reported by Guttentag (1989a), in which one task was considered the primary task, and the other task the secondary task. In the present study, however, participants were encouraged to try to keep up the performance of each of the two component tasks as well as possible.[3] Dual-task costs can therefore be calculated separately for the cognitive and for the balance domain. Like this, performance trade-offs can be detected, which occur if the performance of one of the tasks does not decrease as much as the performance of the other task.

The third methodological assumption refers to potential differences in *task difficulty* between different age groups or individuals. According to the resource framework, the difficulty of a given task influences how many resources have to be invested into its performance (Wickens, 1984, 1991). If a more difficult task is performed concurrently with another task, more pronounced performance decrements in the dual-task situation are expected as compared to an easier task. As a consequence, if a given task is more difficult for one age group than for the other, age differences in dual-task costs might mainly stem from these differences in single-task difficulty. The question whether age differences in dual-task performance are also influenced by age-specific differences in the coordination of two tasks cannot be answered in these cases. Therefore, the ecological approach argues that task difficulties of the component tasks should be tailored to each individual's performance, such that the tasks are equally demanding for all individuals in the single-task condition.

Two studies with children and dual tasks demonstrated the influence of difficulty manipulations on the dual-task performance patterns. A study by Birch (1978) used an auditory matching task (judging whether two words are from the same category or not) and a compensatory tracking task. Three different groups were studied: two groups of 8-year olds and one group of 13-year olds. In one of the 8-year old groups, each individual was paired with a member of the 13-year olds and trained to perform the single-task at the same performance level as the older participant. The other group of 8-year olds did not receive any

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[3] An exception was the last session of the study, in which participants were instructed to focus more strongly on one task domain than on the other.

training and showed poorer performance levels under single-task conditions. Under dual-task conditions, the 13-year olds and the trained 8-year olds showed no performance decrements, but the performance of the untrained 8-year olds was significantly reduced. If one assumes that the practice reduced task difficulty for the trained 8-year olds, and thereby eliminated age differences in dual-task decrements, it can be concluded that there are no age differences in the ability to time-share over and above the differences in baseline performance.

A study with second- and fifth-graders by Irwin-Chase and Burns (2000) used two target detection tasks. The authors controlled for individual differences in single-task performance by adjusting the task presentation parameters individually such that all participants performed at 80 % correct. They further used different task-emphasis instructions in the dual-task phase. After the manipulation of task difficulty, no age differences could be detected in dual-task performance when tasks were of equal priority.[4] The authors argue that changes in dual-task performance with age are due to changes in the ability to coordinate and control the allocation of attention. In the current study, participants were trained on the three tasks under single-task conditions. Following the training phase, task difficulty of the two cognitive tasks was adjusted by manipulating list length and inter-stimulus intervals individually.

In its' fourth point, the ecological approach suggests that participants should be challenged to exert *control over their resource allocation operations*. This can be done by instructing them to focus their attention more strongly on one task than on the other in a dual-task situation. Participants are able to flexibly allocate their resources only if the resulting pattern of dual-task performances reflects the different emphasis instructions. In the current study, a differential-emphasis instruction was implemented in the last session.

Several studies have been conducted to investigate the influence of SOC-processes on dual-task performances by following the recommendations of the ecological approach (Bondar, Krampe, & Baltes, in preparation; K.Z.H. Li et al., 2001; Lindenberger et al., 2000; Rapp, Krampe, & Baltes, in preparation; for an overview see also Krampe, Rapp, Bondar, & Baltes, 2003). These studies have always combined a sensorimotor task (either walking on a narrow track or maintaining balance) with a cognitive task (e.g., episodic memory, working memory, or reaction-time tasks). They are described in the next section, following some basic remarks on the interrelatedness of cognitive and sensorimotor functioning across the lifespan.

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[4] However, only fifth grade children could differentially allocate their attention when tasks were of different priorities.

2.3.1 Cognitive-Sensorimotor Dual-Task Situations

As stated by the ecological approach, the tasks used in dual-task studies should mimic everyday processing demands in multi-tasking (Krampe et al., 2003; K.Z.H. Li et al., in press). Many of the dual-task situations that occur in everyday life comprise a sensorimotor task and a cognitive task, for example when people are driving a car while concurrently listening to the radio, or when they are walking while concurrently being engaged in a conversation. Interference can occur if the amount of available processing resources is not sufficient to concurrently keep up the performance of both tasks. This assumption only holds, however, if the resources needed to perform the two tasks are identical, or if at least some of the required resources are needed for both tasks.

The ecological approach argues that sensorimotor functioning is also in need of cognitive resources, and that there are age differences in the amount of cognitive resources that have to be invested into successful sensorimotor performance. The next section reports theoretical assumptions on the interrelatedness of cognitive and sensorimotor functioning across the lifespan.

2.3.2 Interrelatedness of Cognitive and Sensorimotor Functioning

Many sensorimotor activities of everyday life seem to be rather automatic. For example, simply walking along a hiking path or going by bike does not seem to tax cognitive resources like attentional capacity very much. However, theses tasks can become more difficult if the environmental circumstances change. For example, if the ground somebody walks on is very icy and slippery, it makes sense to carefully watch out for where to step. Likewise, if the street somebody is riding his bicycle on is very busy and crowded with cars, paying attention to the traffic becomes adaptive and is necessary to protect oneself from accidents. Another factor possibly influencing the need of resource investment into the sensorimotor domain is experience with the task at hand or practice: For a child who has just started to learn how to ride a bicycle, paying attention to the activity enables skill acquisition and is an important aspect of the learning situation. Furthermore, changes in biological constraints of the body with aging can have an influence on how much attention is needed for sensorimotor functioning. With aging, visual acuity, flexibility of the joints, and muscle strength are often reduced (Anstey, Lord, & Williams, 1997; Clark, 1994), and these declines make the sensorimotor task more demanding. For example, if a person does not see precisely which parts of the grounds are icy and which are not, more attention has to be paid to watch out for where to step. In addition, the dangers of falling are more pronounced in older adults, with falls possibly leading to severe physical impairments (Fuller, 2000).

Theoretical assumptions exist in the literature for each of the factors mentioned above, namely for the influence of (a) task difficulty, (b) practice, and (c) age-related changes on the interplay of cognitive and sensorimotor functioning. Task difficulty has already been discussed above in relation to the resource framework. The underlying idea is that more resources have to be invested into a more difficult task, and fewer resources remain for the investment into the other task in a dual-task situation (Wickens, 1984, 1991). This assumption is not specific to cognitive-sensorimotor dual-task situations, but is relevant for any dual-task situation.

Concerning the influence of practice and task difficulty, there are studies with a specific concern for the automatization of sensorimotor skills with practice and the resulting influence on dual-task performance (Beilock, Carr, MacMahon, & Starkes, 2002; Beilock, Wierenga, & Carr, 2002). The literature on the acquisition of cognitive skills (Anderson, 1982, 1987; Shiffrin & Schneider, 1977) suggests that during learning, one has to invest more cognitive effort into a task until it is automatized and can be performed without conscious control. Beilock, Wierenga, and Carr (2002) argue that the acquisition of a complex sensorimotor skill (such as golf putting) also requires active memorial maintenance of skill knowledge, and that extensive attentional resources have to be invested into the successful implementation of a skill at these early stages of acquisition. With practice and higher levels of expertise, the skill becomes increasingly automatized, and attentional resources can be devoted to secondary task demands if necessary. Automatized performance is often described as being fast, smooth, error-free, resistant to interference, taking up little conscious attention, being achieved with little stress, and being integrated with other skills with little or no performance decrement (Fawcett & Nicolson, 1992, citing Norman, 1982).

