Plasticity of Executive Control Induced by Process-Based Cognitive Training Across the Life-Span

DISSERTATION

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Abstract

Plasticity is a central concept within the life-span approach of development and is defined as the ability of an individual to change and reorganize in response to environmental challenges (e.g., P. B. Baltes & Singer, 2001). Such intraindividual changes can be induced by systematic cognitive training. Recent studies suggest that substantial amounts of plasticity can be induced in executive control functions with a process-based training approach. These newer studies showed that repeated practice on executive control tasks not only improved performance on these trained tasks, but also led to improvements in nontrained tasks (i.e., transfer; e.g., Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Karbach & Kray, 2009). Executive control processes are especially relevant from a developmental perspective because executive control is involved in a wide range of complex cognitive activities (e.g., van der Sluis, de Jong, & van der Leij, 2007) and is one of the most central areas of cognitive development (e.g., Craik & Bialystok, 2006).

The current thesis aimed at elucidating several important questions concerning the plasticity of executive control functions induced by systematic cognitive training. Firstly, the amount, range, and stability of plasticity in adolescents and older adults were investigated. Secondly, the studies explored if training design, age, and interindividual differences moderate the amount and range of plasticity. Furthermore, the current thesis aimed at exploring how process-based training specifically leads to transfer effects.

To explore these questions, all studies employed a pretest-posttest-design comparing a group of participants that was trained with a process-based training approach to a group of control participants that did not receive the training. Pretraining and posttraining sessions incorporated systematic assessment of transfer measures in different cognitive domains. The first study set out to investigate if executive control can be trained in adolescents with a task switching training. Additionally, the study explored what particular domains of executive control may underlie training and transfer effects, and if acute bouts of exercise directly prior to cognitive training enhance training effects. Analyses indicated substantial training effects for both training groups (with or without acute exercise) and near transfer to a similar switching task. Other findings of transfer were limited to a speed task and a tendency for faster reaction times in an updating task. Thus, findings indicate, for the first time, that executive control can be enhanced in adolescents through a short training. Furthermore, analyses suggest that updating may be of particular relevance for the effects of the task switching training. Analyses revealed no additional effects of the exercise intervention.

The second study set out to explore, for the first time, the effects of a process-based training approach in old-old age (above 80 years). After ten sessions of practice on working memory tasks, the training group improved in four of the five trained tasks, emphasizing the potential for plasticity even in old-old age. The gains in the training group were largely driven by individuals who started out with a low capacity in the training tasks. Thus, the findings suggest that working memory can be improved with a short executive control training even in old-old age, particularly for low-capacity individuals. The absence of transfer effects in this study may point to the limits of plasticity in this age group.

The third study aimed at further elucidating the mixed findings regarding the amounts of training and transfer effects induced by executive control training in older adults. For that purpose, a sample of older adults covering a wide range from young-old to old-old age (65 to 95 years) was either trained for nine sessions on a visuospatial and a verbal working memory as well as an executive control task; or served as controls. Analyses revealed significant training effects in all three trained tasks, as well as near transfer to verbal working memory and far transfer to a nonverbal reasoning task. Remarkably, all training effects and the transfer effect to verbal working memory were even stable at a nine-month follow-up. These findings suggest that cognitive plasticity is preserved over a large range of old age and that even a rather short training regimen can lead to (partly specific) training and transfer effects. However, analyses also revealed that there are a range of factors that may moderate the amount of plasticity, e.g., age and baseline performance in the training domain.

To summarize, the current thesis explored effects of short executive control trainings on cognitive functions in adolescents and older adults. The findings suggest a high potential for intraindividual variability across the whole life-span. Plasticity was shown on the level of training and transfer tasks, as well as on the level of stability of effects. Furthermore, the results support the notion that process-based training improves executive control processes that in turn lead to improvements in tasks that rely on these processes. The current thesis makes important contributions to the conceptual debate about the potentials and limits of training-induced plasticity across the life-span. It benefits the debate in that it specifically delineates factors that moderate the obtained effects.

1 General Introduction

According to life-span theory of development (see for an overview, P. B. Baltes, Lindenberger, & Staudinger, 2006), development is not restricted to the early years of our lives. Rather, changes (including both gains and losses) accompany each individual over the whole life-span. The ability of an organism to change and reorganize in response to environmental challenges has been termed plasticity (P. B. Baltes & Singer, 2001; Li, 2003). Plasticity is a central concept within the life-span approach of development because it encompasses the potential of an individual to learn through experience and change over a short period of time (P. B. Baltes et al., 2006).

One crucial area of developmental research comprises exploring the amount and the possible limits of plasticity across different age groups. These issues have explored within the life-span approach with a range of intervention studies. Until recently, research has focused on strategy-based interventions to improve episodic memory performance in individuals of different ages (e.g., P. B. Baltes & Kliegl, 1992; Singer, Lindenberger, & Baltes, 2003; Verhaeghen & Marcoen, 1996). In these studies, participants were taught mnemonic strategies on how to perform episodic memory tasks, e.g., the method of loci (P. B. Baltes & Kliegl, 1992; Verhaeghen & Marcoen, 1996). The studies found that, regardless of age, participants were able to improve their performance on trained tasks. That is, plasticity seems to be preserved across the whole life-span although the amount of plastic change was found to decrease with age (P. B. Baltes & Kliegl, 1992; Singer et al., 2003). In general, improvements were restricted to the trained tasks; hardly any improvements were found on other cognitive tasks that have not been trained (i.e., transfer; see, e.g., Lustig, Shah, Seidler, & Reuter-Lorenz, 2009; Noack, Lövdén, Schmiedek, & Lindenberger, 2009, for recent reviews).

Recently, the concept of plasticity has moved back into the focus of developmental psychology research. Instead of teaching strategies to improve memory functions, newer studies focused on executive control functions and used a process-based training approach. The process-based approach relies on repeated performance of executive control tasks with adaptive difficulty and feedback and tries to limit the use of strategies (see, e.g., Klingberg, 2010, for a review). These newer studies showed that repeated practice not only improved performance on these trained tasks, but also led to transfer, for example, even to tasks measuring fluid intelligence (see, e.g., Jaeggi et al., 2008; Karbach & Kray, 2009). This is especially relevant from a developmental perspective because executive control is involved in a wide range of complex cognitive activities (e.g., Engle, Tuholski, Laughlin, & Conway, 1999; van der Sluis et al., 2007) and is one of the most central areas of cognitive development (e.g., Cepeda, Kramer, & Gonzalez de Sather, 2001; Craik & Bialystok, 2006).

The recent promising findings of plasticity in executive control functions induced by systematic training served as a starting point for the current thesis. Within the growing body of research on process-based executive control training, several questions are currently under debate. What is the range of general benefit that can be achieved with such trainings in different age groups? Does the amount of plasticity induced by process-based trainings vary with age as is suggested by strategy-based training studies? Why do some studies find broad transfer effects while others suggest only limited transfer? Does it matter what particular domain of executive control is the target of the training? The present work aims at exploring these issues in further detail and shedding more light on the mixed findings in this developing field of research.

In the following section, the general concept of cognitive plasticity and previous research within the life-span approach of development will be presented in more detail (Section 1.1). The next section presents a conceptual overview about executive control functions (see Section 1.2), the domain of cognition that has been the target of most of the recent process-based training studies. Theses studies on process-based executive control training will be discussed in detail afterwards (Section 1.3) as they served as the primary starting point for the current work. Building upon this theoretical background, Chapter 2 outlines the aims and research questions of the empirical studies of the current thesis. The empirical studies themselves are presented in Chapters 3, 4, and 5. Closing the current work is Chapter 6 that summarizes and discusses the empirical results in the light of the research questions, considers their implications, and presents an outlook for future studies.

1.1 Plasticity of cognitive functions

Plasticity is the potential of an organism to change and reorganize in response to environmental challenges or demands (P. B. Baltes & Singer, 2001; Bialystok & Craik, 2006; Kliegel, Zinke, & Hering, in press; Li, 2003). A mismatch between individual functional capacity and environmental demands is a prerequisite for plasticity (Lövdén, Bäckman, Lindenberger, Schaefer, & Schmiedek, 2010). Plasticity can be described on neuronal and behavioral levels. Neuronal plasticity refers to the capacity of the nervous system to change and reorganize cortical representations and networks, whereas behavioral plasticity signifies the same on the level of behavior, e.g., memory and learning (P. B. Baltes & Singer, 2001). Animal studies have provided evidence that neuronal plasticity is not restricted to early brain development. Even the adult brain is able to display surprisingly plastic changes, e.g., by neurogenesis, synaptogenesis and angiogenesis, in response to environmental ”enrichment” (as has been demonstrated in animal studies, Kempermann, 2006, 2008; Nithianantharajah & Hannan, 2006; van Praag, Kempermann, & Gage, 2000). In humans, ”enrichment” can be cognitively challenging activities or systematic cognitive training (Hertzog, Kramer, Wilson, & Lindenberger, 2009). Plasticity after such cognitive interventions would be evidenced on the level of behavior (increased performance in trained tasks and possibly generalization to a larger range of nontrained tasks) and on the neuronal level (structural and functional changes).

Plasticity of cognitive functions has been explored in psychology with different intervention studies employing systematic training approaches. These intervention studies provide the opportunity to explore the amount of plasticity in different domains of cognitive functioning and possible age-related differences in plasticity (Hertzog et al., 2009; Lindenberger & Baltes, 1995). An early, prominent example of this interventional research is the testing-the-limits approach by Baltes, Kliegl and colleagues (P. B. Baltes & Kliegl, 1992; Kliegl, Smith, & Baltes, 1989; Lindenberger & Baltes, 1995). Participants of these studies are extensively trained on certain cognitive tasks until they show no further improvement (Kliegl et al., 1989; Lindenberger & Baltes, 1995). This allows to estimate the latent potential of the individual in the trained domain, that is, the maximum range of plasticity. Teaching younger and older adults a mnemonic strategy using the testing-the-limits approach revealed that older adults were able to increase their memory performance, however their latent potential was significantly smaller than the respective potential in younger adults (e.g., P. B. Baltes & Kliegl, 1992).

These and other studies show that humans maintain their ability to show substantial changes in response to environmental influences from childhood into old adulthood (P. B. Baltes & Singer, 2001; Boyke, Driemeyer, Gaser, Büchel, & May, 2008; Li, 2003). Plasticity is preserved in healthy older adults (Mahncke et al., 2006). Remarkably, even in old-old adults, substantial and relatively stable changes are found (Yang, Krampe, & Baltes, 2006; Yang & Krampe, 2009). Yet in this line of research on strategy-based interventions, the amount of training-induced plasticity was found to depend on the targeted age group. Despite impressive amounts of plasticity even in older adults, the potential for plasticity was found to be generally larger in children, adolescents, and younger adults compared to older adults (P. B. Baltes & Kliegl, 1992; Brehmer et al., 2008; Kliegl et al., 1989). That is, the ability to profit from strategy-based interventions seems to be greatly reduced in older adults (P. B. Baltes & Singer, 2001; Singer et al., 2003; Verhaeghen, Marcoen, & Goossens, 1992).

According to life-span theories of development, plasticity is a crucial aspect of lifelong development because it encompasses the adaptive potential of an individual to learn through experience (P. B. Baltes et al., 2006; Willis & Schaie, 2009). Studying the trainability of cognitive functions as one aspect of plasticity may further elucidate potentials and limits of learning across the life span (P. B. Baltes & Singer, 2001; Dahlin, Nyberg, Bäckman, & Stigsdotter Neely, 2008). Recently, a new training approach has moved the concept of plasticity back into the focus of developmental research. The process-based approach of training executive control seems to be very promising with regard to the amount and range of plasticity that can be achieved across the life-span. Therefore, the next section will delineate the relevance of executive control functions as central processing resources and crucial areas of development across the life-span. The section that follows gives an overview about the existing studies on the training-induced plasticity of executive control. The discussion of the state of the field of research and the open issues arising from this discussion serve as the starting point of the current work.

1.2 Executive control functions

It has been suggested that two broad factors account for intelligent thought and behavior: accumulated knowledge (also termed crystallized ability) and the ability to use that knowledge flexibly (also termed general fluid ability, see, e.g., Cattell, 1971; Craik & Bialystok, 2006; Horn & Cattell, 1966). One of the most central fluid abilities is executive control (Craik & Bialystok, 2006). Executive control is the ability to plan, execute, monitor and regulate goal-directed behavior (Norman & Shallice, 1986; Miller & Cohen, 2001). Executive control processes are involved in a range of complex cognitive functions that require planning or maintaining multiple goals, like problem solving or reasoning (Baddeley, 2003; Engle et al., 1999; Kane et al., 2004; van der Sluis et al., 2007). Furthermore, executive control is strongly related to skills that are of everyday relevance over the whole life span. For example, in children and adolescents executive control abilities have been shown to predict language acquisition (Baddeley, 2003), reading and arithmetic skills (Daneman & Carpenter, 1980; van der Sluis et al., 2007), as well as classroom behavior and self-regulation (Riggs, Blair, & Greenberg, 2003; Diamond, Barnett, Thomas, & Munro, 2007). In children and adults, executive control has even been related to health outcomes (Dunn, 2010; Kusche, Cook, & Greenberg, 1993). Furthermore, it has been speculated that executive control functions may mediate some of the age-related decline in other cognitive functions, e.g., deficits in memory (Hasher & Zacks, 1988; Salthouse, Atkinson, & Berish, 2003; West, 1996).

According to a model by Miyake et al. (2000), that has been derived empirically using structural equation modeling, executive control consists of different distinguishable components: updating, inhibition, and shifting/switching. Updating describes the ability to monitor incoming information for task relevance, replacing older, no longer relevant information with newer information and maintaining these representations in working memory. Updating is needed, for example, when holding two ideas in mind at the same time or doing mental arithmetic. Deliberately suppressing dominant, automatic, or prepotent responses when necessary has been termed inhibition, for example when resisting to play with friends instead of doing home work or chores. The third component, switching, encompasses the ability to flexibly shift back and forth between multiple tasks or mental sets, for example switching between writing an e-mail and answering the phone. These three components have been established in studies with young (Miyake et al., 2000; Friedman et al., 2006) and older adults (Fisk & Sharp, 2004), as well as children and adolescents (Lehto, Juujärvi, Kooistra, & Pulkkinen, 2003, possibly with a somewhat weaker inhibition factor, see, e.g., Huizinga, Dolan, & van der Molen, 2006; van der Sluis et al., 2007), suggesting comparable organization of executive control across the life span.

Executive control functions show marked developmental trajectories that follow an inverted U-shaped function over the life span (e.g., Bedard et al., 2002; Cepeda et al., 2001; Craik & Bialystok, 2006). Studies have shown that even young preschool children are able to perform simple executive control tasks (Best & Miller, 2010; Davidson, Amso, Anderson, & Diamond, 2006). Performance improves in childhood and across adolescence for inhibition and switching tasks and even into young adulthood for updating tasks (Best & Miller, 2010; Luna, Garver, Urban, Lazar, & Sweeney, 2004; Huizinga et al., 2006). With advancing age, all components of executive control have been shown to be prone to decline (Bopp & Verhaeghen, 2005; Cepeda et al., 2001; Hasher & Zacks, 1988; Park et al., 2002; Reimers & Maylor, 2005). This decline is already evident in young-old adults (60-80 years), but is particularly pronounced, e.g., for updating, in old-old adults (over 80 years, Craik, 2000; Gilinsky & Judd, 1994; Hale et al., 2011).

These behavioral developmental trajectories are paralleled by age-related neural changes in the prefrontal cortex, a region that has been associated with executive control functions (Miller & Cohen, 2001). Prefrontal areas mature the latest in adolescence and young adulthood, both on a structural (gray and white matter volume changes, Giedd et al., 1999) and functional level (localization and connectivity, see, e.g., Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Luna, Padmanabhan, & O'Hearn, 2010). In older age, deterioration and atrophy of the brain primarily begins with the (pre)frontal regions and the degree of decline is larger in these areas, paralleling the finding that executive control functions are more susceptible to the effects of aging than other cognitive functions (Craik & Bialystok, 2006; Raz, 2000; West, 1996).

Considering the importance of executive control for general cognitive functioning, the question of possibly modifying developmental trajectories is relevant from both a developmental psychology and an applied perspective. On the one hand, intervention studies may be useful to explore mechanisms that underlie development of executive control functions. For this purpose, one may look at intraindividual changes induced by an executive control training in trained and nontrained functions (as has been suggested by Best & Miller, 2010). The potential for such plastic changes may differ across the life-span. From an application perspective, interventions can be aimed at supporting the developing executive control functions in childhood and adolescence. Furthermore, the possibility of attenuating, delaying or even reversing cognitive decline in old age may have important practical implications by improving older adults' ability to lead independent lives. This possible malleability (plasticity) of executive control has been a target of recent process-based training studies. Thus, the next section will provide an overview of the current state of research on executive control training and will delineate open issues in this field of research that are currently under debate and serve as the primary starting point for the empirical studies of the current thesis.

1.3 Cognitive training of executive control functions

There is a small, but growing body of promising research showing that executive control functions can be enhanced by systematic cognitive training with tasks requiring updating (Dahlin, Stigsdotter Neely, Larsson, Bäckman, & Nyberg, 2008; Dahlin, Nyberg, et al., 2008; Jaeggi et al., 2008), working memory (Holmes, Gathercole, & Dunning, 2009; Klingberg et al., 2005; Klingberg, 2010), task switching (Karbach & Kray, 2009), or dual task performance (Bherer et al., 2005; Liepelt, Strobach, Frensch, & Schubert, 2011). A typical cognitive training study includes one group that is trained with a certain training regimen and a control group. These groups are compared using a pre-posttest design, that is, performance on different cognitive tasks (trained and nontrained) is assessed in both groups before and after the training intervention. Substantial training benefits would constitute larger pre-posttest gains in the training group as compared to the control group.

A frequently cited example of an executive control training study is the one by Jaeggi et al. (2008) where young adults were trained on a task that required updating: a dual n-back task. In this task two series of stimuli were synchronously presented, one consisting of single visuospatial locations of a square, the other consisting of auditory presentation of single letters. The task was to decide for each stimulus if it was the same as the one n items back. The difficulty of the task (that is, the value of n) was continuously adapted to the performance of the individual participants. One group of participants was trained on the dual n-back task for 8, 12, 17, or 19 daily sessions, the control group of participants did not receive any training. Findings indicated significant performance gains in the trained task and, importantly, significantly larger pre-posttest gains in a nonverbal reasoning task (variants of the Raven Matrices, Raven, 1990) in the training group compared to the control group. That is, this study provides evidence for a transfer effect of an updating training to a reasoning task and the authors conclude that they were able to improve fluid intelligence with this type of training (Jaeggi et al., 2008; Sternberg, 2008, but see, e.g., Moody, 2009 for criticism on this conclusion). Furthermore, findings indicate that the amount of transfer gain depended on the amount of training sessions.

Another prominent example of an executive control training study - one of the few training studies that directly compared training effects between different age groups - involved 8 to 10-year old children, young adults (18 - 26 years), and older adults (62 - 77 years, Karbach & Kray, 2009). The study involved four training sessions (one per week). The participants of the training groups were trained to switch between two tasks within blocks; the participants of the control group performed these same tasks in separate blocks without switching between them. The training task involved two simple tasks with the same stimuli: deciding whether a picture shows a plane or a car, and deciding whether there are one or two vehicles on the picture. The control groups practiced each of the tasks alone, the training groups had to remember to switch from one task to the other on every second trial. Thus, the task switching training required the participants to maintain the predefined sequence of tasks, keep track of the tasks performed, and switch from one task set to the other at the right time. The trained participants showed significant improvements in performance on the switching task over the course of training, i.e., lower reaction time costs when switching from one task to the other. Training benefits were larger in children than adults. Furthermore, the study found significant transfer effects to a similar switching task (near transfer) and to other executive control tasks, like working memory, inhibition, and nonverbal reasoning tasks (far transfer), in all age groups. These impressive findings - achieving relatively broad transfer effects with a rather short training across age groups from the whole life-span - were a starting point for the first study of the current work (see Chapter 3). The task switching training of this study closely followed the one employed by Karbach and Kray (2009). A major aim of the first study was to explore if similar effects of a task switching training can also be achieved in a group of adolescents.

Both studies exemplify the process-based training approach and provide evidence that executive control training leads to training and transfer effects in different age groups. The next two sections will further delineate the state of the literature with regard to findings of transfer to nontrained situations and stability of training and transfer effects (see also Hertzog et al., 2009; Klingberg, 2010 for reviews on this issue). As will become clear, the findings and the range and stability of transfer effects are mixed and call for further investigation. Thus, the current empirical work was set up to systematically evaluate these issues (see Chapters 3 to 5).

1.3.1 Transfer effects of executive control trainings

Most of the process-based executive control training studies have included at least some measures of transfer in addition to their respective training tasks. In addition to training effects, most of these studies were able to show transfer effects to nontrained tasks within the respective trained domain (near transfer). For example, training on verbal and visuospatial working memory tasks transferred to nontrained simple and complex working memory span tasks (Holmes et al., 2009; Klingberg et al., 2005) and training on switching tasks transferred to other switching tasks (Karbach & Kray, 2009; Minear & Shah, 2008). Furthermore, some of these executive control training studies provide evidence for transfer to other executive control domains (far transfer), e.g., inhibition (Chein & Morrison, 2010; Karbach & Kray, 2009; Klingberg et al., 2005; Olesen, Westerberg, & Klingberg, 2004), and other cognitive functions, e.g., episodic memory (Brehmer et al., 2011; Richmond, Morrison, Chein, & Olson, 2011) or measures of nonverbal reasoning (Jaeggi et al., 2008; Jaeggi, Buschkuehl, Jonides, & Shah, 2011; Klingberg et al., 2005; Rueda, Rothbart, McCandliss, Saccomanno, & Posner, 2005). A few of these studies even suggest transfer to abilities of high everyday relevance, e.g., reading performance (Chein & Morrison, 2010; Loosli, Buschkuehl, Perrig, & Jaeggi, 2012). On a neural level, process-based working memory training has been shown to be associated with specific changes in brain activity (see for reviews Klingberg, 2010; Lustig et al., 2009). For example, working memory training has been found to lead to increases in brain activity related to working memory in the middle frontal gyrus and superior and inferior parietal cortices (Olesen et al., 2004), as well as changes in dopamine receptor density (McNab et al., 2009). These findings suggest substantial behavioral and neural plasticity induced by these cognitive trainings.

However, some studies suggest that transfer may be restricted to only the trained domain (e.g., Dowsett & Livesey, 2000; Holmes et al., 2010; Li et al., 2008; Strobach, Frensch, Soutschek, & Schubert, in press). For example, Li et al. (2008) showed transfer of an updating training only to those tasks that shared the updating aspect, not to tasks that required different executive control functions (see, e.g., Dahlin, Stigsdotter Neely, et al., 2008 for similar findings). That is, improvement seemed to be restricted to task-specific aspects of the updating tasks. Furthermore, recent findings by Strobach et al. (in press) suggest that training on dual tasks does not transfer to a switching task. It has been suggested that transfer is likely to occur if training and transfer task share common processes. For example, it has been demonstrated that transfer occurs if training and transfer tasks engage overlapping brain regions, that is, to the extent that the tasks engage the same processing components and neural networks (Dahlin, Stigsdotter Neely, et al., 2008). Furthermore, some studies suggest that transfer may be restricted in range and stability to particular age groups (e.g., Dahlin, Nyberg, et al., 2008; Li et al., 2008). Transfer effects were restricted to the young participants in the study by Dahlin, Nyberg, et al. (2008) and did not generalize to the older adults. Maintenance level of transfer effects in the study by Li et al. (2008) was lower for older than younger adults (see for further discussion of a possible influence of age on training benefits, Section 1.3.3.2).

Direct comparisons between studies are rather difficult because studies have used different training tasks (e.g., updating or task switching) as well as transfer tasks (e.g., some assess working memory span or nonverbal reasoning, some do not). Training regimen and assessment procedures differ tremendously with regard to duration and other design features (see for further detail Section 1.3.3.1). Additionally, studies report transfer to some of the tasks included but not to others or do not even report that additional transfer measures (with null results) had been included in the study. Thus, although some studies have reported substantial transfer effects, findings are inconsistent with regard to whether transfer can be obtained using an executive control training regimen.

Following up on this issue, a major aim of the current work was to delineate the amount and range of plasticity with a systematic and broad assessment of transfer after executive control trainings. As Klingberg (2010) pointed out, it is important for training studies to evaluate transfer on different levels. Following Klingberg's (2010) suggestions, the current studies aimed at exploring possible transfer on different levels: transfer within the same domain but to other stimuli and different response modes (near transfer) and transfer to other cognitive constructs (far transfer).

1.3.2 Maintenance of training and transfer effects of executive control trainings

In addition to investigating training and transfer effects immediately after training, it is conceptually important to explore whether these benefits will remain stable over time. Findings of maintenance effects would further support the notion that substantial plastic changes can be achieved via cognitive training. Despite the importance of this issue, only some of the previous executive control studies have explored the stability of training and/or transfer effects and findings have been mixed.

Whereas training studies with working memory and updating tasks in children have reported training and transfer effects to be relatively stable for three to six months (Holmes et al., 2010; Jaeggi et al., 2011; Klingberg et al., 2005; Klingberg, 2010), reports on maintenance effects have been more mixed in adult populations. Whereas training and near transfer effects seemed to be relatively stable for as long as 18 months in some studies (Borella, Carretti, Riboldi, & de Beni, 2010; Dahlin, Nyberg, et al., 2008; Li et al., 2008), stability of (some) far transfer effects was only found in one study after eight months (Borella et al., 2010). Other studies did not find any training or transfer effects one year after training (Buschkuehl et al., 2008) or largely reduced training and transfer gains at a three-month follow-up for the older participants (Li et al., 2008). Examining maintenance effects as an indicator of profound plasticity seems to be especially warranted in older adult populations because these findings have been more mixed than those in child populations (although this has to be interpreted cautiously, because stability of training effects has not been investigated in all training studies with children). Therefore, the question of the stability of effects was examined in detail in the last study of the current work, that included older adults (see Chapter 5).

1.3.3 Factors that may influence the efficiency of executive control training

The previous sections on transfer and maintenance effects have shown that not all executive control training studies are able to demonstrate profound transfer effects that remain stable over time. Different factors may influence the efficiency of the studied trainings and the current thesis set out to explore those factors in more detail. When looking at the astonishing variability in training procedures and tasks, it is reasonable to assume that a range of training design features may influence the reported effects. These include the amount and length of training, the particular training task or target domain, and context variables such as activities that precede the training (e.g., physical exercise). Furthermore, age is an important factor that has been identified as a substantial moderator of plasticity in previous strategy-based training studies. Additionally, individual differences (e.g., in basic abilities or initial performance on trained tasks) may influence the amount and range of plasticity induced by training. Both groups of possible moderating factors (training design features as well as age and individual differences) will be explained in further detail in the following two sections.

1.3.3.1 Training design features

Previous training studies vary considerably in the amount of training their procedure includes. Training duration ranges from 4 weekly sessions (120 minutes overall, Karbach & Kray, 2009) up to very extensive training regimen of 25 sessions (1000 minutes overall training time, Klingberg et al., 2005) or even 100 daily sessions (6000 minutes overall training time, Schmiedek, Lövdén, & Lindenberger, 2010). It is not yet clear if training and transfer effects that are achieved with extensive trainings are comparable to those achieved with relatively short durations of training. Only recently a few studies provide first evidence that shorter training durations may be sufficient to produce substantial benefits (Karbach & Kray, 2009; Loosli et al., 2012). Furthermore, the study by Loosli et al. (2012) reported that the largest improvements in training tasks were found in the first four sessions. After that, increases in performance leveled off. The current work aimed at extending this research by exploring the effects of short executive control trainings in all studies. From an applied perspective shorter training durations are of high relevance because they may be easier to implement in a real-life context outside the laboratory.

With regard to executive control training regimen, currently, another conceptual issue is especially under debate: Does it matter what domain of executive control is being trained? Some studies have targeted a range of cognitive domains at the same time in preschool children (Diamond et al., 2007) and older adults (Schmiedek et al., 2010). However, this broad approach makes it difficult to delineate which domain may underlie the observed effects. Therefore, the current overview focuses on training studies that target a circumscribed domain, allowing observed transfer effects to be clearly attributed to training in this specified domain.

The most consistent findings for executive control trainings have, so far, been achieved in a range of studies that train tasks requiring updating (e.g., Dahlin, Nyberg, et al., 2008; Jaeggi et al., 2008, 2011) or working memory (Holmes et al., 2009; Klingberg et al., 2005; Loosli et al., 2012; see Klingberg, 2010, for a review). These studies have mostly found robust transfer to other working memory tasks and even some far transfer to other executive control domains (e.g., inhibition, Borella et al., 2010; Klingberg et al., 2005), reasoning (Jaeggi et al., 2011; Klingberg et al., 2005), episodic memory (Borella et al., 2010; Brehmer et al., 2011), and mathematical or reading performance (Holmes et al., 2009; Loosli et al., 2012). Much less consistent findings come from the few training studies using inhibition tasks. One study was able to show near transfer of an inhibitory control training to a nontrained inhibition task (Go/No Go, Dowsett & Livesey, 2000). A study that closely modeled an inhibition training paradigm to a previously successful working memory training (Klingberg et al., 2005) neither found evidence for near nor for far transfer to other executive control tasks (Thorell, Lindqvist, Nutley, Bohlin, & Klingberg, 2009). With respect to the third facet of executive control, switching, the available literature is also scarce: Although there are a range of studies showing practice-related improvements in task switching paradigms (Buchler, Hoyer, &

Cerella, 2008; Kramer, Hahn, & Gopher, 1999; Kray, Eber, & Karbach, 2008), fewer have explored transfer to other tasks. Those that have, report transfer to other switching tasks (Minear & Shah, 2008) and to other domains of executive control like working memory, inhibition, and reasoning (Karbach & Kray, 2009; Kray, Lucenet, & Blaye, 2010).

Summarizing the existing research on the different domains of executive control functions, the very few findings for the inhibition domain are inconclusive and do not seem to be very promising. In contrast, a broad range of findings in the updating domain suggest more consistent training and transfer effects. Furthermore, the few findings from the task switching domain seem to be promising concerning the range of transfer effects achieved even with a rather short training duration, especially the study by Karbach and Kray (2009). Thus, the empirical studies of the current work focused on trainings that target task switching and updating or working memory functions.

Another factor that may contribute to executive control training efficiency concerns the interplay of cognitive and physical activation as it can be found, for example, in school settings. It has been shown that physical activity (e.g., exercising on a treadmill or a stationary bicycle) has short-term (acute) effects on cognitive functions (see for reviews, Lambourne & Tomporowski, 2010; Tomporowski, 2003). Facilitating effects of acute exercise have been found repeatedly for basic information processing, for example increased speed in simple and more complex reaction time task (Ellemberg & St-Louis-Deschênes, 2010; Hogervorst, Riedel, Jeukendrup, & Jolles, 1996). Furthermore, studies have found effects of acute exercise on behavior and electrophysiological measures in tasks requiring inhibition (e.g., Stroop task, Hogervorst et al., 1996; Yanagisawa et al., 2010; Flanker task, Magnié et al., 2000; Hillman et al., 2009), working memory (Pontifex, Hillman, Fernhall, Thompson, & Valentini, 2009), and attention switching (Pesce, Capranica, Tessitore, & Figura, 2003). However, other studies have failed to find an influence on inhibition (Stroth et al., 2009; Themanson & Hillman, 2006) or mental set-shifting (Tomporowski, Davis, Lambourne, Gregoski, & Tkacz, 2008). Although these studies all relate to cognitive performance (not training) right after exercise, several authors such as Hillman et al. (2009) or Noack et al. (2009) have recently suggested that it may be valuable to look at the effects of acute exercise on cognitive control training, that is, to combine both types of interventions. It could be speculated that transient effects of exercise may facilitate or enhance neural change that may be induced by cognitive training. It may be that effects of physical activation are ”setting the stage” (Kempermann, 2008, p. 165) on which experience-related plasticity and learning can act

(Noack et al., 2009; Lambourne & Tomporowski, 2010; Pesce, Crova, Cereatti, Casella, & Bellucci, 2009). This notion is an exploratory question because findings have not been consistent as to what cognitive functions are affected and when (Dietrich, 2006; Stroth et al., 2009). Empirically investigating this question for the first time was therefore an exploratory aim of the first study of this work (see Chapter 3).

1.3.3.2 Individual difference factors

In addition to factors of the training design, different factors that lie within the individual may influence the plasticity induced by trainings. There may be subgroups of participants that differ in their benefits from executive control trainings. Individual difference characteristics that may play a role in this regard include age, baseline cognitive functioning and initial performance on tasks of the training domain (as has also been suggested in a recent review by Morrison & Chein, 2011). Exploring these factors may shed more light on the inconsistencies of findings between executive control studies. Furthermore, from an applied perspective, these factors may be important starting points to optimize future cognitive trainings to increase training gains for particular populations.

The targeted age group may explain some of the variance between findings of different process-based training studies, as is also suggested by previous findings from the strategy-based training literature (see, e.g., P. B. Baltes & Kliegl, 1992; Singer et al., 2003). Executive control training studies have mostly targeted clinical populations of children (e.g., children with ADHD, Klingberg et al., 2005; or children with low working memory abilities, Holmes et al., 2009), young (Jaeggi et al., 2008; Karbach & Kray, 2009) and older adults (Dahlin, Nyberg, et al., 2008; Li et al., 2008). Evidence for training and transfer effects in typically developing preschool and school children has only recently been accumulated (Jaeggi et al., 2011; Karbach & Kray, 2009; Loosli et al., 2012; Thorell et al., 2009). Also, only one process-based training study has included adults that range into old-old age (mean age of 80 years, Buschkuehl et al., 2008). Directly comparing children, younger, and older adults, Karbach and Kray (2009) found training benefits to be larger in children than in adults. As has been discussed in Section 1.3.1 and 1.3.2, findings of transfer effects and stability have been more consistent and robust in children and younger adults (Jaeggi et al., 2008, 2011; Klingberg et al., 2005) than in older adults (Buschkuehl et al., 2008; Dahlin, Nyberg, et al., 2008; Li et al., 2008; see for a review Richmond et al., 2011). This is paralleled by findings of strategy-based interventions showing a decline in the ability to benefit from these interventions (i.e., reduced plasticity) in older adults compared to children and younger adults (Brehmer et al., 2008; Verhaeghen et al., 1992), especially in old-old adults (Singer et al., 2003). Because no process-based study has directly investigated the possible influence of age with a sample of older adults that spans the whole young-old to old-old age range, it remains to be tested if the effects of process-based training interventions parallel the findings of strategy-based interventions with reduced plasticity in old-old age. It could be, considering the substantial changes that have been achieved with process-based training, including neural changes, that process-based training regimes are as effective in old-old adults as they are in young-old adults, or even more so. This is of particular relevance from a developmental psychology perspective because it may shed more light on the possible age-effects of the potential for intraindividual change and learning from experience. Investigating this particular questions was a major aim of the last empirical study of the current work (see Chapter 5).