This assumption was supported in a study in which novice and experienced golf players performed a putting-task under single-task and dual-task conditions (Beilock, Wierenga, & Carr, 2002). In the dual-task condition, participants had to perform the putting task along with a concurrent auditory word searching task. Experienced golfers did not differ in putting accuracy from single- to dual-task conditions, and they also showed higher word recognition than the novices. However, when using an arbitrarily weighted “funny putter” designed to disrupt the mechanisms of skill execution, experienced golfers showed decreased dual-task putting accuracy and recognition memory.

In another study with experienced golfers, Beilock, Carr, MacMahon, and Starkes (2002) showed that the golfers putted more accurately while concurrently performing an auditory shadowing task than when they directed their attention to step-by-step putting performance. A similar pattern was found in expert and novice soccer players: When using their dominant right foot, experts performed better in the dual-task situation. However, when using their less proficient left foot, the focus on skill execution actually helped the experts in their dribbling performance. Novices always performed better in the skill-focused condition, regardless of foot. The authors conclude that whereas novices and the less-proficient performances of experts benefit from online attentional monitoring of step-by-step performance, high-level skill execution is harmed.

A study by Passingham (1996) showed that the reduction of interference between a cognitive and a sensorimotor task with increasing levels of sensorimotor practice can also be demonstrated at a neurological level. In that study, participants were performing a motor sequence task and a verb generation task simultaneously. Measures of cerebral glucose metabolism were assessed with a PET procedure. It could be shown that new learning of a motor sequence activated the prefrontal and anterior cingulate cortex, and that the activation subsided if the motor sequence had been practiced for an hour. On the behavioral level, interference between the two tasks was much stronger in early motor learning. Passingham concluded that the interference occurs centrally in either prefrontal or anterior cingulated cortex.

Concerning *age-related changes* in the interplay of sensory and cognitive functioning, evidence for a stronger relationship between these two domains with age stems from the Berlin Aging Study, a large age-representative sample of older individuals aged 75 to 101 (Baltes, Mayer, Helmchen & Steinhagen-Thiessen, 1993; Lindenberger & Baltes, 1994). Intelligence was assessed with 14 tests measuring five cognitive abilities, namely speed, reasoning, memory, knowledge, and fluency. Sensory functioning was assessed with measures of visual and auditory acuity. Visual and auditory acuity accounted for a large proportion of the age-related variance in intelligence, suggesting that sensory functioning is a strong late-life predictor of individual differences in intellectual functioning. This relationship was a lot weaker in a sample of younger adults (aged 25-69 years; Baltes & Lindenberger, 1997). Furthermore, a measure of balance and gait also accounted for substantial amounts of variance in intellectual functioning, in about the same order of magnitude as vision or hearing. The authors suggest a *common cause hypothesis*, arguing that visual and sensory acuity are indicators of the physiological integrity of the aging brain. Balance and gait are interpreted as measures of sensorimotor bodily efficacy, which are also influenced by the physiological status of the brain. Lindenberger and Baltes (1994) argue that

> “decrements in sensory functioning may require the aging individuals to invest an increasing amount of cognitive resources (e.g., attention) into the ongoing coordination and compensatory management of sensorimotor behavior. As a result (…), the cognitive reserve capacity available for other cognitive activities (…) is reduced.” (p. 353)

Based on that assumption, Lindenberger and Lövdén (in press) recently introduced the concept of *human engineering technologies* (HET) for older adults. One function of these technologies is to counteract negative adult age changes in sensory/sensorimotor and cognitive domains. The authors argue that one central aim should be to reduce the cognitive demands of sensory/sensorimotor aspects of behavior, such that cognitive resources are released and can be invested into genuinely cognitive task requirements and activities. It should be assured that the cost associated with using the technology is lower than the gain achieved by using it (net resource release). Furthermore, HETs should be adapted to individual users (person specificity), and should be evaluated on multiple timescales and dimensions (proximal versus distal frames of evaluation).

But what about the relationship between cognitive and sensorimotor functioning at the other end of the lifespan, in childhood? Do children also face a situation in which they have to invest more of their cognitive resources into the sensorimotor domain? The assumptions about the acquisition of sensorimotor skills might be relevant in this age group. Young children have to learn a large variety of rather basic sensorimotor tasks when they are toddlers, like walking or maintaining an upright posture. At a later age, more culture-specific skills like riding a bicycle might come into play (Clark, 1994). However, skill acquisition might last for a longer time period during childhood, because children usually keep on improving their performance in diverse sensorimotor tasks until adolescence (see for example Figura, Cama, Capranica, Guidetti, & Pulejo, 1991, for the improvement of balancing abilities during childhood). Therefore, higher dual-task costs for children as compared to young adults would be expected, since their sensorimotor functioning still requires more cognitive resources, which cannot be concurrently devoted to the cognitive task.

Boudreau and Bushnell (2000) conducted a study with 9- to 10-month old infants who were learning goal-directed behaviors like reaching for a toy that was covered. The data showed that when mental processing resources were directed to thinking about movement, cognitive performance became compromised, and conversely, when processing resources were directed to thinking about the goal-state, the motor planning and execution became compromised. The authors interpret this pattern as an attention-driven cognition/action trade-off for infants' goal-directed actions.

Esther Thelen has proposed a theory on the development of motor skills in childhood, in which both motor development and cognitive development are considered. In several publications (1993, 1995, 2000), Thelen points out that developmental change arises within a context as the product of multiple, developing elements. It includes series of states of stability, instability, and phase shifts. Only after the stability of the system is disrupted, new configurations can emerge. These are then progressively tuned to become efficient, accurate, and smooth. Times of instability are therefore essential to give the system flexibility to select adaptive activities. Citing Bernstein (1967), Thelen argues that there is initially a great flexibility of the motor system to meet the demands of the task. She argues that the biomechanical aspects of early movement should be considered more explicitly, because they constrain the range of each individual's possibilities. Variation and individual differences, for example in body dimensions, muscle qualities, and energy levels, strongly influence the developing system. In that sense, individuals must fit their own bodies to their own tasks. With development, solutions to common motor problems often converge across individuals, because the system settles on efficient solutions. Concerning the relationship of cognition and motor skill development, Thelen reports that these dimensions were initially expected to be unrelated. However, the tight linkage between movement and cognitive development was acknowledged later, for example by investigating the influence of crawling on changes in spatial cognition and emotional development. Through movement, proprioceptive and haptic senses are continuously receiving information. According to Thelen, movement can therefore be considered a form of perception, and it has an important influence on the development of cognition. However, Thelen does not explicitly state that the acquisition of motor skills also relies heavily on cognitive resources.

An alternative approach to the interrelatedness of cognitive and sensorimotor functioning in childhood is to refer to neuroanatomical evidence for structural interference. For aging, the common cause hypothesis (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994) assumes that the physiological integrity of the brain has an influence on the ability to perform two tasks concurrently. Following this line of reasoning, the development of different brain areas needed for cognitive and sensorimotor tasks is of interest.