With regard to the whole life-span, executive control training studies with adolescents (especially above 12 years) are surprisingly very rare, as are studies with old-old adults (above 80 years of age). This fact is rather remarkable because executive control processes are highly relevant in the daily life of adolescents and very old adults and show distinct development trajectories through adolescence and in old-old age (see in more detail Section 1.2). Taking findings about developmental trajectories into account, one can predict the potential for plasticity through executive control training to be especially large in adolescents. On the other hand, whereas the potential for plasticity may be smaller in old-old adults, training on executive control skills might be particularly beneficial for these individuals as they suffer from substantial decline of these important functions (Noack et al., 2009). Therefore, the three studies of the current work included participants of these particular age groups to explore whether and under which circumstances training benefits can be achieved.

Another individual factor that may underlie differential training effects is the participants' functional status before training. Considering the previous literature, two possible predictions can be derived about what subgroups of participants may profit more from training than others. On the one hand, it may be that especially in old-old adulthood only those participants who have maintained a certain cognitive status profit from a training intervention (M. Baltes, Kühl, Gutzmann, & Sowarka, 1995; Bissig & Lustig, 2007). Thus, cognitive training would amplify the differences in performance on trained tasks that were present at baseline. On the other hand, resting on the disuse hypothesis (Gatz et al., 2001; Hultsch, Hertzog, Small, & Dixon, 1999; Kliegel, Zimprich, & Rott, 2004), it may be that participants who start with a low cognitive status (a possible result of a decline in using cognitive resources) are able to reactivate some of their potential with the help of training. Thus, cognitive training would have a compensatory effect for low-capacity individuals (see for example Kramer et al., 1999, for a compensatory effect of cognitive training on age differences). To address this question, baseline performance on trained tasks was included as a potential predictor for training effects in older adults in studies two and three of the current work (see Chapters 4 and 5).

Transfer effects may strongly depend on individual effects of training. Exploring these individual differences and their relationships to transfer effects can be fruitful from a conceptual perspective. The rationale for process-based trainings hypothesizes that improvements in executive control generalize to other tasks that depend on executive control. Following this rationale, larger individual gains in the executive control training task should be related to larger gains in transfer tasks. Surprisingly, this hypothesis has only been investigated directly in a handful of studies. In the study by Jaeggi et al. (2008) the amount of transfer varied as a function of training amount (8 to 19 sessions). A later study found that only participants who exhibited substantial improvements in the trained task showed transfer effects (Jaeggi et al., 2011). Furthermore, improvements in the respective training tasks were found to be correlated with improvements in transfer tasks (Chein & Morrison, 2010; Schmiedek et al., 2010). Because exploring the relationships between training and transfer improvements may further elucidate the mechanisms of how executive control training works, two studies of the current work aimed at exploring this question (see Chapters 3 and 5).

2 Outline and Central Questions

The previous chapter outlined the state of the art in the developing research field of process-based executive control training. As illustrated in the introduction, a range of questions await further investigation with regard to training-induced plasticity over the life-span. The current work set out to clarify, first, what amount of plasticity can be obtained with executive control training over the life-span. In particular, studies were set up to explore plasticity on the level of training and transfer tasks, as well as on the level of stability of training and transfer effects. Another major question concerned the possible role training design, age, and individual differences may play in moderating the amount and range of plasticity. Furthermore, the current thesis aimed at clarifying how process-based training specifically leads to transfer effects. These central questions of the current thesis will be explained in more detail in the following sections.

To explore these questions, all studies employed a pretest-posttest-design comparing (at least) one group of participants that was trained with a process-based training approach to (at least) one group of control participants that did not receive the training. Pretraining and posttraining sessions incorporated systematic assessment of transfer measures allowing to investigate transfer effects in different cognitive domains, i.e., if trained participants improved performance in transfer tasks more from pretraining to posttraining than control participants.

2.1 What amount of plasticity does executive control training induce in different age groups?

The first central question of the current work concerned the amount of plasticity that can be obtained with an executive control training. Plasticity was explored on the level of training and transfer tasks, i.e., if training leads to improvements in trained tasks (*trainability*) and what range of transfer effects can be achieved (*transferability*). Three studies were set up to investigate the effects of executive control training in age groups that are of particular relevance from a developmental perspective: adolescents and older adults. These two age groups lend themselves to the exploration of plasticity because both groups are not (yet or any more) at the peak of their executive control performance but may differ in their potential for change. It is especially interesting from a life-span perspective to investigate the possibility of influencing executive control performance that is either still evolving or already declining. Furthermore, previous findings in these age groups have been inconclusive (older adults, studies two and three) or studies are practically nonexistent (adolescents, study one). Considering the impressive findings of training and transfer effects in previous studies in children and young adults, we expected similar findings in adolescents (study one) and in young-old adults (study three). An open question is whether training-induced plasticity is at all possible in old-old age. So far, no process-based training study has included older adults that were well within old-old age (above 80 years of age). Therefore, study two will specifically address this open issue.

2.2 Do training and transfer effects of executive control training remain stable over time?

The third study of the current thesis concerned another dimension of plasticity (*stability*) and tried to answer the question whether training benefits are maintained over time. For that purpose, study three included a follow-up session after eight months. This provided the opportunity to explore whether training and transfer effects, that are achieved immediately after training, remain stable. If substantial training and transfer effects can be achieved with the particular training, this should also be evidenced on the level of stability with (some) differences maintained over a longer time.

2.3 Do training design, age, and baseline performance moderate the amount of plasticity?

Following up on the inconsistent findings concerning the amount and range of training and transfer effects, a third major question of the current thesis was what factors may influence the amount of training benefits. The studies explored factors of (a) the *training design* and (b) *individual difference factors*. The first study put its focus on design features, i.e., the target domain of the training as well as the context preceding the training. Thus, in addition to investigating the efficiency of a short duration training of one particular executive control domain (task switching), study one asked if physical activation through exercise directly preceding cognitive training may influence training efficiency in adolescents. Following up on findings about short-term effects of exercise on cognitive task performance and a recently proposed (but not yet tested) combination of exercise and cognitive training, it was hypothesized that exercise would have an additional positive effect on executive control training outcomes.

The following two studies included older participants where considerable interindividual variability in baseline performance or general abilities can be expected due to normal aging and associated decline in cognitive functions. Thus, these two studies put their focus more strongly on individual difference factors that may influence the amount of training benefits, like age and baseline cognitive performance. A short duration training of working memory was employed. Study three included a broad age range of participants of old age (65-95) allowing to systematically explore the influence of age on training and transfer gains. Resting on previous findings of age-differences in plasticity (mostly coming from strategy-based training studies), one would expect the potential for plastic changes to be smaller in old-old age. The influence of baseline performance on training tasks on training effects was explored in both studies two and three. The question was explored whether those who have maintained a certain (high) cognitive status are those who profit most from the training (amplification model) or if low capacity individuals profit most (compensation model).

2.4 Are changes in trained tasks specifically related to changes in transfer tasks?

Furthermore, and importantly from a conceptual perspective, in studies one and three, the *relationship between training gains and transfer gains* was explored. The rationale for process-based trainings is that training a basic processing resource like executive control functions leads to improvements in this resource. Because executive control is thought to underlie a range of cognitive functions, this improvement is thought to implicitly lead to improvements in performance in these other cognitive functions. Although this hypothesized relationship forms the basis of these training approaches, it has rarely been investigated. Thus, pathways by which a certain training (or aspects of the training) lead to changes in transfer tasks are unclear. For that reason, the current thesis tried to shed more light on the question of how changes in trained tasks are specifically related to changes in transfer tasks.

3 Study 1 - Effects of a Task Switching Training in Adolescents

3.1 Introduction

Executive control is the ability to plan, execute and monitor goal-directed behavior (Norman & Shallice, 1986). It is a central neurocognitive process that is involved in a range of cognitive functions that are of everyday relevance, like problem solving or reasoning (Baddeley, 2003; Engle et al., 1999; van der Sluis et al., 2007). According to a model by Miyake et al. (2000) that has been derived empirically in adult and child populations (Lehto et al., 2003), executive control consists of different distinguishable components: maintaining and monitoring working memory representations (updating), deliberately suppressing prepotent responses (inhibition), and shifting between different tasks or mental sets (set-shifting or switching).

There is a small, but growing body of promising research showing that executive control functions can be enhanced by systematic cognitive training with tasks requiring updating (Dahlin, Nyberg, et al., 2008; Jaeggi et al., 2008), working memory (Holmes et al., 2009; Klingberg et al., 2005; Klingberg, 2010), task switching (Karbach & Kray, 2009), or dual task performance (Bherer et al., 2005; Liepelt et al., 2011). In addition to increases in performance on trained tasks, some of these studies were able to show transfer effects to non-trained tasks within the trained domain (e.g., working memory training transferred to complex working memory span tasks, Holmes et al., 2009) as well as to other executive control domains (e.g., inhibition tasks, Karbach & Kray, 2009; Klingberg et al., 2005; Olesen et al., 2004) or measures of non-verbal reasoning (Jaeggi et al., 2008; Klingberg et al., 2005). However, other studies have failed to find any transfer to similar tasks or suggest that transfer may be restricted to the trained domain (e.g., Dowsett & Livesey, 2000; Li et al., 2008; Strobach et al., in press). All of these studies have used a process-based training approach, where repeated performance on tasks, feedback and often gradual adjustment of difficulty (Klingberg, 2010) implicitly leads to improvements.

Executive control training studies have targeted young (Jaeggi et al., 2008; Karbach & Kray, 2009) and older adults (Buschkuehl et al., 2008; Dahlin, Nyberg, et al., 2008; Li et al., 2008; Zinke, Zeintl, Eschen, Herzog, & Kliegel, 2012), as well as clinical populations of children, for example children with ADHD (Klingberg et al., 2005) or with low working memory abilities (Holmes et al., 2009). Evidence for training and transfer effects in typically developing children has only recently been accumulated (Jaeggi et al., 2011; Karbach & Kray, 2009; Loosli et al., 2012), whereas studies with older children and adolescents (especially above 12 years) are surprisingly very rare. This fact is rather remarkable because executive control processes are on the one hand highly relevant in the adolescents' daily life and school-related academic activities, e.g., reading or arithmetic (van der Sluis et al., 2007). Besides their ubiquitous relevance, executive control functions are on the other hand among the few functions that show development trajectories well into adolescence (Anderson, 2002; Huizinga et al., 2006) corresponding to relatively late maturation of prefrontal brain regions (Bunge et al., 2002; Luna et al., 2010). Recent studies suggest an ongoing development of different executive control functions across adolescence and even into young adulthood (Huizinga et al., 2006; Luna et al., 2004; Rubia et al., 2006). Taking these findings into account it appears straightforward to predict that the potential for plasticity through executive control training may be especially large in this age group. For that reason, it was the first aim of the current study to explore if an executive control training can also benefit cognitive functions in a population of adolescents.

With regard to executive control training, currently, one conceptual issue is especially under debate: Does it matter what domain of executive control is being trained? The most consistent findings for executive control trainings have, so far, been achieved in a range of studies that train tasks requiring updating (e.g., Dahlin, Nyberg, et al., 2008; Jaeggi et al., 2008, 2011) or working memory (Holmes et al., 2009; Klingberg et al., 2005; Loosli et al., 2012; see Klingberg, 2010 for a review). These studies have mostly found robust transfer to other working memory tasks and even some (but limited) far transfer to other executive control domains or reasoning (Jaeggi et al., 2011; Klingberg et al., 2005), and mathematical or reading performance (Holmes et al., 2009; Loosli et al., 2012). Much less consistent findings come from the few training studies employing inhibition tasks. One study was able to show transfer of an inhibitory control training to a non-trained inhibition task (Go/No Go, Dowsett & Livesey, 2000), whereas another study did not find any transfer to other executive control tasks (Thorell et al., 2009). With respect to the third facet of executive control, switching, the available literature is also scarce: Although there are a range of studies showing practice-related improvements in task switching paradigms (Buchler et al., 2008; Kramer et al., 1999; Kray et al., 2008), fewer have explored transfer to other tasks. Those that have, report transfer to other switching tasks (Minear & Shah, 2008) or to other domains of executive control like working memory, inhibition, and reasoning (Karbach & Kray, 2009; Kray et al., 2010). Summarizing research on the different domains of executive functions, a broad range of findings in the updating domain suggest consistent training and transfer effects, whereas the very few findings for the inhibition domain are inconclusive and do not seem to be very promising. In contrast, the few findings from the task switching domain seem to be promising concerning the range of transfer effects, especially the study by Karbach and Kray (2009). For that reason, the current study aimed at training task switching abilities and closely modeled the training regime after the study by Karbach and Kray (2009). Extending that study, which had targeted primary school children, young adults, and older adults, the current study aimed at exploring if similar effects of this particular task switching training can also be achieved in adolescents.

Task switching requires participants to switch from performing one (mostly) simple task (e.g., deciding whether a picture shows a vegetable or a fruit) to performing a second simple task (e.g., deciding whether an object is small or large) from trial to trial. Task switching paradigms usually involve single-task blocks where only one task has to be performed the whole time and mixed-task blocks where the participant has to switch between tasks. Switching to a new task is usually accompanied by costs (slower and more error-prone task execution). The literature distinguishes between mixing costs as the difference in mean performance between mixed-task and single-task blocks and switching costs as the difference in mean performance between switch and nonswitch trials within mixed-task blocks (see, e.g., Karbach & Kray, 2009). These costs are thought to reflect different executive control processes. Mixing costs are thought to reflect a more global ability to maintain and select two different task sets, whereas switching costs reflect more specifically the actual act of switching from one task to the other (Braver, Reynolds, & Donaldson, 2003; Kray & Lindenberger, 2000). With regard to task switching training, studies mostly report practice-related reductions in both types of costs during training (Cepeda et al., 2001; Kray et al., 2008). Studies comparing both types of costs suggest larger decreases (or even elimination) with training in mixing costs as compared to switching costs (Berryhill & Hughes, 2009; Strobach, Liepelt, Schubert, & Kiesel, 2012). Transfer has been found for mixing costs only (Minear & Shah, 2008) or both types of costs (Karbach & Kray, 2009).

What aspects of task switching are actually trained and may underlie the transfer to other switching or executive control tasks is not well understood. It has been suggested that different executive control processes are involved in switching from one task to the other. These include maintaining several task sets in working memory, selecting and configuring the appropriate task set (as is thought to be indicated by mixing costs), or focusing attention on relevant aspects and inhibiting now irrelevant aspects of the stimulus or task set (as is thought to be indicated by switching costs, Mayr, 2003; Minear & Shah, 2008; Kramer et al., 1999). Thus, it is reasonable to assume that changes in some or all of the three facets of executive control may be of importance for the possible effects of task switching training. In line with this assumption, Karbach and Kray (2009) suggest that task switching training may not only improve task-set selection, but also improve maintenance of goals (updating) and/or improve inhibitory control to suppress currently irrelevant features. Findings of transfer to mixing costs (Minear & Shah, 2008; Karbach & Kray, 2009) may point to the relevance of updating processes in mediating training and transfer effects, because mixing costs are thought to reflect the more global ability to maintain different task sets (Braver et al., 2003; Kray & Lindenberger, 2000). The involvement of inhibitory processes in task switching training effects may be inferred from transfer that has been found for an inhibition task (i.e., Stroop task, Karbach & Kray, 2009). However, the transfer tasks used in Karbach and Kray's study were not specifically chosen to tap all different domains of executive control - therefore, one cannot directly infer from their data which of the executive control domains may be specifically associated with the training and transfer effects. Following up on this issue, as a second aim, the current study was set up to systematically explore transfer to all three executive control domains, namely shifting (e.g., with a number switch task), updating (e.g., with an n-back task), and inhibition (e.g., with a Stroop task). Because effects may be different for speed and accuracy of responses (as may be inferred from differing developmental trajectories for reaction time, RT, and accuracy measures for executive control tasks, e.g., Davidson et al., 2006), measures for both RTs and error rates were included.

A third open question addressed by the current study concerns the specific conditions under which executive control training is most effective. Besides the conceptual question of pathways leading to training and transfer effects, this question was also motivated by the applied aspect of how to implement training regimes best for adolescents. One possible contributing factor in this regard concerns the interplay of cognitive and physical activation as it can be found in school settings. Here, another line of research is relevant to consider that is concerned with the acute effects of physical exercise on cognitive functions (see for a review, Tomporowski, 2003). Most of these studies measure performance on different cognitive tasks during or right after the participants have exercised for a predefined time, for example on a treadmill or a stationary bicycle. Facilitating effects of acute exercise have been found repeatedly for basic information processing, for example increased speed in simple and more complex reaction time tasks (Ellemberg & St-Louis-Deschênes, 2010; Hogervorst et al., 1996). Results are more mixed for higher order functions like executive control functions. Studies have found effects of acute exercise on behavior and electrophysiological measures in tasks requiring inhibition (e.g., Stroop task, Hogervorst et al., 1996; Yanagisawa et al., 2010; Flanker task, Magnié et al., 2000; Hillman et al., 2009), working memory (Pontifex et al., 2009), and attention switching (Pesce et al., 2003). However, other studies have failed to find an influence on inhibition (Stroth et al., 2009; Themanson & Hillman, 2006) or mental set-shifting (Tomporowski et al., 2008). A recent meta-analysis by Lambourne and Tomporowski (2010) explored overall effects of acute exercise on cognitive functioning during and after exercise. Results suggest that facilitating effects can be found mostly after exercise and for speed in decision making tasks, memory and executive functioning tasks.

Although these studies all relate to cognitive performance (not training) right after exercise, several authors such as Hillman et al. (2009) or McDaniel and Bugg (in press) have recently suggested that it may be valuable to look at effects of acute exercise on cognitive control or memory training, respectively. It could be speculated that acute exercise may facilitate or enhance neuronal change that may be induced by cognitive training. Also, if acute exercise directly enhances memory processes (see, e.g., Lambourne & Tomporowski, 2010; Pesce et al., 2009) it may impact learning during cognitive trainings. However, findings have not been consistent as to what cognitive functions are affected and when. Some findings even suggest detrimental effects of physical exercise on executive control functions during or right after exercise (e.g., Dietrich & Sparling, 2004; Dietrich, 2006). For these reasons, as an exploratory third research question, the current study aimed at evaluating the conceptual proposal (Hillman et al., 2009; McDaniel & Bugg, in press) of a possible added value of an acute bout of exercise prior to cognitive training sessions.

In summary, the aims of the current study were the following. The first central question was if executive control functions can be trained in adolescents - an age group where executive control functions are highly relevant and still developing. The study set out to explore whether and which particular training and transfer effects can be achieved in the domain of task switching in adolescents using the training by Karbach and Kray (2009). Specifically, transfer effects would constitute larger gains in performance from pre- to posttraining in the task switching training groups as compared to the control groups. Furthermore, as the second aim, the study systematically explored possible transfer effects to all three main executive control facets suggested by Miyake et al. (2000) with RT and accuracy measures. Third, the current study is the first to empirically explore the recent proposition of possible favorable effects of acute bouts of exercise on cognitive control training. If acute bouts of exercise have a favorable effect, we would expect differences in the size of training and transfer effects depending on whether participants received prior acute bouts of exercise or not.

3.2 Methods

3.2.1 Participants

The 80 participants of the study were adolescents aged between 10 and 14 years (mean age: 11.9, $SD = 1.3$). They were recruited in local schools and youth clubs and were reimbursed for their participation with four Euros per hour. All participants and parents received extensive oral and written information about the study. Only if parents and participants gave written informed consent, adolescents were included into the study. The study was approved by the ethics committee of the German Society of Psychology. Each participant was individually assigned to one of four groups by randomly drawing group assignments. The study had a three-factorial design with two between-subjects factors, cognitive training (yes vs. no) and exercise intervention (yes vs. no), and one within-subject factor, time of measurement (pretraining vs. posttraining). Hence, there were two cognitive training groups: one combined training group (acute physical exercise right before each cognitive training) and one cognitive training only group; and two control groups: one exercise only control group (acute physical exercise) and a no-contact control group. The four groups of 20 participants were matched in age, gender, BMI, fitness, and basic cognitive functioning (see Table 1). The participants were free of any neurological, psychiatric or physical disorders and did not take medication according to parents' reports. Baseline cognitive functioning was assessed with two tests. Verbal abilities were measured using the vocabulary subscale of the German adaptation of the Wechsler Intelligence Scale for children (WISC-IV, Petermann & Petermann, 2010), where children have to define words. Fluid abilities were assessed with the Digit Span

Table 1: Participant characteristics of the training groups (with and without prior exercise) and the control groups (exercise only and no-contact, all n = 20)

	Cognitive training groups		**Control groups**	
	with exercise	no exercise	exercise only	no-contact
Measure	$M(SD)$	$M(SD)$	$M(SD)$	$M(SD)$
Gender	9 girls	9 girls	9 girls	9 girls
Age	11.9 (1.2)	11.9 (1.4)	11.8 (1.2)	11.9 (1.3)
BMI	18.0 (1.9)	19.5 (2.8)	18.2 (2.0)	18.1 (2.0)
Fitness in watts/kg	3.0 (0.4)	3.0 (0.5)	2.9 (0.5)	2.9 (0.5)
Vocabulary	13.2 (2.3)	13.0 (2.8)	13.2 (3.0)	13.2 (2.7)
Digit span	10.9 (3.2)	10.0 (2.9)	11.0 (2.6)	9.9 (2.2)

subtest, where children have to repeat digit sequences of ascending length in the same or reverse order (Petermann & Petermann, 2010).

3.2.2 Cognitive training task

The cognitive training material was closely modeled after Karbach and Kray (2009). The participants' task was to switch as fast and accurately as possible between two simple tasks. The first task was to decide via key press whether the picture presented was a car or a plane (vehicle task). The second task was to decide via key press whether there were one or two objects on the picture (number task). Both tasks were mapped onto the same keys (left key: “car” or “one”; right key: “plane” or “two”) which were to be pressed with the left and the right index finger, respectively. Each training session consisted of two short practice blocks (8 trials each) and 24 mixed-task blocks consisting of 17 trials, each starting with a fixation cross (700 ms), followed by a picture until a response was made. Participants were told to switch between tasks on every second trial, that is, to perform the vehicle task twice, then the number task twice, then the vehicle task twice again, and so on. At the beginning of each block, participants were reminded of the sequence and could start over new in case they lost track. During training, participants received a feedback after each block about how many trials they answered correctly and how fast they reacted. Additionally, several times during training, the experimenter verbally encouraged the participants to try to be even more accurate and/or answer faster. The main dependent variables were mean switching cost for RT data (mean RT switch trials - mean RT non-switch trials) and for errors (error rate switch trials - error rate non-switch trials).

3.2.3 Acute exercise intervention

The physical exercise intervention was modeled after similar interventions in other acute exercise studies (e.g., Hillman et al., 2009; Stroth et al., 2009). Participants had to cycle on a stationary bike (Kettler, Model X3) for 20 minutes at about 60 % of their individual maximal heart rate, a moderately intense physical exercise. Heart rate was monitored with POLAR heart rate monitors (Polar Electro, Model FT1) that send their measurements to the stationary bike. The stationary bike was set to a program that automatically adjusted resistance to help the participant stay in the target heart rate zone.

3.2.4 Fitness assessment

Fitness was assessed with a graded maximal exercise test on a stationary bike (Kettler, Model X3) following standards of the WHO to test fitness and a standardized protocol from large German study on fitness in children and adolescents (Bös, Worth, Opper, Oberger, & Woll, 2009). Difficulty of cycling started at a resistance of 25 watts with watt-load being increased by 25 watts every 2 minutes while the participant was asked to keep the pedaling rate above 60 rotations per minute. Heart rate was monitored with a POLAR heart rate monitor (Polar Electro, Model FT1) and testing was stopped if one of the prespecified stopping criteria was reached. These criteria were: a) heart rate above 180 bpm for over 15 seconds, b) the pedaling rate below 50 for more than 20 seconds, c) report of subjective exhaustion, or d) any sign of discomfort, pain, sudden changes in heart rate, etc. The main measure of physical fitness was maximal watt performance related to body weight (watt/body weight in kg, following Bös et al., 2009).

3.2.5 Transfer tasks

To assess transfer to different domains, a range of tasks were used in the current study. Tasks were chosen to cover the three domains of executive control (switching, updating, and inhibition) with tasks including picture or verbal stimuli. Furthermore, tasks were included to cover the speed domain that has been shown to be a relevant outcome variable in acute exercise research. Because effects may be different on the level of RT and accuracy, measures for both levels were included in each domain.

3.2.5.1 Task Switching

To assess near transfer of task switching training, a task switching task was used that was structurally similar to the training task but included different pictures and tasks. The first task was to decide via key press whether the picture shown was a fruit or a vegetable (food task). The second task was to decide via key press whether the picture was small or large (size task). Both tasks were mapped onto the same keys (left key: “fruit” or “small”; right key: “vegetable” or “large”) which were to be pressed with the left and the right index finger, respectively. Participants were instructed on how to perform each single task separately and had one practice block of 17 trials for each task. After that they were instructed for the mixed-task block: they were told to switch between tasks on every second trial, that is, to perform the food task twice, then the size task twice, then the food task twice again, and so on. Thus, trials where participants had to switch and trials where they had to repeat the task alternated. The participants had two mixed-task blocks with 17 trials each to practice. After that there were 20 more blocks with either single-task performance (5 for vehicle task, 5 for number task) or mixed-task performance (10 blocks) with a reminder of the respective instruction at the beginning of each block. Each block consisted of 17 trials each starting with a fixation cross (1400 ms), followed by the picture until a response was made. Main dependent variables on a RT level were mixing costs (mean RT mixed-task blocks - mean RT single-task blocks) and switching costs (mean RT switch trials - mean RT non-switch trials). On the level of error data dependent variables were mixing costs (error rate in mixed-task blocks - error rate in single-task blocks) and switching costs (error rate in switch trials - error rate in non-switch trials).

Furthermore, a switching task with verbal material (numbers 1 to 4 and 6 to 9) was used: a number switch task[1] (see, e.g., Koch & Allport, 2006) where participants had to switch between judging whether the number presented on the screen was smaller or larger than five or whether it was even or odd. An external cueing paradigm was used (with a fixed CSI of 0 ms), that is, the task to be executed was written above the stimuli (“smaller or larger than 5?” or “even or odd?”) and was present until a response was made. There was a blank interstimulus interval of 1000 ms in between trials. There were two single-task blocks of 40 trials each for the size task and the even/odd-task, respectively. Afterwards participants performed another block of 80 trials where tasks

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[1] In the traditional binary taxonomy of near and far transfer tasks, this number switch task is difficult to allocate, as it assesses the same construct as in training, i.e., task switching. However, because the paradigm is different, it may also require different cognitive functions. Therefore, this task could be considered at an intermediate level of transfer.

were randomly intermixed. That is, in approximately half of the trials participants had to switch between tasks, in the remaining trials they had to repeat the previous task. Main dependent variables were the same as in the other switching task, that is, mixing and switching cost on the level of RT and error data, respectively.

3.2.5.2 Updating

As a measure of updating, an animal picture 2-back task was used. The participants were to decide if the animal presented was the same as the one next-to-last with a key press ("yes" if they were the same, "no" if they were not). Line drawings of animals (taken from Snodgrass & Vanderwart, 1980) were presented for 1500 ms each, followed by a 1000 ms blank interstimulus interval. After a short practice of seven trials, participants performed a block of 122 trials (the first two trials were excluded from the analyses because there is no next-to-last picture on these trials), 25 % of the pictures were target pictures. Main dependent variables were mean RT for correct decisions and percentage of correct target hits.

As a measure of updating with verbal stimuli a keep-track task following Miyake et al. (2000) was used. In this task, words (e.g., uncle) that belong to 6 different semantic categories (e.g., relatives) were presented for 1500 ms one after another. The participants were instructed to remember the last word presented from each target category and name them at the end of each trial. Six to fifteen words were presented in each of five trials and two to four categories were to be tracked in each trial. Target categories were shown on the bottom of the screen for the whole trial. Because several words from each target category were presented on each trial, correct responses required successful updating of working memory content during the trial. Main dependent measure was the percentage of words recalled correctly.

3.2.5.3 Inhibition

To assess inhibition, a version of a visual Flanker task following the classic paradigm by Eriksen and Eriksen (1974) was used. The participants had to decide via key press if the small target square presented in the middle of the screen was red or blue. Two larger, colored squares were presented simultaneously on each side of the small target square: either the same color as the target (congruent trials) or a different color (incongruent trials). After a practice block of 12 trials, participants worked on a block of 100 randomized trials, half of the trials congruent, half of them incongruent. Main dependent variable on the RT level was the difference in mean RTs between correct incongruent and congruent trials (interference score) and percentage of correct answers on the accuracy level.

The Stroop interference task (German version of the color-word-Stroop test taken from the Nürnberger Altersinventar, NAI, Oswald & Fleischmann, 1995) was used to measure inhibitory control with verbal material. Here, the participant first had to read out loud 36 color names (printed in black on a sheet) as fast as possible; in the second run the participant had to name 36 color patches; in the last run he/she had to name the print color of 36 color words printed in different colors. Overall time was taken for each run. The main dependent variable was the difference in overall naming time between the third and the second run (interference score)[2].

3.2.5.4 Speed

A simple reaction time task was used to assess speed in detection of visual stimuli. A white circle was presented in the middle of the screen with a variable time interval of 1000 to 2000 ms in between. The participant was to press a key as fast as possible whenever a circle appeared. The circle disappeared at the time of key-press. After a practice block of 10 trials, participants worked on a test block of 50 trials. Dependent variable was the mean RT.

A choice reaction time task was used to assess speed in simple decision making. A white arrow, either pointing to the right or the left, was presented in the middle of the screen with a variable time interval of 1000 to 2000 ms in between. The participant was to press the left arrow key as fast as possible whenever a left-pointing arrow appeared and the right arrow key whenever a right-pointing arrow appeared. The arrow disappeared at the time of key-press. After a practice block of 10 trials, participants worked on two test blocks of 54 trials each. Dependent variable was the mean RT on correct trials and percentage of correct decisions.

3.2.6 Procedure

All adolescents participated in a pretraining and a posttraining assessment, where performance in transfer tasks was assessed with parallel versions, respectively. The order of tasks was held constant in all assessments. Testing started with speed tasks, followed by the near transfer switching task, 2-back task, Flanker task, and digit span. After a

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[2] Because error rates are generally extremely low in this task (mean error rate was below 1 % in the current study, see Table 4), only RT data serves as dependent variable.

5-minute break, testing continued with the number switch task, keep track task, Stroop task, and fitness assessment in the pretest session and vocabulary in posttest session.

Pretraining and posttraining sessions were scheduled in week one and five for each participant. In weeks two to four, participants of the two training groups and the exercise group had three training/exercise sessions, the no-contact control group did not have any sessions. These training sessions were scheduled with up to three adolescents at the same time and lasted for about 20 to 25 minutes for the cognitive training group and the exercise only control group and 45 minutes for the combined training group.

3.3 Results

Prior to RT data analyses, for the switching tasks, trials that had RTs faster than 100 ms or longer than 4000 ms were excluded (following Karbach & Kray, 2009). For 2-back, Flanker, and speed tasks all trials with RTs faster than 100 ms and slower than 1500 ms were excluded prior to analyses. Excluded trials were counted as errors in the analyses of accuracy data.

3.3.1 Training gains in trained tasks

The first set of analyses was conducted with the two training groups to answer the first and third research question: if task switching can be improved in adolescents via cognitive training and if prior physical exercise influences training gains. To test for significant performance changes over the course of the training days and possible differences between the training groups with and without additional exercise intervention, separate repeated measures ANOVAs were conducted for RT and error data. Training group (cognitive training vs. combined training) served as between-subjects factor and time of measurement (training days) as the within-subject factor.

For the RT data, analyses revealed a significant main effect of time for switching costs, $F(1.6, 61.5) = 25.9$, $p < .001$, partial $\eta^2 = .41$ (Greenhouse-Geisser corrections for lack of sphericity were applied), indicating that both training groups showed reductions of RT switching costs over the course of all training days (see Figure 1). Neither the main effect of training group nor the interaction term (Time x Training group) reached significance, indicating that training groups neither differed in their RT switching costs overall nor in their reduction of switching costs over training. An additional dependent t-test for paired samples revealed that mean reductions in RTs from the first training

Table 2: Mean RT and error data for task switching training task in all three training sessions for the combined and the cognitive training only group

	Training session 1		Training session 2		Training session 3	
	M	(*SD*)	*M*	(*SD*)	*M*	(*SD*)
COMBINED TRAINING GROUP						
mean RT in ms						
Nonswitch Trials	718	(182)	638	(233)	576	(162)
Switch Trials	949	(301)	769	(244)	697	(247)
Error rate in %						
Nonswitch Trials	10.5	(7.9)	12.3	(7.5)	12.9	(9.2)
Switch Trials	16.4	(9.4)	16.3	(9.2)	16.6	(8.2)
COGNITIVE TRAINING ONLY GROUP						
mean RT in ms						
Nonswitch Trials	726	(131)	636	(105)	596	(93)
Switch Trials	931	(199)	776	(199)	700	(163)
Error rate in %						
Nonswitch Trials	6.2	(3.6)	7.6	(4.3)	10.2	(5.1)
Switch Trials	13.2	(7.8)	12.1	(5.9)	13.8	(6.7)

day to the last training day (see Table 2 for complete mean RT and error data) were larger for switch trials, M = - 241.5 ms, SD = - 145.9, corresponding to a reduction of about 25 %, than for nonswitch trials, M = - 136.1 ms, SD = - 84.1, corresponding to a reduction of about 18 %, $t(39) = 6.6$, $p < .001$. Reduction rates did not differ significantly between the two training groups. This indicates that participants of both training groups showed larger improvements in RT on switch trials than on non-switch trials.

For the accuracy data, analyses revealed a significant effect of time for switching costs, $F(2, 76) = 9.3$, $p < .001$, partial $\eta^2 = .20$, indicating that all trained participants showed reductions of error switching costs over the course of training days (see Figure 1). Neither the main effect of training group nor the interaction term (Time x Training group) reached significance, indicating that training groups neither differed in their error switching costs overall nor in their reduction of error switching costs over training.

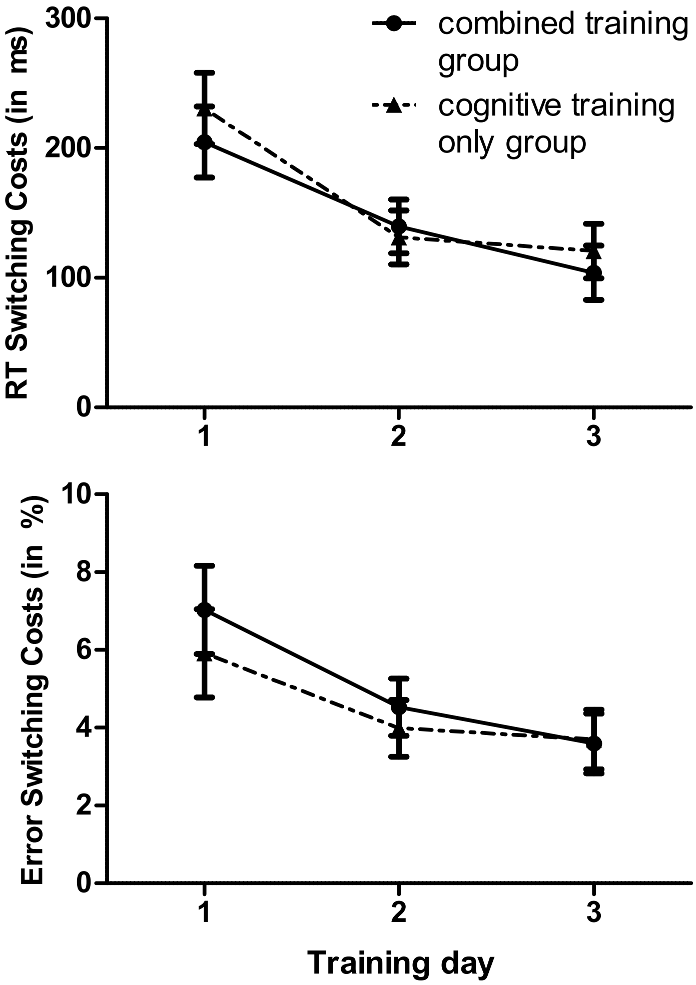

Figure 1: Trajectories of RT switching costs (mean switching costs in ms ± SE) and error rate switching costs (mean switching costs in % ± SE) in the training task over the course of the three training days in the combined training group and the cognitive only training group.