In an overview article, Adele Diamond (2000) argued that there is a close interrelation of motor development and cognitive development during childhood, and that certain brain structures, like the cerebellum and the prefrontal cortex, are involved in both kinds of tasks.

These two brain structures both reach maturity late in development. Projections from one area to the other and cross-talk can be observed with neuroimaging data. The cerebellum might be recruited for the following aspects of cognitive performance: recognition of (temporal) patterns, error detection, comparison of intention and performance, grouping of response elements, prediction of the occurence of anticipated stimuli, and timing functions. Increasing mental effort, high task difficulty, and changing task conditions often lead to the additional recruitment of both brain areas. Although Diamond does not discuss this point directly, in the context of the present report it might be conceivable that children, in whom these brain structures are still developing, more often encounter situations in which they recruit both of these regions either for cognitive or for sensorimotor tasks. If a cognitive and a sensorimotor task have to be performed concurrently, this might lead to more interference in children than in young adults, because young adults might have a more modularized way of processing, and do not recruit additional brain regions except when the tasks are extremely difficult.

2.3.3 Performance Patterns in Cognitive-Sensorimotor Dual Tasks: Studies Within the Ecological Approach

Several studies with older adults have taken the concerns of the ecological approach into consideration. A study by Lindenberger, Marsiske, and Baltes (2000) used the sensorimotor task of walking on narrow tracks of either high complexity (aperiodic track) or low complexity (oval track). Participants were instructed to walk as fast and accurately as possible, by trying to avoid any missteps on the tracks. The cognitive task was an episodic memory task, for which participants were instructed in a mnemonic technique (Method of Loci; see also Section 2.1.1) to memorize word lists. Participants belonged to three different age groups: young adults (20-30 years), middle-aged adults (40-50 years), and older adults (60-70). Walking and episodic memory were assumed to possess high degrees of ecological validity, both being of central importance for older persons' everyday competence, and to undergo substantial decrements with advancing age. Furthermore, the tasks were rather demanding. Performance in the memory task under single-task conditions was trained until each participant reached a certain criterion level. Dual-task performance decrements were calculated in relation to each individual's single-task performance. Single-task performance in the memory task was assessed when people were sitting or standing, whereas dual-task performance was assessed while concurrently walking on the track. Over and above age differences in baseline performances, young adults showed fewer relative dual-task costs in memory than middle-aged and older adults. Furthermore, cognitive dual-task costs were higher on the more complex track. For walking speed, young adults again showed less pronounced performance decrements than middle-aged and older adults, and there was no effect of walking track complexity. Overall, dual-task costs increased with age in both domains. Relative to young adults, the effect size of the overall increase was 0.98 standard deviation units for middle-aged and 1.47 standard deviation units for old adults. The authors conclude that sensory and motor aspects of performance are increasingly in need of cognitive control and supervision with increasing age.

The current study focuses on indicators of selection processes in dual-task situations. In that respect it is interesting to investigate whether participants showed more pronounced dual-task costs in one task domain as opposed to the other (trade-off pattern) in the study by Lindenberger et al. (2000). This requires that the dual-task costs in memory are compared directly to the dual-task costs in walking speed under the same condition.[5] Dual-task costs of the two domains are depicted in Figure 1.

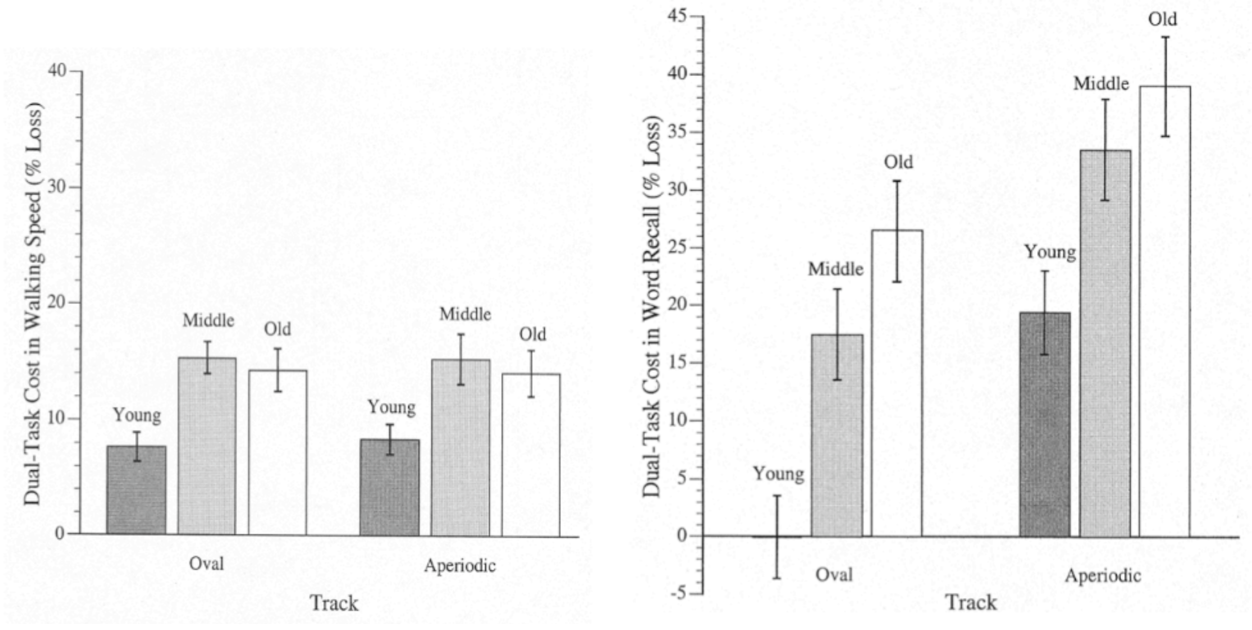

Figure 1. Age Differences in Task Prioritizing During Cognitive and Sensorimotor Performance (Lindenberger et al., 2000). The figures are adapted from Lindenberger et al. (2000). The left figure depicts the dual-task costs in walking speed, and the right figure depicts the dual-task costs in memory performance. Error bars depict standard errors of the mean.

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[5] To do so, one has to assume that the proportional dual-task metric (which expresses dual-task costs in relation to each individual's single-task performance) allows for comparisons across tasks domains. For example, a 10 % reduction in walking speed from single- to dual task has to be comparable to a 10 % reduction in word recall from single-to dual task. This assumption is open to debate.

For the less complex walking track, young adults showed a prioritization of the cognitive task, because they had virtually no dual-task costs in that domain, but reliable dual-task costs in walking speed. The middle-aged adults did not demonstrate any differences between walking and memory on the less complex track, and older adults showed a pattern of prioritization opposite to the young adults: They seemed to focus more strongly on the walking task, because their dual-task costs in word recall were higher than their costs in walking speed. Interestingly, when participants were walking on the more complex aperiodic track, all three age groups showed a prioritization of their walking performance, with smaller dual-task costs in walking speed than in memory. This pattern can be explained with processes of loss-based selection if one assumes that older adults have to focus their attention more strongly on walking in any dual-task situation, while middle-aged and younger adults still have enough resources available to optimize their memory performance. As soon as people have to conduct a more difficult sensorimotor task, namely walking on the complex track, all three age groups seem to prioritize the walking performance.