An additional dependent t-test for paired samples revealed that error rates for nonswitch trials increased from the first training day to the last training day, M = 3.2 %, SD = 6.5, whereas error rates for switch trials did not change, M = 0.4 %, SD = 6.9, $t(39) = 3.8$, $p < .001$ (see Table 2 for complete mean RT and error data). Changes in error rates did not differ significantly between the two training groups.

3.3.2 Transfer effects of task switching training to non-trained tasks

The second set of analyses was conducted with all participants to answer the second and third research question, that is, what specific transfer effects can be found in adolescents after task switching training and if prior exercise influences transfer effects. To explore performance changes in transfer tasks between the pretraining and posttraining assessments, differences between the cognitive training and control groups, and possible differences between exercise and no exercise groups, two separate three-factorial MANOVAs were conducted for RT data (switching and mixing costs, RT, and interference scores) and error data (error rate switching and mixing costs and accuracy rates) in the transfer tasks. Cognitive training (training vs. no training) and exercise intervention (exercise vs. no exercise) served as between-subjects factors and time of measurement (pretraining vs. posttraining) as the within-subject factor. To account for multiple comparisons, we first looked at effects of the three factors on the combined dependent variables of RT and accuracy transfer measures, respectively. If the multivariate analyses were significant, separate follow-up ANOVAs were conducted to disentangle which of the single dependent variables contributed to the multivariate effect.

3.3.2.1 Transfer effects to RT measures

A three-factorial MANOVA for RT measures included near transfer mixing and switching costs, number switch mixing and switching costs, RT for correct trials on the 2-back task, Flanker interference score and Stroop interference score, as well as simple and choice reaction time (see Table 3 for mean performance on these dependent measures before and after training in the four different groups, and Table A1 for complete mean RT data for switching and inhibition tasks). Analyses revealed a significant effect of time of measurement on the combined dependent variable of RT transfer measures, $F(9, 68) = 24.9$, Wilks' Lambda = .23, $p < .001$, partial $\eta^2 = .77$, indicating overall changes in RT measures from pretraining to posttraining assessments. Furthermore,

Table 3: Performance on main dependent RT measures in transfer tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact)

Training groups	**COMBINED TRAINING**				**COGNITIVE TRAINING**			
	Pretraining		Posttraining		Pretraining		Posttraining	
	M	(*SD*)	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)
Switching Tasks								
Food/Size MC (RT in ms)	213	(134)	97	(99)	206	(102)	64	(104)
Food/Size SC (RT in ms)	221	(128)	137	(125)	242	(93)	114	(115)
Number MC (RT in ms)	727	(214)	537	(243)	724	(246)	560	(232)
Number SC (RT in ms)	199	(172)	81	(133)	121	(174)	123	(141)
Updating Tasks								
2-back RT in ms	875	(118)	793	(111)	861	(97)	752	(130)
Inhibition Tasks								
Flanker interference in ms	19	(26)	11	(25)	23	(28)	20	(38)
Stroop interference in s	18	(7)	15	(8)	19	(8)	18	(10)
Speed Tasks								
Simple RT in ms	286	(42)	281	(39)	284	(57)	294	(63)
Choice RT in ms	440	(52)	426	(50)	441	(88)	415	(70)
Control groups	**EXERCISE ONLY**				**NO-CONTACT**			
Switching Tasks								
Food/Size MC (RT in ms)	200	(109)	134	(107)	242	(124)	175	(75)
Food/Size SC (RT in ms)	218	(125)	136	(85)	309	(157)	163	(136)
Number MC (RT in ms)	675	(325)	540	(211)	828	(217)	690	(173)
Number SC (RT in ms)	148	(140)	123	(175)	167	(201)	126	(144)
Updating Tasks								
2-back RT in ms	865	(109)	794	(99)	868	(101)	816	(106)
Inhibition Tasks								
Flanker interference in ms	17	(41)	21	(26)	9	(20)	10	(33)
Stroop interference in s	17	(8)	13	(4)	18	(11)	15	(5)
Speed Tasks								
Simple RT in ms	282	(36)	293	(36)	277	(30)	280	(37)
Choice RT in ms	439	(62)	439	(54)	428	(59)	426	(49)

Note. MC = Mixing Costs; SC = Switching Costs; Flanker interference (RT incongruent trials - RT congruent trials); Stroop interference (overall naming time 3rd run - overall naming time 2nd run).

there was a significant interaction interaction term between time of measurement and cognitive training, $F(9, 68) = 2.7$, Wilks' Lambda = .74, $p < .009$, partial $\eta^2 = .26$, indicating that changes from pretraining to posttraining differed between groups with and without cognitive training. None of the other main or interaction effects reached significance. Therefore, follow-up analyses were conducted to explore the contribution of the individual RT measures for the effects of time and the interaction of time and cognitive training.

For RT mixing costs in the near transfer switching task (i.e., the food-size switching task), the separate ANOVA revealed a significant main effect of time, $F(1, 76) = 70.9$, $p < .001$, partial $\eta^2 = .48$, and a significant interaction term (Time x Cognitive Training), $F(1, 76) = 7.2$, $p < .009$, partial $\eta^2 = .09$. That is, the training groups reduced their RT mixing costs more from pre- to posttraining than the control groups - suggesting transfer to RT mixing costs in the near transfer switching task (see Figure 2). For switching costs in the near transfer task, analyses revealed a significant main effect of time for RT switching costs, $F(1, 76) = 72.5$, $p < .001$, partial $\eta^2 = .49$, indicating reductions of switching costs from pre- to posttest. The interaction term (Time x Cognitive Training) did not reach significance, indicating that training and control groups did not differ in their reduction of RT switching costs from pre- to posttest.

For the number switch task, analyses revealed a significant effect of time for RT mixing costs, $F(1, 76) = 53.7$, $p < .001$, partial $\eta^2 = .41$, and for RT switching costs, $F(1, 76) = 4.3$, $p < .04$, partial $\eta^2 = .05$. This indicates reductions of RT mixing and switching costs from pre- to posttest in all participants. The interaction term (Time x Cognitive Training) did not reach significance, indicating that training and control groups did not differ in their reduction of mixing or switching costs from pre- to posttest.

In the domain of updating, a significant effect of time was found for RT on correct responses in the 2-back task, $F(1, 76) = 67.7$, $p < .001$, partial $\eta^2 = .47$. This indicates that, overall, participants reacted faster posttraining than pretraining on the 2-back task. Importantly, there was a tendency for a significant interaction term (Time x Cognitive Training) for mean RT for correct responses, $F(1, 76) = 3.2$, $p < .08$, partial $\eta^2 = .04$, that is, cognitive training groups tended to reduce their RTs more from pre- to posttest than control groups.

In the inhibition domain, no significant effects were found for the Flanker interference score, indicating neither changes from pre- to posttraining nor differences between cognitive training and control groups. For the Stroop interference score, analyses revealed a significant main effect of time, $F(1, 76) = 7.8$, $p < .006$, partial $\eta^2 = .09$, corresponding

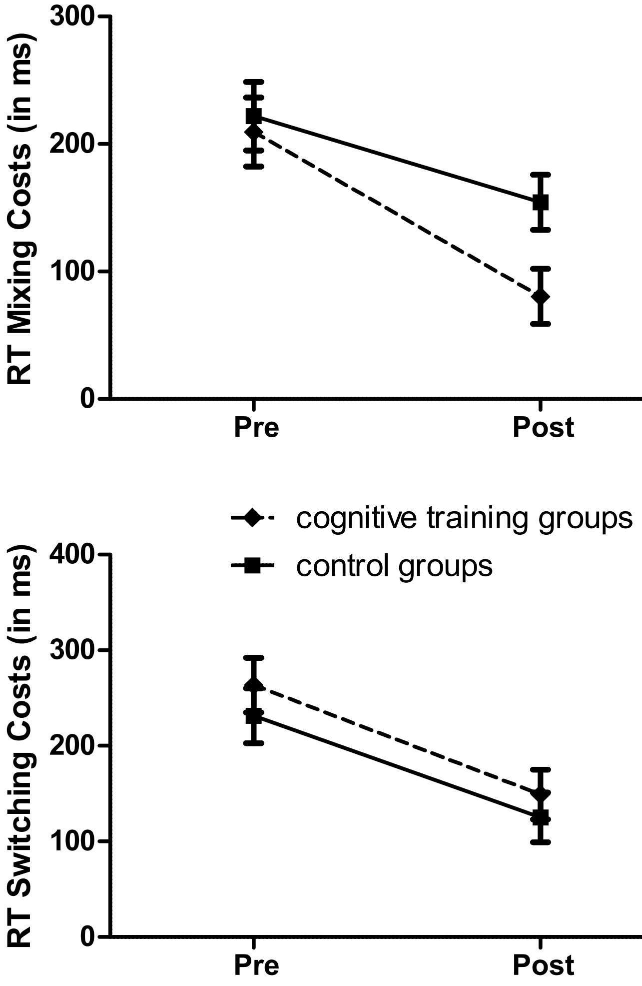

Figure 2: Changes of RT mixing and switching costs (in ms ± SE) in near transfer switching task from pre- to posttraining assessments in the cognitive training groups and the control groups.

to reductions in the interference score from pretraining to posttraining. No other effects reached significance, indicating no differences between groups in changes from pre- to posttraining.

For mean choice reaction times, analyses revealed a significant main effect of time, $F(1, 76) = 7.1$, $p < .009$, partial $\eta^2 = .09$, that is, participants performed the task faster at posttraining assessments than prior to training. Furthermore, there was a significant interaction term (Time x Cognitive Training) for mean choice reaction time, $F(1, 76) = 5.5$, $p < .02$, partial $\eta^2 = .07$, that is, cognitive training groups reduced their RTs more from pre- to posttest than control groups. No significant effects were found for the simple reaction time task.

In summary, on the level of RT measures, transfer effects of a tasks switching training (as indicated by a significant interaction between time and cognitive training) were found. In particular, mixing costs in the near transfer task (switching) and choice reaction time (speed) contributed to this overall transfer effect. There was also a tendency for a contribution of the 2-back task (updating), but not for any of the other tasks included. Furthermore, on a RT level, there was no indication of an additional effect of the exercise intervention as would be indicated by a significant three-way interaction term between time, cognitive training, and exercise intervention.

3.3.2.2 Transfer effects to accuracy measures

A three-factorial MANOVA for accuracy measures included near transfer mixing and switching costs derived from error rates, number switch mixing and switching costs derived from error rates, accuracy rate (hits) for the 2-back task, accuracy rate in the keep track, the Flanker, and the choice reaction time task (see Table 4 for mean performance on these measures before and after training in the four different groups Table A2 for complete mean error data for switching tasks). Analyses revealed only one significant effect: the effect of cognitive training for the combined accuracy transfer measure, $F(8, 69) = 2.2$, Wilks' Lambda $= .80$, $p < .04$, partial $\eta^2 = .20$, indicating overall differences in accuracy measures for participants with and without cognitive training. No other main or interaction effects reached significance. Therefore, follow-up analyses were conducted to explore the contribution of the separate accuracy measures to the cognitive training effect.

On the accuracy level, analyses revealed no significant effect for switching costs in the near transfer tasks. For mixing costs on this tasks, analyses revealed a significant main effect of cognitive training group, $F(1, 76) = 7.2$, $p < .009$, partial $\eta^2 = .09$,

Table 4: Performance on main dependent accuracy measures (in %) in transfer tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact)

Training groups	**COMBINED TRAINING**				**COGNITIVE TRAINING**			
	Pretraining		Posttraining		Pretraining		Posttraining	
	M	(*SD*)	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)
Switching Tasks								
Food/Size MC (error)	3.9	(4.2)	4.5	(5.7)	3.0	(5.2)	5.1	(8.6)
Food/Size SC (error)	3.0	(5.1)	3.1	(7.1)	4.7	(4.6)	4.7	(7.4)
Number MC (error)	0.8	(11.3)	4.4	(8.9)	2.1	(6.5)	2.3	(6.4)
Number SC (error)	2.6	(5.7)	6.5	(8.7)	5.0	(9.4)	4.7	(9.2)
Updating Tasks								
2-back accuracy (hits)	69.0	(11.2)	72.8	(16.2)	70.5	(11.1)	71.5	(12.4)
Keep Track accuracy	59.8	(13.3)	63.8	(17.0)	62.5	(16.4)	67.4	(15.7)
Inhibition Tasks								
Flanker accuracy	91.3	(10.8)	93.7	(4.4)	91.6	(6.1)	90.6	(7.2)
Stroop accuracy	99.3	(1.1)	99.8	(0.7)	99.4	(0.8)	99.7	(0.7)
Speed Tasks								
Choice reaction accuracy	94.5	(4.5)	93.8	(4.3)	92.2	(5.8)	91.7	(7.7)
Control groups	**EXERCISE ONLY**				**NO-CONTACT**			
Switching Tasks								
Food/Size MC (error)	1.6	(5.0)	1.3	(4.8)	1.5	(4.4)	2.6	(4.5)
Food/Size SC (error)	4.6	(3.9)	1.9	(6.9)	3.4	(4.6)	3.4	(5.5)
Number MC (error)	2.6	(4.8)	3.8	(7.7)	2.9	(5.9)	-0.4	(10.8)
Number SC (error)	1.2	(6.5)	3.1	(7.6)	4.3	(7.5)	5.4	(6.1)
Updating Tasks								
2-back accuracy (hits)	66.2	(13.5)	69.7	(15.9)	67.0	(17.2)	71.8	(15.4)
Keep Track accuracy	62.2	(12.2)	63.6	(15.5)	63.1	(10.7)	64.2	(16.)
Inhibition Tasks								
Flanker accuracy	89.4	(18.0)	93.7	(4.6)	93.6	(3.7)	92.2	(5.5)
Stroop accuracy	99.4	(0.7)	99.6	(0.8)	99.4	(1.0)	99.7	(0.6)
Speed Tasks								
Choice reaction accuracy	95.4	(2.9)	95.8	(3.4)	94.9	(2.6)	95.0	(3.2)

Note. MC = Mixing Costs; SC = Switching Costs; RT = Reaction Time.

indicating higher error rate mixing costs in the cognitive training groups compared to the control groups. For the number switch task, no significant effects were found for either switching or mixing costs derived from error rates. Neither in the updating domain (for accuracy in the 2-back task) nor in the inhibition domain (for accuracy in the Flanker task), significant effects were found, indicating no differences between cognitive training and control groups. For choice reaction accuracy rates there was a significant effect of cognitive training, $F(1,\ 76) = 5.9$, $p < .02$, partial $\eta^2 = .07$, with cognitive training groups having lower accuracy rates than control groups, overall.

To summarize, no transfer effect was found on the accuracy level for any of the tasks (as would be indicated by a significant interaction between time and cognitive training). Furthermore, there was no indication of an influence of the exercise intervention on the transfer effects on the accuracy level (as would be indicated by a significant three-way interaction term between time, cognitive training, and exercise intervention). Analyses indicated differences between groups with and without cognitive training. In particular, mixing costs (error) in the near transfer task and accuracy on the choice reaction time task contributed to this effect, with control participants performing better overall than trained participants.

3.3.3 Relationships between training gains and transfer gains

To explore possible relationships between observed training gains and changes in performance in transfer tasks on the level of RTs, correlational analyses were conducted for the cognitive training groups. Training gains in RT switching costs (difference between first and last training day) were correlated with transfer gains (difference between pre- and posttraining assessment) in tasks where transfer effects had been indicated in the previous analyses, namely RT mixing costs in the near transfer switching task, choice reaction time, and RT for correct responses in the 2-back task. One significant correlation emerged between training gains in RT switching costs and pre-posttraining gains in RT in the 2-back task, $r = .42$, $p < .007$, indicating larger reductions of RT switching costs during training being associated with larger reductions in 2-back RT from pre- to posttraining in the trained groups.

3.4 Discussion

Current study set out to explore if executive control can be trained in the age group of adolescents with a task switching training. Transfer was investigated systematically in all three executive control facets, i.e., switching, updating, and inhibition. Furthermore, current study aimed at exploring the recently proposed favorable effect of acute bouts of exercise on cognitive training. Analyses indicated that both training groups significantly reduced their switching costs (both on a RT and error rate level) over the course of three training sessions and also reduced their RT mixing costs in a near transfer task more from pre- to posttraining than the non-trained control groups. These findings indicate that executive control can be enhanced in adolescents through cognitive training. This is the first study to demonstrate plasticity of cognitive control in a group of adolescents and thus adds some novel findings to the growing literature on plasticity of executive control in different non-clinical age groups (Jaeggi et al., 2008; Karbach & Kray, 2009; Loosli et al., 2012). Interestingly, reductions of switching costs in this task switching training were found to be rather similar to those reported by Karbach and Kray (2009) for children and adults. This suggests a robust finding of significant reductions in switching costs over the course of very few (three or four, respectively) sessions of training with one session per week. A comparison of RTs over the course of training suggests that this training effect was driven by larger reductions in RTs in switch trials as compared to nonswitch trials. This may indicate that training specifically improves processes necessary to switch from one task to the other as compared to a general speed up of responses. For error rates analyses indicated slight increases over training for nonswitch trials whereas error rates in switch trials remained stable. Speculating on this finding, these changes in error rates may relate to slight reductions in motivation over training or increases in the relative focus on switch trials because of increased salience of the switching requirement.