An additional study with walking and memorizing was conducted by K.Z.H. Li, Lindenberger, Freund, and Baltes (2001). Their aim was to investigate SOC-related processes more closely within the dual-task framework, again using walking on a narrow track as the sensorimotor task, and the strategic memorization of word lists (MOL) as the cognitive task. Participants were young (20-30 years) and older (60-75 years) adults, who were trained extensively in the two component tasks until they reached a pre-specified criterion. In some conditions, task difficulty was manipulated, by placing obstacles on the track for the walking task, or by reducing the presentation times for the to-be-remembered words in the cognitive task. Task difficulty was manipulated individually to assure that each subject had to invest a maximum amount of resources into single-task performance. In addition, there were conditions in which participants were allowed to use aids to improve their performance, either by using a handrail for the walking task, or by prolonging the presentation rate of memory stimuli.

Dual-task costs were found for both age groups. A central finding was that age differences in dual-task costs were greater in memory performance than in walking. Older adults had higher memory dual-task costs than young adults, but the walking dual-task costs of both groups were comparable. In addition, when the possibility of using the aids was given, older adults used the handrail more frequently and profited more from its use than young adults, whereas young adults used the memory aid more frequently than older adults. This pattern was interpreted as additional support for the assumption that sensorimotor tasks are increasingly in need of cognitive resources with advancing age (see also Lindenberger er al., 2000), and that older adults prioritize walking over memory, possibly because they would have to deal with severe consequences when neglecting the sensorimotor domain and risking a fall.

As reasoned above, one can also compare the dual-task costs of the two domains directly in order to find out whether trade-off patterns occurred. This would be the case if the dual-task costs in one domain are reliably larger than in the other domain. The resulting patterns of dual-task costs in the two domains are presented in Figure 2. The study by K.Z.H. Li et al. (2001) used a baseline condition for each task, but also manipulated task difficulty of walking and memorizing individually. As a result, four different conditions were used within the dual-task phase, namely a more difficult version of (1) the balance task, (2) the walking task, (3) both tasks, or (4) neither task.

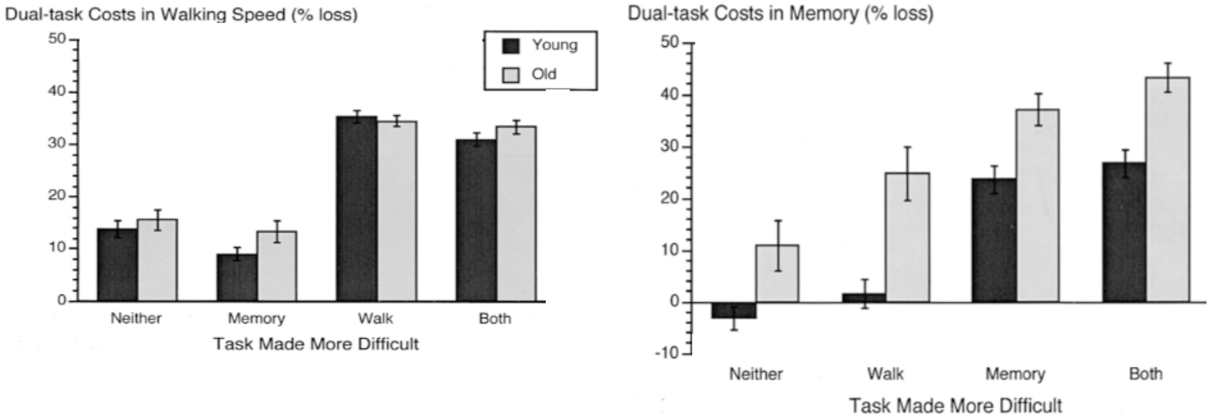

Figure 2. Age Differences in Task Prioritizing During Cognitive and Sensorimotor Performance (K.Z.H. Li et al., 2001). The figures are adapted from K.Z.H. Li et al. (2001). The left figure depicts the dual-task costs in walking speed, and the right figure depicts the dual-task costs in memory performance. Note that the order of task difficulties differs between the two figures. Error bars depict standard errors of the mean.

When no task was made more difficult, young adults had lower dual-task costs in memory than in walking, and there were no differences between the two domains in older adults. When memory was made more difficult, both age groups showed a prioritization of the walking domain, by having smaller dual-task costs in walking than in memorizing. When the walking task was made more difficult, young adults showed a clear trade-off in favor of the memory task. A similar, but less pronounced prioritization of memory was found in the older adults under that condition. Finally, when both tasks were made more difficult, young adults did not show any trade-off in their dual-task costs, while older adults had smaller dual-task costs in the walking domain as opposed to the memory domain. However, it cannot be claimed that all of these differences would have reached significance in statistical analyses.

Taken together, there is no evidence for systematic patterns of task trade-offs in that study. Depending on which task was made more difficult, different task domains seem to be prioritized, and age groups sometimes show the same and sometimes diverging patterns of task preference. However, over all conditions, older adults seemed to have a stronger tendency to focus on the sensorimotor task than young adults. Especially under the most challenging condition, when both tasks were made more difficult, older adults clearly prioritized the walking domain, presumably because they were operating at the limits of their performance in that condition.

Other cognitive-sensorimotor dual-task studies following the ecological approach did not always use walking as the sensorimotor task, but also tasks from the domain of postural control, like keeping an upright posture on a stable or moving platform, or stabilizing oneself after unexpected balance perturbations (Bondar, 2002; Rapp, 2002). Several authors (see Woollacott & Shumway-Cook, 2002, for a review) have pointed out that posture control becomes increasingly difficult in old age, and that there is an increase of cognitive involvement in posture control with advancing age (Brown, Sleik, Polych, & Gage, 2002; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997). Dual-task paradigms have been used to demonstrate that this is especially relevant when the attentional load of the concurrent task is high.

Bondar, Krampe, and Baltes (2003) investigated age-related differences in the ability to adjust performances according to experimental instructions. In their study, young and older participants performed the sensorimotor task of maintaining stability on a force plate despite unpredictable platform perturbations of different degrees. Large or small perturbations were used as a difficulty manipulation. Postural stability was expressed in terms of center-of-pressure movements over time (COP areas). The cognitive task was either a one- or a two-choice response time task, which required manual responses to acoustic stimuli. The one-choice version was considered to be easier than the two-choice version of the task. In the dual-task situation, participants were either instructed to focus primarily on balance, or on cognition, or to perform both tasks equally well. Dual-task costs were greater in the cognitive than in the balance domain, and older adults showed higher dual-task costs than young adults. Young adults could keep up their performance level in the balance domain even under dual-task conditions, whereas older participants did show significant performance reductions in the balance task. Both age groups were able to follow the task-priority instructions, although they were more successful in following instructions in the easy as compared to the difficult task conditions. Successful performance variation according to instruction was more obvious in the cognitive domain, with reaction times varying smoothly according to instructions. The balance performance of older adults remained stable under all instructional conditions. This pattern of findings was taken as an indication

> "that there is an age-related deficit in concurrent performance of a sensorimotor and a cognitive task (…) and that there is a domain-specific asymmetry in resource allocation. That is, individuals invest more resources into the sensorimotor than into the cognitive domain. (…) Age-related resource limitations and the ecological relevance of sensorimotor tasks force older adults to prioritize postural control at the expense of cognitive performance. By contrast, young adults were able to sacrifice the low-priority sensorimotor performance in order to optimize the high-priority cognitive task when instructed to do so." (K.Z.H. Li, Krampe, & Bondar, *in press*).

The ecological approach has also been applied to populations of older individuals with pathological cognitive decline. A study by Rapp, Krampe, and Baltes (in preparation) compared the dual-task performance of younger adults, healthy older adults, individuals with early Alzheimer's dementia (AD), and older adults with low scores on a test of cognitive speed. Participants performed a working memory task (N-back; see Section 2.1.2) either while standing on a stable platform or under conditions of continuous platform movements. When the two tasks were performed concurrently under the easy condition of the balance task (stable platform), older adults showed higher dual-task costs in both cognition and balance compared to younger adults. Balance dual-task costs on the stable platform were further exaggerated in the Alzheimer's patients, who swayed almost twice as much as in the single-task condition. On the moving platform under single-task conditions, sway increased in all age groups, and this effect was most pronounced in the AD patients. However, concerning the dual-task situation, older adults and especially AD patients showed surprisingly low costs in balance, in combination with increased costs in cognition. Young adults, on the other hand, showed increased dual-task costs in the balance task compared to the stable platform condition. Importantly, all older adults maintained a high level of functioning while balancing on the moving platform at the cost of cognitive performance. The authors concluded from this pattern that the priorization skill typical of older adults remains effective even in AD patients.

The following section presents research on cognitive-sensorimotor dual tasks in children as compared to young adults.

2.3.4 Cognitive-Sensorimotor Dual Tasks in Children and Young Adults

Huang and Mercer (2001) published an overview article comparing different dual-task studies with cognitive and motor tasks in adults and children, primarily focusing on studies with gait or postural stability as sensorimotor tasks. The purpose of several of these studies was to investigate the attentional demands of motor tasks or the effects of concurrent tasks on motor performance. Most of the studies have used the primary and secondary task paradigm. The underlying assumption is that the central processing capacity is limited and has to be divided between the two tasks. Huang and Mercer point out that the performance patterns depend on a number of factors, like for example performer's age, level of skill, and the nature of the tasks involved, and that even highly-practiced activities like walking or postural control are attention-demanding.

Studies with young and older adults have shown that the attentional demands increase as the balance requirements of a task increase (Lajoie, Teasdale, & Bard, 1993; Maylor & Wing, 1996; Shumway-Cook & Woollacott, 2000; Shumway-Cook, Woollacott, Kerns, & Baldwin,1997). In children, improvements in the ability to coordinate a cognitive and a motor task might be due to greater cognitive resources and more efficient allocation of these resources in older children, or improvements with age in their abilities to use cognitive strategies (Bjorklund & Harnishfeger, 1987; Guttentag, 1984; Manis, Keating, & Morrison, 1980; Kee & Davies, 1988).

Several studies have used maximum speed finger tapping to investigate the "functional distance" principle of cerebral organization, stating that the amount of interference between two incongruous activities varies inversely with the functional distance between their respective cerebral control centers (Hiscock, 1982, Hiscock & Kinsbourne, 1978, Hiscock, Kinsbourne, Samuels, & Krause, 1885, 1887). A central finding was that speaking produces greater interference with right-hand finger tapping than with left-hand finger tapping in right-handed children, and the degree of asymmetry remained constant across the age range of three to 12 years.

More complex motor task have been used by Whitall (1991). She investigated the influence of concurrent cognitive tasks on two locomotor skills, running and galloping. The cognitive tasks were singing or memorizing letter strings. Subjects were females ranging from three to ten and from 18 to 34 years of age. For the motor task, Whitall distinguishes between coordination variables defining the movement's pattern (like for example temporal phasing), and control variables specifying the overall parameters of the movement (like for example its velocity or the step length). The results indicated that coordination variables were unaffected by the addition of a cognitive task regardless of the subject's age, whereas the control variables such as step length decreased, and they decreased more strongly for the younger than for the older participants. Letter memorization caused greater effects on the locomotor skills than singing, and the effect was greater in running than in galloping for the younger age group. Concerning the cognitive tasks, no performance decrement was observed for the letter memorization, for which the length of the to-be-remembered letter strings varied according to age group by design. For the singing task, the song took longer to sing during the gallop than the run, and this effect did not interact with age group. Whitall concludes that the interlimb coordination variables are operating at an automatized level, with the phasing pattern in place at an very early age, and that only certain locomotor performance variables, such as gait speed, step length, and step time, become more automated and such less attention-demanding with additional practice.

Nicolson, Fawcett, and colleagues use dual-task situations with balance as a sensorimotor task in order to investigate the “Dyslexic Automatisation Deficit Hypothesis” (Fawcett & Nicolson, 1992, 1999; Fawcett, Nicolson, & Dean, 1996; Nicolson & Fawcett, 1990; Nicolson, Fawcett, Berry, Jenkins, Dean, & Brooks, 1999; but see also Raberger & Wimmer, 1999; Wimmer, Mayringer, & Raberger, 1999, for a critique of that approach). This hypothesis attributes the performance deficits of dyslexic children to an inability to become completely fluent in cognitive and motor skills. Following that line of reasoning, it is not only the skill of reading and writing that is compromised in these children, but also any other skills, like for example balancing. Nicolson and Fawcett argue that performance deficits in dyslexics do not have to be detectable in situations that are not very demanding. However, in a dual-task situation requiring the concurrent performance of a cognitive and a balance task, balance performance is expected to suffer disproportionately in dyslexic children, because their skill is not automatized and still requires attentional control.

The ecological approach and dual-task research in children. The studies presented by Huang and Mercer did not explicitly refer to the ecological approach as suggested by K.Z.H. Li and colleagues. However, the design of some of the studies takes the considerations of the ecological approach at least partly into account. For example, there are studies using balance (Fawcett & Nicolson, 1992; Shumway-Cook & Woollacott, 2000) or locomotion (Whitall, 1991) as sensorimotor tasks, and these are laboratory tasks that mimic everyday demands in multi-tasking. Furthermore, some studies have investigated dual-task decrements in both task domains (Fawcett & Nicolson, 1992; Whitall, 1991), instead of only considering one of the task domains as the primary task. However, performance decrements were only expressed in raw scores, and no standardization procedure was used in these studies (like for example the calculation of proportional dual-task costs), such that dual-task costs cannot be compared directly across task domains, and potential trade-off patterns are hard to detect. Some studies also varied the difficulty of the tasks by adjusting task parameters to individual performance or by providing additional training for bad performers (e.g., Fawcett & Nicolson, 1992), or by using tasks of different difficulty levels for different age groups (Whitall, 1991). This assured that the tasks were about equally demanding for all participants under single-task conditions. The last concern of the ecological approach, namely that participants should be encouraged to exert control over their resource allocation procedures, could be implemented by instructing them to focus more strongly on one task than on the other in a dual-task situation. In the studies presented above, this has not been done. In order to find out how the ecological approach can be implemented in cognitive-sensorimotor dual-task research with children and young adults, we conducted a first study in our lab at the Max Planck Institute for Human Development. This study is described in the following section.