Regarding transfer of the task switching training, current findings indicate some, but limited transfer of the training on the level of RT measures. First, transfer was found to a near transfer task that was structurally similar to the one trained. Specifically, transfer was observed for RT mixing costs but not for RT switching costs. In contrast to the study by Karbach and Kray (2009), that found transfer for both types of costs in a near transfer switching task, our findings correspond to other studies that found transfer only to mixing costs (Minear & Shah, 2008). In Minear and Shah's and the current study transfer was found for the type of costs that corresponds to the more global ability to maintain and select two different task sets as opposed to switching costs that reflect more specifically the actual act of switching from one task to the other (Braver et al., 2003; Kray & Lindenberger, 2000). One may speculate that the specific task switching training used emphasizes the ability to maintain different tasks at the same time because there are no external cues and may therefore transfer reliably to other instances where maintenance is needed. During the task switching training, the participant has to maintain the tasks to be executed, keep track of how many times one task is executed, and keep track of which task to perform next. There is some evidence from other studies suggesting that updating or working memory (especially verbal rehearsal) is indeed crucial for performing these kinds of task switching tasks (Allen & Martin, 2010; Kray et al., 2010), especially if they are not cued trial-by-trial. The current study design does not allow to specifically investigate the changes of mixing costs during training. Because the training regimen by Karbach and Kray (2009) that we used in the current study does not include single-task blocks comparing performance between single and mixed tasks blocks (mixing costs) is not possible. Exploring changes of both types of performance costs over the course of training (that includes single-task blocks) and their relationship with transfer would therefore be an important avenue for future studies and would help to support our tentative suggestions about involved processes.

Improvements in the task switching training on a RT level were correlated with improvements in the speed of responses in an updating task. Furthermore, although not significant, a tendency for a transfer effect was found for the speed of responses in the updating task. This may support the importance of updating as a process possibly underlying the training and transfer effects in task switching trainings and may indicate that this particular (self-cued) task switching training improved the more general ability to update. This is in line with a recent study that demonstrated transfer of the same task-switching training to a near transfer switching and an updating task that was associated with changes in right prefrontal and superior parietal brain regions as well as the striatum (Karbach & Brieber, 2011, September).

However, findings of transfer were generally rather limited as has also been suggested in other studies (e.g., Dowsett & Livesey, 2000; Li et al., 2008; Strobach et al., in press). In addition to transfer in one task switching and one updating task, transfer was found for a speed task on the RT measure (suggesting larger improvements in speed of simple decisions in the training as compared to the control groups), but neither for inhibition tasks nor to the other updating or switching tasks. Furthermore, in contrast to the RT measures, no indication of transfer was revealed on the level of accuracy in the transfer tasks. This may point to differential effects for speed- and accuracy-related measures. Findings may suggest that effects of a task switching training in adolescents manifest more in faster task execution (possibly related to faster updating and decision making) than in more accurate execution of tasks.

The transfer effects were not as strong as the ones reported by Karbach and Kray (2009) although the training regimen were very similar. Different possible factors may explain this discrepancy. Firstly, it may be that one modification we did to their protocol in terms of duration (three versus four sessions) has resulted in a training dose that was not enough to produce robust transfer effects. That is a possibility, especially when comparing current training regimen with considerably more extensive training regimen like the ones used by Jaeggi and colleagues (2008, with 8 to 19 sessions) or Klingberg and colleagues (2005, with 25 sessions) and recent study that even included as many as 100 training sessions (Schmiedek et al., 2010). However, Karbach and Kray (2009) found a range of transfer effects with only four training sessions. In addition, more importantly, training improvements in the current study were comparable to those reported by Karbach and Kray (2009). Nevertheless, it is reasonable to assume that a certain amount or intensity of executive control training may be a prerequisite for substantial changes to occur (see, e.g., Klingberg, 2010) and we would find broader transfer effects with a larger amount of training. Considering plasticity as the potential of brain and behavior to change in response to environmental challenges (e.g., cognitive demands of an executive control training), the amount of plastic changes and therefore the amount of transfer may strongly depend on the intensity and duration of the challenge. Spacing of the cognitive training sessions may also play a role here, that is, whether training sessions are concentrated over a short period of time (e.g., daily sessions like in the study by Jaeggi et al., 2008) or spaced over several weeks like in the current study.

Furthermore, the target age group of the current study may be of relevance for the observed lower amounts of transfer. It may be that in the group of adolescents, although there are still mean level changes observable in normative developmental studies, domains of executive control may show different developmental trajectories (Huizinga et al., 2006) and may therefore be more or less prone to training and transfer effects than in other age groups. It is also possible that the specific transfer tasks used did not share enough relevant features or required processes with the trained task to find reliable transfer. For example, it could be that task switching training enhanced aspects of maintenance ability and transfer to the number switch task was not found because task choice was cued and requirements to maintain task order and number were very low in this transfer task (the cue was present the whole time until a response was made, thus very little maintenance is needed). Thus, future studies on the plasticity of executive control functions should explore the moderating effects of training domain and training intensity, as well as the role of age-dependent differences on the effects of cognitive trainings (Klingberg, 2010).

The third exploratory research question concerned a novel proposal in the training literature (e.g., Hillman et al., 2009), i.e., possible effects of a combination of an acute exercise intervention with the cognitive training. Analyses revealed no reliable effects of this intervention on training or transfer tasks. Thus, our initial data does not provide strong evidence in favor of the suggestion that this type of exercise intervention may have a positive impact on the effects of cognitive training. However, of course, our findings are preliminary and could be due to different factors. It could be that, in this context, acute exercise has no effect on task switching and/or learning. This is in accordance with studies that have not been able to show an effect of acute exercise on switching (e.g., Tomporowski et al., 2008, but see, e.g., Pesce et al., 2003 for findings of positive effects). Other domains of cognitive control may be more receptive for these kinds of effects, e.g., there are a range of studies showing improvements in inhibition tasks (e.g., Hillman et al., 2009; Yanagisawa et al., 2010, but see, e.g., Stroth et al., 2009 for findings of no such effect). It is also possible that different intensities or types of exercise would have different effects, for example exercise that requires more coordination skills than cycling as has been suggested in a study by Budde, Voelcker-Rehage, Pietrassyk-Kendziorra, Ribeiro, and Tidow (2008). In addition, it is important to note from a methodological point of view that most studies on acute exercise effects used a within-subjects design (see, e.g., Pontifex et al., 2009; Stroth et al., 2009; Yanagisawa et al., 2010) whereas current study employed a between subjects design to compare exercise to non-exercise. That may have made it more difficult to detect possibly small effects. To further explore the proposed effects of exercise, future research will have to further examine these issues by exploring the effects of different types of exercise on cognitive training efficiency.

To summarize, current study showed that task switching abilities can be trained in adolescents. Transfer was revealed at the level of RT measures in a similar task switching task, a speed task and a (tendency for) an updating task. Conceptually interesting, updating seems to play a crucial role in this task switching training and its possible transfer effects. The importance of updating processes is in line with a range of cognitive training studies that have used updating and working memory tasks and have been able to show robust training and transfer effects. An additional positive effect of acute exercise could not be demonstrated - thus, possible factors that influence the amount of training and transfer effects remain to be explored in future studies.

4 Study 2 - Effects of a Working Memory Training in Old-Old adults

4.1 Introduction

Aging is associated with functional loss in many cognitive domains, in particular processing speed, memory, and executive functions (Park et al., 2002). For a long time, the possible modifiability of this functional decline in old age, in particular through cognitive training interventions, has received a lot of interest in gerontology and geriatrics. This line of research has led to mainly positive news; especially for young-old adults (60-80 years). Young-old adults seem to be able to recruit effective encoding and retrieval strategies to compensate for some aspects of the cognitive losses arising during late life: a range of training studies suggest that in young-old adults episodic memory capacity can be enhanced through teaching mnemonic strategies (e.g., the method of loci, Verhaeghen et al., 1992). In contrast, although there are far fewer studies targeting old-old adults (80+ years), this age has been described as an age of substantial loss in cognitive plasticity. Available reports clearly suggest a decline of old-old adults' ability to benefit from strategy-based interventions, with considerably smaller improvements obtained in those interventions (Singer et al., 2003) for old-old adults as compared to young-old adults.

Over the last few years, a promising conceptual alternative to strategy-based episodic memory training interventions has emerged which focuses on training working memory (WM) capacity. WM has been defined as the ability to maintain (store) and manipulate (process) information within short periods of time and comprises a verbal (phonological), a visuospatial, and an executive subsystem (Baddeley, 2003). WM is a central neurocognitive processing resource that is involved in most conscious everyday mental activities. It is thought to support a wide range of complex cognitive activities, including logical reasoning and problem solving, has been shown to be strongly related to measures of fluid intelligence (Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle et al., 1999), and is even involved in emotion regulation and social interactions

(Baddeley, 2003; Engle et al., 1999).

Given its importance for cognitive functioning, it is rather surprising that so far research on WM training is scarce (Baddeley, 2003; Conway et al., 2002; Engle et al., 1999). One reason for the scarcity of WM training studies may be that, until recently, WM capacity had been conceptualized as a stable trait representing inter-individual differences (Engle et al., 1999). However, the rationale for the newer process-oriented training studies is that WM performance may be improved through repeated practice on WM tasks (rather than through teaching strategies). Secondly, because WM is involved in a wide range of cognitive functions, training gains in WM may possibly lead to improvements in those functions also. Indeed, recent training studies targeting WM processes through repeated practice have revealed promising results in this regard. They have been able to show improvements in WM functions for children with ADHD, children with low WM skills (Klingberg et al., 2005; Holmes et al., 2009), and young adults (Jaeggi et al., 2008). Additionally, some studies have also provided preliminary evidence for transfer effects to non-trained tasks (Klingberg et al., 2005; Jaeggi et al., 2008).

Importantly for present purposes, very recently those effects have also been shown for older adults. Besides its general importance for human cognitive functioning, the possibility of improving WM capacity in older adults is of particular relevance for gerontology and geriatrics as cognitive aging research has revealed substantial mean level decreases in WM in old age (in both verbal and spatial WM tasks, Park et al., 2002; Bopp & Verhaeghen, 2005). Particularly in old-old adults, WM capacity has been shown to decrease substantially (Craik, 2000; Gilinsky & Judd, 1994). However, until now only a handful of WM training studies have been conducted with participants of an older age range, and only one of them has approached the old-old age range. Those studies provided evidence for some training-induced plasticity in young-old adults (60 to 80 years), for example by applying an executive control training using a task switching paradigm (Buchler et al., 2008). Also, after five weeks of training on an updating task (i.e., recalling the last items out of sequences of consecutively presented items) young-old adults with a mean age of 68 were comparable in their performance gains on the trained task to a young control group (Dahlin, Nyberg, et al., 2008). Similarly, Li and colleagues found improved performance in young-old adults with a mean age of 75 after six weeks of training on a visuospatial n-back task (Li et al., 2008). So far, only one study has investigated plasticity of WM on the edge to old-old age, with promising results: after a three-month intervention to train visuospatial WM a group of 80-year-old adults improved their WM performance on all trained tasks (Buschkuehl et al., 2008).

Findings on transfer effects in all the mentioned studies, however, were heterogeneous and suggest that transfer may be restricted. Dahlin and colleagues (2008) found transfer after their updating training only in their young participants. Buschkuehl and colleagues (2008) found a clear transfer effect only for a visuospatial WM task, not for a verbal one. Since their WM training tasks were all visuospatial, their transfer effects seem to be specific to the type of memory content. Although Li and colleagues (2008) demonstrated transfer of their visuospatial n-back WM training to visuospatial as well as numerical n-back tasks in both young and old participants, they found no transfer to more complex WM span tasks. Thus, transfer was restricted to WM tasks that were very similar to training tasks with regard to involved processes.

Following up on this recent development, the present study set out to examine a range of open issues that are currently under debate. (i) Because of the small number of WM training studies in old age, it is not yet clear whether plasticity in WM is still preserved in old-old age and whether and to what extent transfer effects may be observed (see, e.g., Mayr, 2008, who pointed out the importance of this open issue). The current study focused on far transfer tasks because, although transfer to some similar WM tasks has already been demonstrated, it is not yet clear whether WM training can transfer to more complex (executive control) tasks. (ii) Another open question is the issue of optimal training time. Most former training studies have used extended periods of training over several weeks or months to achieve effects (e.g., Li et al., 2008 trained for six weeks; Buschkuehl et al., 2008 for 12 weeks). However, both from a theoretical perspective studying underlying processes and from an applied perspective in clinical contexts, in which clinicians are often confronted with time constraints, it is important to explore when those effects emerge and whether shorter durations of training are powerful enough to induce similar effects. Therefore, the second aim of the present study was to explore whether and to what extent adults who are well within the old-old age range can still profit from a WM training that is set up as a considerably shorter training regimen. (iii) A third research question that the present study aimed to address is whether differential training effects can be observed depending on the participants' functional status before training. In other words: can subgroups of participants be identified who profit more from training than others? In particular, the role of WM ability level at the beginning of training was explored. Considering the previous literature two possible predictions can be derived. On the one hand, it may be that especially in old-old adulthood only those participants who have maintained a certain cognitive status profit from a WM intervention that requires a considerable amount of attentional resources (Bissig & Lustig, 2007; M. Baltes et al., 1995; Yesavage, Sheikh, Friedman, & Tanke, 1990). On the other hand, resting on the disuse hypothesis (Gatz et al., 2001; Kliegel et al., 2004), it may be that participants who start with a low cognitive status (a possible result of a decline in using cognitive resources) are able to reactivate some of their potential with the help of training.

4.2 Methods

4.2.1 Participants

Participants of the study were old-old adults between the ages of 77 and 96. The training group consisted of 20 old-old adults and was matched for age, gender, education, and functional health to a control-group comprising 16 old-old adults (see Table 5 for demographic characteristics and cognitive functioning of the two groups). Exclusion criteria were neurological or psychiatric disorders known to cause cognitive dysfunction, in particular Mild Cognitive Impairment or Alzheimer's disease. This was screened for with the Mini Mental Status Test (MMST) German short form for old-old adults by Kliegel, Rott, d'Heureuse, Becker, and Schönemann (2001) which takes possible age-associated impairments in visual or motor functioning in extreme old age ranges into account. Maximum sum score on this test is 21. All individuals scored above the levels indicating cognitive decline (Rott, d'Heureuse, Kliegel, Schönemann, & Becker, 2001). The two groups were comparable in cognitive functioning (MMST) and crystallized intelligence, assessed with a German vocabulary test (MWT, Lehrl, Merz, Burkhard, & Fischer, 1991).

4.2.2 Training tasks

Following the WM training regime by Klingberg, Forssberg, and Westerberg (2002); Klingberg et al. (2005), the training material comprised both verbal (Digit span forward and backwards, HAWIE-R, Tewes, 1994) and visuospatial WM tasks (Corsi block tapping forward and backwards, Berch, Krikorian, & Huha, 1998; K-ABC Icons, Kaufmann Assessment Battery for Children, Melchers & Preuss, 1991). Thus, training included tasks that mostly require storage of information (Digit span and Corsi block tapping forward; K-ABC Icons) as well as tasks that additionally require processing components of WM (Digit span and Corsi block tapping backwards). All tasks were administered in

Table 5: Participant characteristics of the training group (n = 20) and the control group (n = 16)

	Training group *M*(*SD*)	**Control group** *M*(*SD*)
Gender	14 women	11 women
Age	86.8 (4.9)	87.1 (3.7)
Education in years	11.7 (3.3)	10.1 (1.9)
Cognitive functioning (MMST)	19.4 (1.4)	19.3 (1.5)
Crystallized Intelligence (MWT)	31.1 (3.3)	29.4 (3.0)

Note. MMST = Mini Mental Status Test short form for old-old adults by Kliegel et al. (2001) with a maximum score of 21; MWT = Mehrfach-Wortschatz-Intelligenztest version A by Lehrl et al. (1991).

individual face-to-face sessions using paper-pencil materials instead of a computerized format since the old-old population usually has no computer experience. Difficulty levels were individually adapted because adaptivity has been shown to be an essential feature of effective training regimes Klingberg et al. (2002, 2005).

In the Digit span task, participants had to repeat numbers that were verbally presented in sequences of increasing length in either the same order (forward) or, in the second half of the task, in reversed order (backwards). In the Corsi block tapping task the experimenter tapped a number of blocks on a board in sequences of increasing length. The participant had to reproduce the sequences by tapping immediately after the experimenter had finished, either in the same order (forward) or, in the second half, in reversed order (backwards). In both tasks, the number of items presented was increased when the participant was successful in completing a sequence. For motivational purposes, the training block ended if the participant failed to recall two sequences of the same number of items correctly. The (modified) K-ABC-Icons task is an adaptive visuospatial WM task where the participants had to process and maintain the spatial arrangement of multiple stimuli. An increasing number of pictures of objects (icons) was presented to the participant, first in a 3x3 grid and than in a 3x4 grid to adaptively increase WM load. The participant had to memorize the icons and their individual locations within the presentation time of three seconds and reproduce the icons and their positions on an empty grid afterwards. The task ended when the participant unsuccessfully completed two items with the same number of icons.

4.2.3 Training procedure

Training was administered in daily sessions of 25-30 minutes over two weeks. To avoid sequence effects, the order of tasks was counterbalanced and varied daily. Parallel versions of the tasks were used each day. The training group received 10 training sessions over two weeks, including a weekend break. The compliance rate was high: 96 % of all training task blocks were fully completed. The control group received no treatment.

4.2.4 Assessment of transfer

Two to three days before and after training, respectively, the training group completed a pre-training assessment and a post-training assessment including two standard cognitive tasks to assess far transfer (executive control). Inhibitory control was assessed using a Stroop interference task (German version of the color-word-Stroop test: FWIT, Bäumler, 1985). Nonverbal complex reasoning ability was assessed with the Raven Colored Progressive Matrices (Raven, Court, & Raven, 1976). These tasks were chosen, because they have been shown to be related to WM, the targeted function in the current training regime (Conway et al., 2002). The control group was also assessed twice with these tasks, with approximately two weeks between the two assessments.

4.2.5 Data analyses

Following the studies on WM training by Klingberg et al. (2002, 2005) paired t tests were run for each group to test for significant performance differences between the pre-training and post-training assessments in all training and transfer tasks. Effect sizes were calculated as Cohen's d, that is, the standardized mean difference in performance between pretest and posttest (pre-posttest difference divided by the pooled standard deviation). All d values were corrected for small sample bias following Hedges and Olkin (d', Hedges & Olkin, 1985). Then individual performance gains on each training and transfer task (in percent) were compared between groups using independent t tests. To further analyze the course of performance changes during training in the training group a repeated-measures ANOVA with all training days was conducted. Wherever necessary, corrections for the lack of sphericity were applied. Additionally, to further analyze the longitudinal trends observed in the ANOVAs, paired t tests were used to test for differences between performance in the 1st and 5th training sessions (beginning and end of first training week) and between performance in the 6th and 10th training sessions (beginning and end of second training week). To explore differential training effects, for each training task, the training group was divided via median split on pre-training performance into subgroups of high- and low-capacity individuals. Paired t tests were used to analyze performance gains in trained tasks from pre to post-training in the group of participants with low WM capacity and in the group of participants with high WM capacity separately. To compare the magnitude of training gains between the low and high WM capacity groups and between the low WM capacity training group and the control group independent t tests were applied.

4.3 Results

4.3.1 Comparing performance in trained tasks

For the training group paired t tests comparing pre-post WM performance revealed significant performance gains for Digit span forward ($t(19)$ = -2.1, $p < .05$, *d'* = 0.49), for Digit span backwards ($t(19)$ = -3.0, $p < .01$, *d'* = 0.56), for Corsi block tapping backwards ($t(19)$ = -3.8, $p < .001$, *d'* = 0.93), and for K-ABC-Icons ($t(19)$ = -4.0, $p < .001$, *d'* = 0.98). There was a trend towards significance for performance gains in Corsi block tapping forward ($t(19)$ = -1.8, $p < .09$, *d'* = 0.47). According to Cohen's convention (Cohen, 1988) effects in Corsi block tapping backwards and K-ABC Icons were large, all others were medium.[1] In contrast, there was only one significant retest effect (K-ABC Icons: $t(19)$ = -3.6, $p < .01$, *d'* = 1.04) for the control group (all other $ps > .1$). Importantly, in comparison to the control group, the training group had significantly higher pre- to post-training gains in percent for Digit span forward (37 vs. -9 %, $t(29.0)$ = 2.7, $p < .01$), Corsi block tapping forward (37 vs. 1 %, $t(25.3)$ = 2.2, $p < .04$) and there was a trend toward significance for higher pre-post-training gains in Corsi block tapping test backwards (46 vs. 18 %, $t(34)$ = 1.7, $p < .09$; see Figure 3 for descriptive results).

In a more detailed analysis of the training progress over the ten training sessions, repeated measures ANOVAs with all ten training sessions were computed. Performance on four of the trained tasks changed significantly across training sessions: for K-ABC Icons, $F(5.4, 75.3) = 5.9$, $p < .001$ (Greenhouse-Geisser corrections for lack of sphericity were applied), a trend analysis indicated that the linear trend was significant, $p < .001$,

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[1] Preliminary data from a subset of participants in the treatment group ($n = 9$) suggests that training gains remained relatively stable over a period of two weeks: performance in the Corsi-Block and Digit span tasks forwards and backwards, respectively, did not differ significantly between posttest and follow-up two weeks later (all $p > .05$).

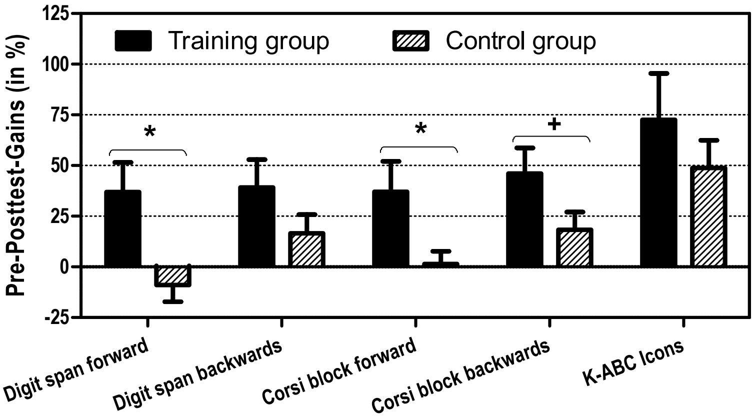

Figure 3: Comparisons between the training group (n = 20) and control group (n = 16) for mean training gains in percent for each training task separately. Error bars indicate standard errors. Significant differences between groups are indicated: $^{*}p < .05$, $^{**}p < .01$, $^{+}p < .10$.

as was the quadratic term, $p < .002$; for Digit span forward, $F(9, 126) = 4.8$, $p < .001$, a trend analysis indicated that the linear trend was significant, $p < .006$, as was the cubic term, $p < .05$; for Corsi block tapping forward, $F(9, 99) = 2.0$, $p < .05$, a trend analysis indicated that the linear trend was significant, $p < .01$, and there was a trend for the quadratic term, $p < .09$; for Corsi block tapping backwards, $F(9, 81) = 3.8$, $p < .001$, a trend analysis indicated that the linear trend was significant, $p < .001$. For Digit span backwards there was a marginally significant effect for changes in performance across training sessions: $F(9, 126) = 1.8$, $p < .07$, a trend analysis indicated that the linear trend was approaching significance, $p < .06$, as was the cubic term, $p < .08$. To further illustrate these training trends, the two training weeks were examined separately. Paired t tests comparing the first and last day of each training week revealed significant performance increases in the first week of training (1st to 5th day) for K-ABC Icons ($t(19) = -5.0$, $p < .001$), and a trend towards significance for Digit span backwards ($t(19) = -1.9$, $p < .07$) and Corsi block tapping forward ($t(18) = -1.8$, $p < .08$). In contrast, in the second week of training (6th to 10th day) performance increased significantly for Corsi block tapping backwards ($t(17) = -2.7$, $p < .02$) and Digit span backwards ($t(17) = -2.1$, $p < .05$). None of the other comparisons were significant. Analyses of effect sizes revealed similar results: in the first week of training medium to large training effects were obtained for K-ABC Icons (*d'* = 0.79) and Corsi block tapping forward (*d'* = 0.44) whereas in the second week medium to large training effects were found for Corsi block tapping backwards (*d'* = 0.75) and Digit span backwards (*d'* = 0.40). All other effect sizes were small.

4.3.2 Exploring differential training effects

Next, to determine who profited most, the training group was divided via baseline median split into approximately equally sized groups of high- and low-capacity individuals for each of the trained WM tasks.[2] In a first step, within each subgroup, pre-and post-training comparisons revealed significant training gains in all trained tasks for low-capacity individuals (Digit span forward: $t(7) = -3.4$, $p < .01$; Digit span backwards: $t(12) = -3.9$, $p < .01$; Corsi block forward: $t(9) = -3.8$, $p < .01$; Corsi block backwards: $t(12) = -8.8$, $p < .001$; and K-ABC Icons: $t(9) = -5.6$, $p < .001$, respectively), whereas there were no significant training gains for high-capacity individuals.[3] Figure 4 exemplifies the longitudinal performance trajectories in the Corsi Block forward task during training for all participants of the training group, separating low- and high-capacity subgroups. Low-capacity individuals generally showed increases in performance across the training period, whereas high-capacity individuals mostly demonstrated either no major changes or decreases in performance. The patterns of trajectories for the low- and high-capacity individuals were similar for all other training tasks.

In a second step, high-capacity individuals' training gains were directly compared to those of low-capacity individuals. Significantly larger training gains for the low-capacity group were found for all training tasks, all $p < .02$. Furthermore, in a third step, trainings gains were compared between the low-capacity training group and the control group. Confirming the previously found pattern, trainings gains were significantly larger in the low-capacity training group than in the control group for all training tasks as well, all $p < .05$ (see Figure 5 and Table 6 for further details).

The relationship between baseline WM capacity and training gains was further sup-

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[2] Considering the available normative data from the MWT-A, mean verbal cognitive abilities of both low- and high-capacity individuals fell within the normal to high functioning range of their population.

[3] To control for task specific effects, analyses were repeated with an overall WM sum score for each individual (sum of scores on all WM tasks on training day 1). The pattern of results was supported: participants with a sum score above the median did not show any significant training gains, whereas for participants with a sum score below the median significant training gains were found with the exception of the Corsi block tapping task forward.

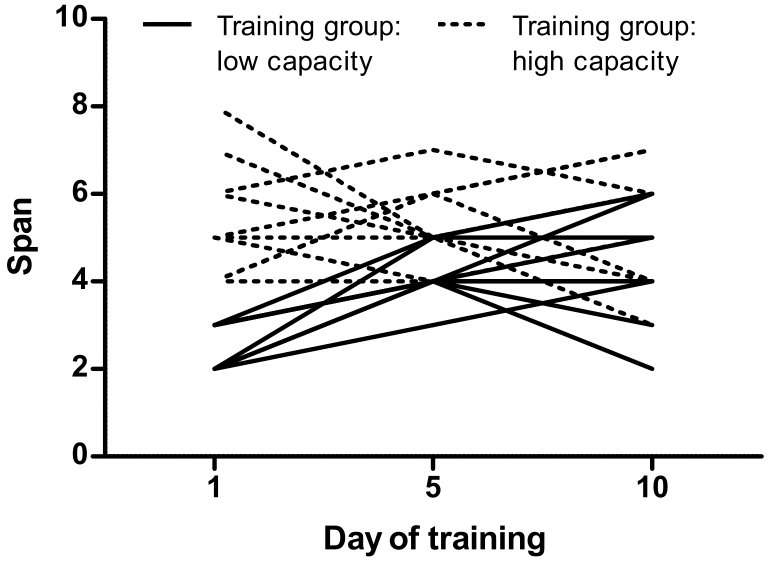


Figure 4: Performance trajectories in Corsi Block tapping forward across training (training days 1, 5 and 10) of training group individuals with low vs. high baseline WM capacity.

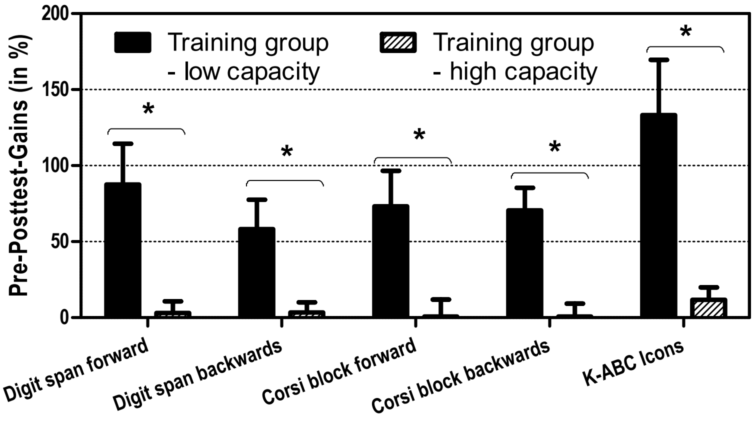


Figure 5: Comparisons between high- and low-capacity training group individuals for mean training gains in percent for each training task separately. Error bars indicate standard errors. Significant differences of training gains between high- and low-capacity group are indicated: $^*p < .05$, $^{**}p < .01$.

Table 6: Percent gains in trained tasks in individuals of the training group with low vs. high working memory capacity and individuals of the control group.

	Training group				**Control group**		**Low vs. high WM capacity**^{a}		**Low WM capacity vs. control**^{a}	
	Low WM capacity		**High WM capacity**							
	$M(SD)$	n	$M(SD)$	n	$M(SD)$	n	p	*d'*	p	*d'*
Digit span forward	87.5 (76.0)	8	3.1 (26.5)	12	-9.0 (32.7)	16	.02	1.6	.008	1.8
Digit span backwards	58.3 (69.2)	13	3.5 (17.6)	7	16.6 (36.9)	16	.02	0.9	.05	0.8
Corsi forward	73.3 (73.4)	10	0.7 (35.4)	10	1.4 (25.3)	16	.02	1.2	.01	1.4
Corsi backwards	70.5 (53.8)	13	0.7 (22.3)	7	18.4 (35.0)	16	.004	1.5	.004	1.1
K-ABC Icons	133.3 (114.4)	10	11.8 (25.6)	10	48.8 (54.6)	16	.008	1.4	.05	1.0

^{a} Percent gains in each task were compared between groups using independent t tests.

ported by the following findings. Correlational analyses revealed significant large negative correlations between baseline WM capacity and training gains for all trainings tasks (Digit span forward: r = -.66, $p < .002$; Digit span backwards: r = -.59, $p < .006$; Corsi Block tapping forward: r = -.65, $p < .002$; Corsi Block tapping backwards: r = -.89, $p < .001$; K-ABC: r = -.80, $p < .001$.).

4.3.3 Exploring transfer effects to non-trained executive functions tasks

Paired t tests comparing pre- and post-training performance in non-trained executive functions tasks revealed that there was a trend for improvement in Stroop interference scores in the training group ($t(17) = 2.0$, $p < .06$, *d'* = 0.3), whereas for the control group no significant differences were found ($t(15) = 1.0$, $p < .3$, *d'* = 0.2). For Raven sum scores, the control group improved significantly from pre- to post-assessment ($t(15) = -2.8$, $p < .01$, *d'* = 0.4), whereas the difference between pre- and post scores was not significant for the training group ($t(19) = -1.5$, $p < .15$, *d'* = 0.2). Importantly, independent t tests revealed no significant differences between groups in percent gains in either Stroop interference scores (training group: M = -9.6 %, SD = 30.9, control group: M = -2.7 %, SD = 30.6; $t(32) = -0.65$, $p > .1$) or Raven scores (training group: M = 5.2 %, SD = 11.5, control group: M = 11.5 %, SD = 16.9; $t(34) = -1.32$, $p > .1$).

4.4 Discussion

The present research is the first study on WM plasticity in older adults that are well within the old-old age range. Results provide initial evidence that (i) training gains in WM capacity are possible even in old-old age and (ii) when applying ten training sessions only. More detailed analyses of the training progress indicated changes in performance over the ten training sessions in almost all tasks that mostly reflected linear ascending trends, with some accelerated components. Moreover, the study is the first to demonstrate that WM plasticity in old-old age is preserved in both WM modalities as verbal and visuospatial training effects were revealed. (iii) With respect to our third research question, results showed that within the training group, individuals with low WM capacity were driving the training effects. While those findings demonstrate potential for behavioural plasticity in old-old age, the present study also suggests some limits. Specifically, gains in trained tasks were higher in the training group than in a passive control group for only some of the tasks. This may have been caused by smaller training gains of participants with high WM capacity (see below for the issue of differential subgroup effects). Furthermore, there was no clear indication of transfer effects of the WM training to non-trained executive functions tests.

Overall, the present results replicate and extend the previous literature in several ways. First, training gains of the current study were comparable in size to those observed by Buschkuehl and colleagues (2008) in a sample on the edge to old-old age (mean age 80 years). Gains on the three WM tasks used by Buschkuehl and colleagues were 44, 62, and 15 %, respectively, while in the present study the training gains ranged from 37 to 72 %. Second, when looking at the low WM capacity individuals who were mainly driving the training effects, training gains in the present study were even larger, ranging from 58 to 133 %. Thus, the WM training adopted in this study, in spite of its overall much shorter duration (10 sessions) as compared to the training regime by Buschkuehl et al. (23 sessions with WM tasks trained consecutively), seems to be very effective in improving WM performance in old-old adults with low WM capacity. In fact, in comparison to the control group, significant training effects were found in all tasks for this subgroup. However, since no significant training effects were found for the high-capacity individuals, the present training regime does not seem to be suitable for high functioning old-old adults.

Third, differential training effects were observed with respect to process requirements of the trained tasks. First of all, significant group differences in training gains (indicating substantial training effects) were only found for some tasks: Digit span forward and Corsi block tapping forward. Since these two tasks mostly require storage of information this may suggest that the training regime applied may have been more effective for improving storage rather than processing components of WM. Moreover, as indicated by the follow up analyses to the longitudinal trends observed in the repeated measures ANOVAs, in the first training week, training gains were mainly larger for tasks focusing on storage of information (Corsi block tapping forward, K-ABC Icons) than for tasks also involving processing components (Corsi block tapping backwards, Digit span backwards). These findings indicate that more training time may have been necessary to improve processing components of WM in old-old adults, possibly because the processing components of WM are more affected in old age than the storage components (Craik, 2000). Alternatively, it is possible that the processing component of WM may not be modifiable in old-old age at all. Future research will have to address this issue in further detail.