2.3.5 Walking and Word Fluency: A Study Comparing Children and Young Adults

The basic assumption of the study was that children would show higher dual-task costs than young adults for a specific combination of a cognitive and a sensorimotor task (Krampe, Schäfer & Baltes, in preparation), because they were expected to invest more of their cognitive resources into the sensorimotor domain. We also wanted to investigate whether participants would show a trade-off pattern between the dual-task costs of the cognitive and the sensorimotor domain, and whether there would be age differences in such a pattern. To take the concerns of the ecological approach into account, we decided to use walking as the sensorimotor task. Locomotion is an important part of everyday behavior in children and young adults, and people often perform some concurrent cognitive task while walking in everyday life. Semantic word fluency, a task in which people are instructed to name as many items as possible for a given semantic category (e.g., “vegetables”), was the cognitive task of the study. By assessing a single-task performance baseline for each task, we were able to calculate dual-task costs for each task domain (walking and cognition) separately, and to compare the costs of the two domains directly. The third concern of the ecological approach states that task difficulties should be varied systematically to challenge each individual’s potential at an age-appropriate level. The design of the study took this concern only partly into account, by using different category difficulties for the age groups in the fluency task. We did not adjust these task difficulties individually, however, and we averaged the performance of different categories when calculating the dual-task costs. We were therefore not able to tell whether a particular category, which might be of medium difficulty for that age group on average, actually is of medium difficulty for a specific individual.[6] The walking task was identical for all age groups. We also did not use any differential-emphasis instructions in that study, and only instructed participants to try to keep up their walking and fluency performances as well as possible in the dual-task situation.

We tested 9-year-old children (*N* = 24), 11-year-old children (*N* = 24), and young adults aged 20 to 27 years (*N* = 24). The sensorimotor task was walking on a narrow oval track as quickly and accurately as possible (for details about the walking task and the properties of the track, see K.Z.H. Li et al., 2001, and Lindenberger et al., 2000.) The cognitive task was a semantic word fluency task, which required participants to name as many items as they could think of belonging to a certain category (e.g., „four-legged-animals“) for a fixed time period. Every trial (walking or fluency or their simultaneous performance under dual-task conditions) lasted 90 seconds. Walking performance was measured by the distance (in meters) covered within this time, and fluency performance by the number of correctly named items for the target category. We used 24 different categories for each age group, which could be split into easy, medium, and difficult categories according to the number of items that were generated on average for the category by the respective age groups. Items for the young adults were taken from a study by Mayr and Kliegl (2000), whereas children's categories were chosen from a sample tested with 24 9-year olds in a pilot study. Categories were counterbalanced across participants in a way that, within each age group, each category appeared equally often under single- and dual-task conditions, and that the different category difficulties were distributed equally across the single- and dual-task trials of the study. Participants attended two sessions. The first session consisted of three warm-up trials, one in the walking task, one in the fluency task, and one for walking and fluency simultaneously (dual-task condition). After two trials in each of the single tasks, four dual-task trials were conducted, followed by the second assessment of single-task performance with two additional trials for each task. The structure of the second session was identical to the first, except that an additional trial was added to each block, which resulted in six single-task and six dual-task trials for each task.

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[6] An adjustment of task difficulty for a fluency task would be rather problematic because the performance for a specific category mainly depends on personalized knowledge structures that have been acquired over a long period of time. This individual learning history is not directly accessible to the researcher.

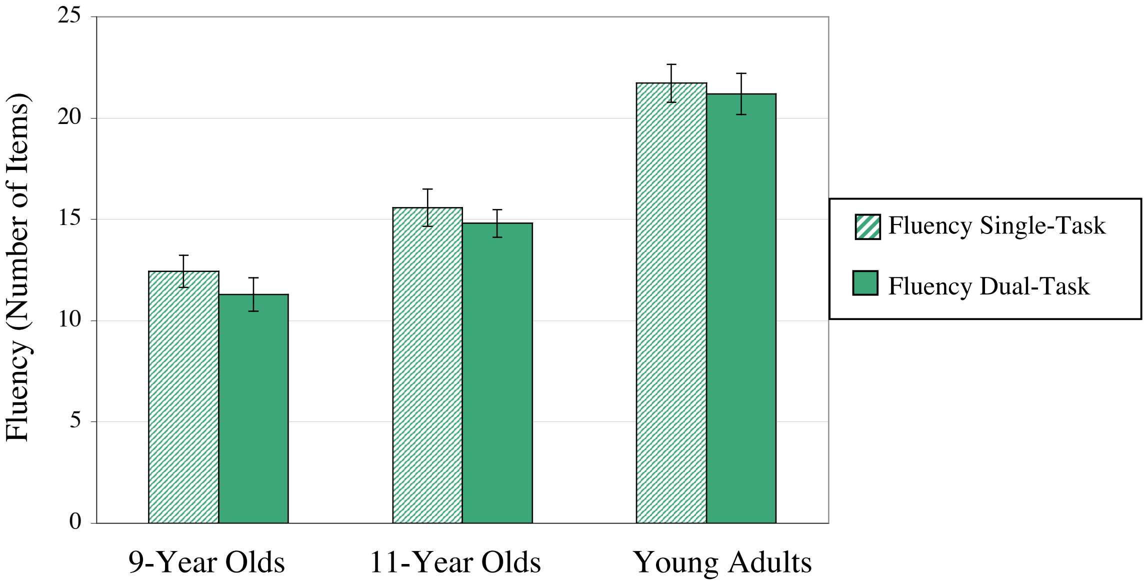

Figure 3. Children Name Fewer Items in the Fluency Task Than Young Adults Under Single- and Dual-Task Conditions

Note. Fluency performance is measured in correct items named within 90 seconds. Single-task performance is presented in the columns with the stripes and dual-task performance in the solid columns. Error bars depict standard errors of the mean.

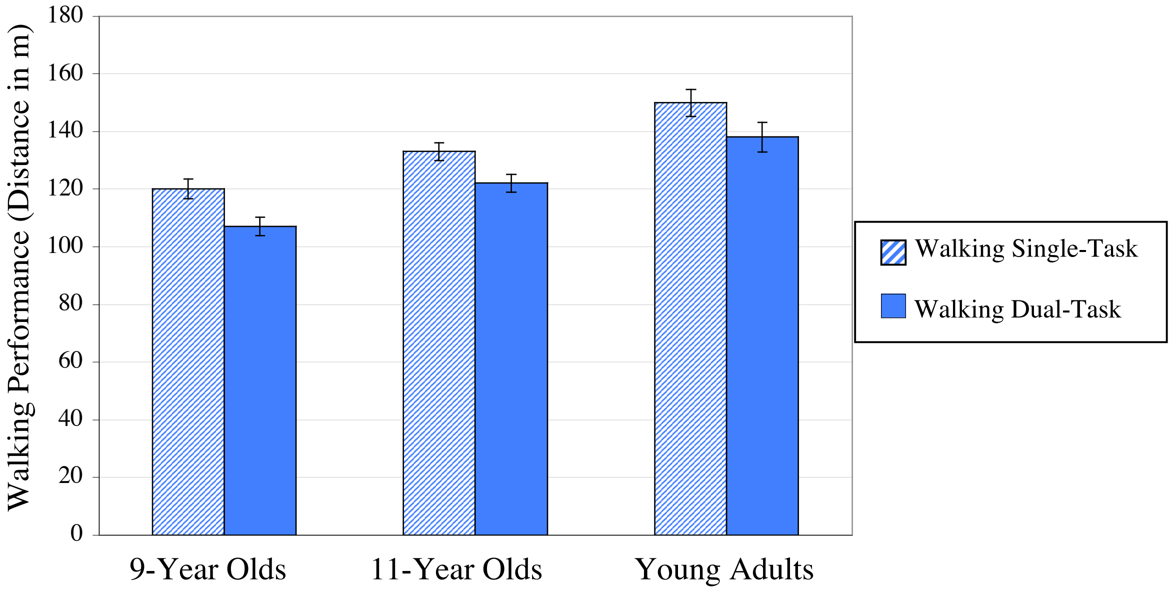

Figure 4. Children Do Not Walk As Far As Young Adults Under Single- and Dual-Task Conditions

Note. Walking performance is measured in distance walked in meters within 90 seconds. Single-task performance is presented in the columns with the stripes and dual-task performance in the solid columns. Error bars depict standard errors of the mean.

Performance was averaged across the two sessions. Figure 3 depicts the pattern of results for the raw data of the fluency task, and Figure 4 for the walking task. When only considering the single-task performance levels in the three age groups, age differences were detected in the performance levels of both tasks: 11-year olds walked faster and named more fluency items than 9-year olds, and young adults outperformed the two children's groups on both measures. However, dual-task research also investigates the difference in performance between single-and dual-task conditions within each age group. The difference between these conditions in the raw data can be interpreted as an absolute measure for dual-task costs. Figures 3 and 4 show that performance decreased for both tasks in all age groups. Participants named fewer fluency items when concurrently walking on the track (Figure 3), and they walked slower when concurrently naming fluency items (Figure 4).

An alternative way to look at dual-task costs is to use a proportional metric, by expressing the performance reduction under dual-task conditions in percentage of single-task performance, as suggested by Baddeley, Della Sala, Gray, Papagno, and Spinnler (1997). The resulting dual-task costs can then be compared across age groups and task domains, and the pattern for this study is depicted in Figure 5. For the 9-year olds, the performance reduction was comparably high in both task domains, with a reduction from single- to dual-task performance of about 10 % for the fluency and the walking task, respectively.

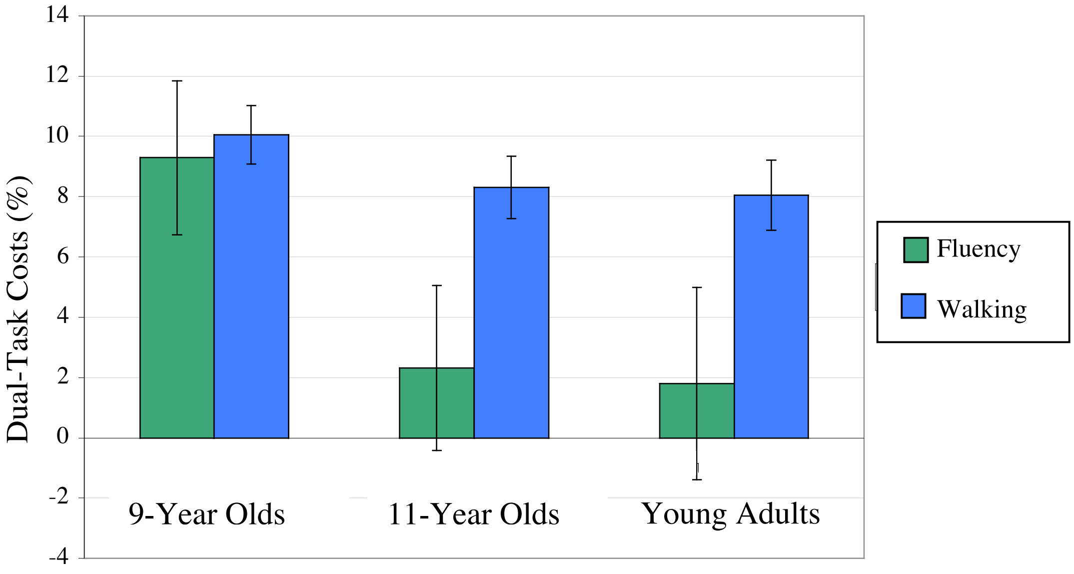

Figure 5. Age Differences in Dual-Task Costs in the „Walking and Fluency“ Study

Note. Dual-task costs have been calculated as percentage of performance decrement from each individual's single task performance. The figure depicts the average proportional dual-task cost for each task domain (fluency and walking) and each age group. Error bars depict standard errors of the mean.

The pattern for 11-year olds and young adults was remarkably similar, with both age groups showing more pronounced performance decrements in the walking domain (about 8 %) than in the fluency domain (about 2 %), where costs were statistically not distinguishable from zero. Therefore, when comparing the two task domains, it can be stated that 11-year olds and the young adults seemed to be able to keep up their fluency performance even under dual-task conditions, but they were not able to keep up their walking performance to the same extent. Nine-year-old children, on the other hand, showed dual-task costs in both tasks domains.

Taken together, the youngest age group showed the highest dual-task costs overall, while the older children and the young adults had lower overall levels of dual-task costs. This pattern might be caused by an increased need of cognitive resources for sensorimotor functioning in the youngest group, such that the two task domains interfere with each other more strongly. The assumption is that older children's walking performance does not require as many cognitive resources any more, and the overall dual-task costs become more adult-like.

Another central finding was that the older children and the young adults showed a *performance trade-off* for the two task domains, with smaller dual-task costs in the cognitive than in the walking domain, whereas the 9-year olds did not show a trade-off pattern. Within the SOC-model, the performance trade-off between the two domains can be interpreted as a *selection* process: Participants seemed to focus more strongly on the cognitive task of word fluency, because they were able to keep up their performance even under dual-task conditions, while performance in the walking task suffered. The 9-year olds did not show any trade-off in their dual-task costs, their costs being comparably high in both domains.

The trade-off pattern in this study obviously deviates from the pattern for older adults found in the study by K.Z.H. Li et al. (2001). In that study, older adults tended to focus more strongly on the walking domain as opposed to the memory domain. It was argued that such a performance pattern, namely investing more attentional resources into the sensorimotor domain and neglecting the cognitive domain, is adaptive for older adults, because avoiding falls is of high importance for that age group. The 11-year olds and the young adults of the study presented above also showed a trade-off pattern, but they focused more strongly on the cognitive domain. It is rather unlikely that this is due to loss-based selection, because these age groups do not have to deal with declining abilities and resources. Instead, it seems more likely to be an instance of elective selection, in which participants chose from a variety of options into which behavior they invest their resources. It is unlikely that older children and young adults are afraid of falls, although there might be individual differences concerning fear of falling within each age group.

The question remains, however, whether the trade-off pattern is the result of a conscious process of resource investment, such that 11-year olds and young adults deliberately chose the fluency domain as being more important and / or more interesting to them. If that was the case, participants should be able to "re-direct" their attentional resources to the alternative domain (in that case, walking) if instructed to do so. On the other hand, the selection process might also work at a pre-conscious level, and participants might not be able to deliberately influence these patterns. The 9-year olds were obviously most taxed by the dual-task situation, because they showed the highest overall dual-task performance decrements of the three age groups. However, it remains unclear why they did not show any trade-off pattern in their dual-task costs. Either they were not able to focus selectively on one task domain, or they would be able to do it in principle, but did not do so in the present study, in which no differential-emphasis instruction was used for the dual-task situation.

Another factor potentially explaining the age differences in overall dual-task costs might be *task difficulty*. The difficulty of the walking task has not been manipulated individually, and walking on the track might have been easier for older children and adults already under single-task conditions. Maybe their resources were not very taxed and could be invested into the concurrent cognitive task under dual-task conditions, thus reducing their overall dual-task costs. Nine-year olds might have been more challenged by the walking task, and fewer resources might have been available to be invested into the fluency task under dual-task conditions.

The difficulty of the semantic word fluency task might also differ across age groups. The task requires active search and retrieval from semantic memory (Mayr & Kliegl, 2000). Baddeley, Lewis, Eldridge, and Thomson (1984) point out that memory search seems to be largely automatic in adults. They report that keeping a concurrent digit load in memory did influence the rate of generating items from semantic categories, but not the accuracy with which people could perform the task.[7] It can be assumed that the retrieval process is more effortful for children than for young adults. One reason is that children do not seem to approach the task in a very strategic way yet. For example, ordering the category exemplars in subcategories and then systematically retrieving the exemplars from one subcategory before moving on to the next subcategory might be such a strategy, which is often referred to as

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[7] However, concurrent tasks during encoding did have a substantial detrimental effect on later memory recall in young adults (Anderson, 1999; Craik, Govoni, Naveh-Benjamin, & Anderson, 1996).

„clustering“ (e.g., when the target category is “nonalcoholic beverages”, first naming all teas, than all juices, and then all soft drinks one can think of). Such a strategy helps retrieving more items than a more “random” search of long-term memory, since the recall is highly organized (Fitzgerald, 1983; Gruenewald & Lockhead, 1980; Herrmann & Pearl, 1981; Troyer, 2000). It probably also decreases the executive control demands of constantly monitoring one’s output to avoid repetitions. Children do not use the clustering strategy spontaneously as often as young adults (Kobasigawa, 1974), thus making their retrieval more effortful. To detect possible clusters in recall and compare age differences in the frequency of clustering behavior in our sample, the time course of the responses in the fluency task would have to be investigated in more detail.

Another factor making the fluency task more difficult for children than for young adults is the organization of children’s knowledge structures. Assuming that knowledge is organized in semantic networks with associations of different strengths, a highly elaborated network with many connections increases the likelihood of retrieving individual items from memory. Children’s networks are not as elaborated yet, and therefore retrieval is more difficult and effortful (Bjorklund, 1987; Chi & Ceci, 1987). Although we tried to de-emphasis this factor by explicitly using categories children are familiar with (e.g., fairytales, games, school subjects, Pokemons), children already named fewer items than young adults in the single-task condition of the word fluency task. The fact that children improve their fluency performance with age can therefore be due to the increasing use of recall strategies such as clustering and to more highly elaborated knowledge structures with age. In addition, practice might have influenced the data pattern, because the two older age groups might have accumulated more practice in walking and retrieving items form long-term memory prior to their participation in the study. Therefore, extensive training of the two component tasks prior to the dual-task assessment maybe would have enabled the younger children to reduce their dual-task costs substantially.

The following section summarizes the implications of the above theories and empirical findings for the present study.

2.4 Summary and Implications for the Present Study

The theoretical background section first presented the childhood development of underlying capacities for the tasks used in the present study, namely episodic memory capacity, working memory capacity, and balance abilities. Children improve their performance in the two cognitive tasks with age (e.g., Schneider & Büttner, 2002; Hitch, Towse, & Hutton, 2001), either due to increases in their cognitive resources or due to an increase in the efficiency with which they use these resources (Case, 1985). They also improve their ability to keep an upright posture and stabilize their body's equilibrium (e.g., Figura et al., 1991).

As presented in Section 2.2, there are several theoretical assumptions on the underlying reasons for performance decrements in dual-task situations. According to the resource account, two concurrent tasks compete for the same resources. These resources can either stem from a general unit or structure (Kahneman, 1973), or from a pool of independent resources (Navon & Gopher, 1979). The output-interference or bottleneck accounts (e.g., Brainerd & Reyna, 1989) claim that it is rather the interference of the output of specific processing stages of two concurrent tasks that leads to performance decrements in a dual-task situation. The choice of tasks is therefore crucial for the type of interference effects that can be expected in a dual-task situation (Damos, 1991). In the present study, the sensorimotor task of balancing was combined with a cognitive task, which could either be a working memory task (N-back) or an episodic memory task (MOL).

It is difficult to distinguish between the predictions that would stem from a resource or a bottleneck perspective for this specific combination of tasks. The definition of resources tends to be rather broad, comprising different basic cognitive capacities like working memory capacity or attention span (Guttentag, 1989) or even more generally referring to mental effort that is invested to improve performance on any task (Wickens, 1991). As long as one assumes that the balance task cannot be performed completely automatic and requires at least some attention or mental effort, the resource framework would predict that dual-task interference occurs when the balance task is combined with a demanding cognitive task. Within the bottleneck perspective, performance decrements in the dual-task situation are only expected if there are certain stages of processing in one of the tasks that interfere with the execution of processing stages of the other task. As a consequence, the timing of dual-task performance is very important in that line of research. In the current study design, task performances in the three component tasks were not measured in a very precise online fashion, except for the balance task. Since dual-task costs were calculated on the bases of aggregated trials, it was not possible to investigate whether dual-task interference only occurs at specific processing stages within a trial, and whether a resource account or a bottleneck account describe the underlying dual-task processes more accurately.

According to a lifespan approach, children and old adults might differ from young adults in their patterns of resource investment into two distinct task domains. The model of selection, optimization, and compensation (SOC model; Baltes & Baltes, 1990) offers a framework for interpreting performance trade-offs and age differences therein in specific dual-task situations. Section 2.3.2 reports findings on the close interrelatedness of cognitive and sensorimotor functioning in childhood, indicating that children – just like older adults in previous studies (e.g., K.Z.H. Li et al., 2001) – have to invest more of their cognitive resources into the domain of sensorimotor functioning. The ecological approach to dual-task research (K.Z.H. Li, Krampe, & Bondar, in press) is introduced, which argues that studies on dual-task situations should mimic everyday processing demands in multi-tasking, and that dual-task costs should be calculated for each task domain under investigation, such that possible performance trade-offs can be detected. Furthermore, the authors point out that dual-task situations should challenge participants at an individual level, and encourage them to exert control over their resource allocation processes.

Several studies with young and older adults that were conducted within the ecological approach are presented in Section 2.3.3 (Bondar et al., in preparation; K.Z.H. Li et al., 2001; Lindenberger et al., 2000; Rapp et al., in preparation). These studies have found different patterns of dual-task decrements for the sensorimotor tasks of walking on a narrow track as opposed to balancing. Walking on the track always led to dual-task costs, with people of all age groups walking more slowly when they had to perform a concurrent cognitive task (see also Section 2.3.5 for the same pattern in children). However, Bondar and colleagues (in preparation) did not always find performance reductions in the balance domain under dual-task conditions. Depending on the condition, performance sometimes remained stable from single- to dual-task conditions, even in old adults. Overall, the interference between a cognitive and a sensorimotor task often tended to be stronger in older than in younger adults, and older adults often showed a pattern of preferential resources allocation into the sensorimotor domain, possibly to prevent themselves from losing the body's equilibrium.

The theoretical background finally presents a study with 9- and 11-year old children and young adults using walking on a narrow track as a sensorimotor task and semantic word fluency as a cognitive task. Over and above age differences in task performance under single-task conditions, the youngest children showed the highest dual-task costs overall, with dual-task costs being comparably high in the two task domains, while 11-year olds and young adults had smaller dual-task costs overall and seemed to prioritize the cognitive domain.