As indicated above, differential patterns also emerged with respect to individual differences in ability levels at the beginning of training. Conceptually, the finding of large training gains in the low-capacity individuals and virtually none in the high-capacity individuals appears to be consistent with the disuse hypothesis (Gatz et al., 2001; Kliegel et al., 2004). The disuse hypothesis assumes that cognitive decline in old age may be due to suboptimal use of cognitive resources. Frequent use of cognitive resources is thought to help maintain high performance levels, whereas lack of practice is thought to lead to low performance levels. In the current study the individuals with low baseline WM-capacity may have lacked frequent practice of WM tasks. When challenged in an adaptive training regime they seemed to be able to reactivate some of their potential. Participants with high baseline WM capacity may have maintained their ability through frequent use of WM processes and therefore might not have profited as much from the applied WM training that focused on practise of these processes. However, current findings are in contrast to previous data showing greater training gains for individuals with higher baseline capacity (Bissig & Lustig, 2007; M. Baltes et al., 1995; Yesavage et al., 1990). These divergent findings could be explained by different methods to define high and low capacity. Previous studies often defined capacity not by the ability the training focused on, but by general measures of cognitive status such as the MMST or intelligence tests (Bissig & Lustig, 2007; M. Baltes et al., 1995; Yesavage et al., 1990). In contrast, in the present study capacity was defined by baseline performance in the trained tasks, thus using a more direct approach to examine the influence of capacity on training gains. In addition, in some of the previous studies, low-capacity individuals were considered as being at risk for development of dementia (M. Baltes et al., 1995; Yesavage et al., 1990), thus limiting their ability to profit from training, whereas in the present study only participants were included who passed a screening test for preclinical and clinical dementia. Furthermore, the training regimes applied in the previous studies focused on teaching and practising rather complex mnemonic strategies (M. Baltes et al., 1995; Yesavage et al., 1990) or depended on the participants' ability to self-initiate the use of encoding strategies (Bissig & Lustig, 2007), thus drawing on a great amount of cognitive resources for successful implementation of the respective training mechanisms. In contrast, the focus of the WM training applied in the current study was adaptive practice of storing and processing of information. Moreover, the WM training in this study may have been particularly tailored for low-capacity individuals by using paper-pencil training tasks with more liberal reaction time limits as compared to computerized trainings previously used, thus enhancing motivation and engagement with the training tasks. This view is supported by the high compliance to the training.

Despite improvements in the trained tasks, the current study did not provide evidence for (far) transfer to executive control tests. At first sight, this is not in line with previous findings of transfer effects after WM training in old age (Buschkuehl et al., 2008; Dahlin, Nyberg, et al., 2008; Li et al., 2008). However, the previously reported transfer effects were restricted with regard to cognitive domain, type of stored information, and involved processes: they were only found in tasks rather similar in these criteria to the trained ones, thus only demonstrating near instead of far transfer. The executive control tests used in the present study to evaluate transfer may have differed too much in these regards from the training tasks to find any transfer. Processes that are thought to be shared between executive functions and WM tasks are those that guide processing of stored information in WM (i.e., the central executive component of WM) (Baddeley, 2003). Since in the present study, training gains were mainly observed in tasks focusing on the storage of information and were just starting to evolve in the second training week for training tasks also requiring processing of the stored information , a longer training period may have been needed to observe transfer to executive functions tests. As Dahlin and colleagues - who also did not find transfer to executive functions tests in young and young-old adults with an even longer training (15 sessions) - pointed out a high level of skill may be required for the occurrence of such far transfer. Consequently, old-old adults who have clear WM deficits in comparison to younger adults may need particularly long training regimes to transfer the practiced skill to other tasks.

Limitations of the present study include the small sample size that made it difficult to demonstrate statistical significance for smaller effects, possibly leading to non-detection of transfer effects. However, power was sufficient to detect training effects. Dividing the training group via median split into high- and low-capacity individuals led to even smaller groups, therefore the findings of these analyses should be considered to be exploratory. Acknowledging the exploratory nature of the findings, only the general pattern of results was interpreted, not single non-significant results. Follow-up studies on the subject should include a greater number of participants to thoroughly test the current exploratory findings despite the challenges in recruiting old-old adults for time-consuming training studies (also note that Dahlin, Nyberg, et al., 2008 and Buschkuehl et al., 2008 had sample sizes similar or even smaller than the present study). Furthermore, to control for the effects of social interactions on training gains which we cannot completely rule out in our study, the engagement of a control group in a placebo training regime would be desirable (again note that Dahlin, Nyberg, et al., 2008 also used a no-contact control group). Follow-up studies should also include a wider range of tests to evaluate near and far transfer effects to allow for a more fine-grained analysis of the potential and limits of transfer induced by WM training in old-old age and the potential influence of cognitive domain, type of memory content, or involved processes. In addition, the experimental evaluation of different training lengths may be useful for determining the most efficient training duration.

In summary, the findings of the present study demonstrate there is potential for cognitive plasticity in old-old age in low-capacity individuals, induced by a short WM training particularly tailored for this population. Findings support the notion that, regardless of age, practice on highly demanding tasks can improve performance. However, the present findings also point to possible limits of cognitive plasticity in old-old age: transfer of training gains may be only attainable with very long training regimes and only to very similar tasks.

5 Study 3 - Factors Moderating Effects of Working Memory Training in Older Adults

5.1 Introduction

Working memory (WM) is a central neurocognitive processing resource that is involved in most conscious everyday mental activities. The term WM describes the ability to maintain (store) and manipulate (process) information over short periods of time. According to the WM model by Baddeley (2003, Baddeley & Hitch, 1974) it comprises a verbal, a visuospatial, and an executive subsystem. The verbal subsystem (phonological loop) stores and processes verbal and other acoustic information. The visuospatial subsystem (visuospatial sketchpad) is involved in storing and processing visual and spatial information as well as mental images. The executive system (central executive) is thought to coordinate the other two subsystems. With these basic components, WM has been shown to support a wide range of complex cognitive functions, including logical reasoning and problem solving, and to be strongly related to measures of fluid intelligence (Conway et al., 2002; Engle et al., 1999). From an aging perspective it is crucial to note that WM functions are among those cognitive processes that are prone to age-related decline: Research has revealed substantial mean level decreases in WM in old age (in both verbal and spatial WM tasks, Bopp & Verhaeghen, 2005; Hale et al., 2011; Park et al., 2002). This decline is already evident in young-old adults (60-80 years), but is particularly pronounced in old-old adults (over 80 years, Craik, 2000; Gilinsky & Judd, 1994; Hale et al., 2011). Considering the importance of WM for cognitive functioning in general, the question of possibly modifying this decline has been raised in aging research.

Although WM capacity has been viewed as a relatively constant trait, recent studies suggest that it can be improved by adaptive and extended training (see Klingberg, 2010, for a review). Earlier studies have investigated enhancing WM with the help of strategies, e.g., rehearsal (Butterfield & Wambold, 1973) or chunking strategies (Ericsson, Chase, & Faloon, 1980), which led to substantial improvements in performance on the targeted tasks but hardly any transfer to other tasks. Recent studies involve a more implicit, process-based approach where improvement in performance is based on repetition, feedback and often gradual adjustment of difficulty (Klingberg, 2010) with tasks where strategy use is rather unlikely. These training studies usually involved repeated performance of tasks focusing on WM capacity (Klingberg et al., 2005; Holmes et al., 2009), updating (Jaeggi et al., 2008), or task switching (Karbach & Kray, 2009). These studies targeted different age groups with most of the studies involving children or young adults. Some recent studies suggest that updating (Dahlin, Nyberg, et al., 2008; Li et al., 2008) and WM training (Borella et al., 2010; Brehmer et al., 2011) may also be effective in enhancing performance on trained tasks in young-old adults and old-old adults (Buschkuehl et al., 2008; Zinke et al., 2012). However, no study has so far included participants across the full age-range of old adulthood. Thus, the first aim of the current study was to verify the potential for training-induced plasticity of WM in older adults ranging from young-old to old-old age (65 to 95 years old).

In addition to improvements in trained tasks, transfer to non-trained tasks has been observed after process-based WM training for tasks within the WM memory domain (e.g., complex span tasks, Holmes et al., 2009) as well as to executive control tasks (e.g., Stroop; Klingberg et al., 2002, 2005; Olesen et al., 2004) or measures of non-verbal reasoning (Klingberg et al., 2005; Jaeggi et al., 2008). On a neural level, WM training has even been shown to be associated with changes in brain activity in frontal and parietal cortex and basal ganglia pointing to increased neural efficiency, as well as changes in dopamine receptor density (Brehmer et al., 2011; McNab et al., 2009; Olesen et al., 2004). Taken together these recent findings suggest that WM training can be used as an intervention to improve WM and associated cognitive functions and that this may be especially helpful for individuals who experience difficulties in everyday life, perhaps as a result of decreased WM capacity (Klingberg, 2010). Although these findings have mostly been acquired with young participants, some recent studies have also targeted older adults. However, the findings regarding transfer effects in old age are more mixed and generally suggest that transfer may be more restricted in old as compared to younger participants Findings regarding transfer, however, are mixed. Whereas some studies did not find any significant transfer effects after training in their older participants (Dahlin, Nyberg, et al., 2008; Zinke et al., 2012), other studies provide evidence for transfer effects to similar tasks. For example, in the study by Li and colleagues (2008), visuospatial n-back WM training transferred to visuospatial as well as numerical n-back tasks in both young and young-old participants but not to more complex WM span tasks. Buschkuehl and colleagues (2008) found a clear transfer effect directly after training for a very similar visuospatial WM task, and some evidence for a performance increase in a visual free-recall task in the experimental group. Recently, some studies have even suggested transfer of WM training to tasks very different from the ones trained, for example sustained attention and episodic memory (Brehmer et al., 2011; Richmond et al., 2011) or fluid intelligence, speed and inhibition (Borella et al., 2010). That is, in some studies transfer effects seem to be generally limited and, if they are found, restricted to WM tasks that were rather similar with regard to format and processing requirements to the trained tasks (near transfer tasks). In other studies evidence for improvements in tasks that assess different cognitive constructs (far transfer tasks) has been found. According to models of neural plasticity, one would expect transfer if training induces plasticity in a common neural network that is shared between the training and transfer tasks (Olesen et al., 2004). For example, studies have shown that WM and fluid intelligence tasks both activate particular lateral prefrontal and parietal regions (Gray, Chabris, & Braver, 2003; Olesen et al., 2004). Thus, if the current training program is able to induce changes in this common neural network we would expect transfer to other WM tasks (near transfer) or fluid intelligence tasks (far transfer). Following up on this issue, the second aim of the current study was to systematically test the emergence and magnitude of near and far transfer effects after WM training in older adults.

In addition to immediate training and transfer effects, it is conceptually important to explore whether benefits that are obtained immediately after training will remain stable over time. So far, findings on the stability of training and/or transfer effects have been mixed. Whereas Buschkuehl et al. (2008) found no maintenance of either training or transfer effects after one year in their study with 80-year old participants, (Dahlin, Nyberg, et al., 2008) were able to show maintenance of training gains 18 months after training for all trained participants. However, stability of the reported transfer effect was only found for the young participants, not for the young-old ones. Borella et al. (2010) showed maintenance of training and some of the transfer gains in young-old adults eight months after training. Thus, the findings on maintenance of training and transfer effects are mixed, particularly with regards to old-old adults. Therefore, the current study assessed stability of training and transfer effects in both young-old and old-old adults nine months after the immediate posttest for the training and control groups.

Given the heterogeneous picture on the emergence of training and transfer effects, the third and key aim of the present study was to explore possible moderators of training and transfer effects that may underlie these inconsistencies. Many factors have been proposed to impact the degree of benefit obtained from WM training. Age is one prominent factor that may moderate training and transfer effects (as has been pointed out by Borella et al., 2010, for example). Previous studies that reported far transfer effects were those with young-old participants (60 to 70 years, Brehmer et al., 2011; 65 to 75 years, Borella et al., 2010), studies with older participants reported no or limited transfer (mean age of 80 years, Buschkuehl et al., 2008; 77 to 96 years, Zinke et al., 2012). Up until now, no study has directly investigated whether the effects of process-based WM training interventions on training and transfer effects may differ with the age of the participants. Considering findings from episodic memory strategy trainings, one would expect reduced training efficiency in old-old as compared to young-old adults (Singer et al., 2003). Therefore, current study for the first time included a large age range of participants covering both young-old and old-old age.

A second possible variable that may influence the efficiency of cognitive training may be the general cognitive ability of the participants. This is especially important in old age, as it may be that only participants who have maintained a high cognitive status profit from a rather complex and demanding intervention such as a WM training. This may be because a relatively high level of functioning could be required to actively engage in the extensive practice of abstract working memory problems (see, e.g., Bissig & Lustig, 2007; Yesavage et al., 1990, for similar effects in memory training). On the other hand, one may predict that especially participants with a low cognitive status profit from such an intervention. This may be because participants' low starting level may be low due to decline in the use of their cognitive resources and engaging in a working memory intervention may help them to reactivate some of their potential as is suggested by the disuse hypothesis (e.g., Hultsch et al., 1999; Kliegel et al., 2004). Therefore, the current study aimed at investigating the possible influence of individual differences in general ability on training and transfer effects.

Further possible moderating factor are more specifically tied to the WM training, e.g., the baseline level of performance on the WM tasks. For example, in one of our own recent training studies focusing on old-old adults, those individuals starting with low levels of WM capacity were the ones that profited most (Zinke et al., 2012). This could indicate that those individuals who start at a relatively low level may show more, or at least equal, training gains. Concerning transfer, a recent study by Jaeggi et al. (2011) on WM training in children suggests that the individual amount of training gains may impact the amount of transfer found. In this study, transfer to a non-trained fluid intelligence task was only observed in the subgroup of participants that improved considerably on the trained WM tasks. Based on these findings, we predict that baseline scores will impact the amount of training gains. Furthermore, we predict that the amount of training gain will impact the amount of transfer.

Taken together, the current study explored the limits and potential of WM plasticity in a sample of older adults ranging from young-old to old-old adults. For that purpose, an experimental approach was used comparing a training group to a control group on measures of training and transfer performance. With an individual difference approach, possible moderating factors of training-related plasticity were investigated for training and transfer gains.

5.2 Methods

5.2.1 Participants

The 80 participants of the study were between 65 and 95 years old (mean age: 77.2 years, $SD = 8.1$). Half of the participants participated in a WM training program for three weeks (training group, $n = 40$); the other half did not receive training (control group, $n = 40$). Training and control groups did not differ significantly from each other regarding age, gender, years of education, and cognitive status (see Table 7). Exclusion criteria were non-corrected visual or auditory impairments and neurological or psychiatric disorders, in particular Mild Cognitive Impairment or Alzheimer's disease. This was screened for via self-report and with the Mini Mental Status Test (MMST), German short form for old-old adults (maximum score of 21; cut-off for risk of dementia = 16; see Kliegel et al., 2001; Rott et al., 2001). Participants were also screened for depression and anxiety disorders with the Hospital Anxiety and Depression Scale (HADS-D, German version, Herrmann, Buss, & Snaith, 1995). Crystallized intelligence was assessed with a German vocabulary test (MWT, Lehrl et al., 1991).

5.2.2 Training tasks

Training material was chosen based on Baddeley's WM conceptualization (2003; 1974) target multiple aspects of WM (as has been done in studies by Klingberg and colleagues) with tasks requiring both verbal and visuospatial WM, as well as executive control processes. The training included tasks that each required both storage and processing of information in WM.

Visuospatial WM span was trained with a picture grid task: *K-ABC Icons* (Kaufmann Assessment Battery for Children, Melchers & Preuss, 1991). The (modified) K-ABC-

Table 7: Participant characteristics of the training and control group (all n = 40)

	Training group $M(SD)$	**Control group** $M(SD)$
Gender Ratio (female : male)	32 : 8	27 : 13
Age	76.7 (8.4)	77.7 (7.9)
Education in years	14.4 (3.4)	13.5 (3.5)
Cognitive functioning (MMST)	20.2 (1.1)	20.0 (1.2)
Crystallized abilities (MWT)	31.4 (3.1)	31.3 (3.2)
Depression and Anxiety (HADS-D)	10.2 (5.2)	9.6 (4.1)

Note. MMST = Mini Mental Status Test (abbreviated version by Kliegel et al., 2001; maximum points = 21, cut-off = 16); MWT = Mehrfach-Wortschatz-Intelligenztest version B; HADS-D = Hospitality Anxiety and Depression Scale - German Version.

Icons task was an adaptive visuospatial WM task where participants had to process and maintain the spatial arrangement of multiple stimuli. An increasing number of icons (pictures of objects), that were either placed in a 3x3 grid or, at higher difficulty levels, in a 3x4 grid, was presented to the participant. The participant had five seconds to memorize each arrangement of icons. Afterwards, an empty grid was presented and the participant was asked to name all icons he/she had seen and show their individual location on the empty grid. The set size (total number of icons to be recalled) ranged from two to nine. Each trial was scored as correct only if the participant recalled all icons and their locations correctly. The main dependent variable was the total number of correctly recalled trials.

Verbal WM span was trained with the *Subtract-2-Span* task (Salthouse, 1988). The experimenter presented number sequences of increasing length. The participant was asked to subtract two from each number that was presented and repeat the (manipulated) sequence of numbers. Set size (total number of numbers to be recalled) ranged from two to eight numbers. The dependent variable was the overall number of sequences correctly recalled.

Executive control was trained with the *Tower of London* task (Ward & Allport, 1997). Participants were asked to move five differently colored balls on a board with three equally long pegs from a start position to a defined end position. The end position and the number of moves required to solve the problem was shown on a picture. Difficulty was adapted by increasing the number of moves necessary to solve the problems (from 3 to 11). Only trials solved in the fewest possible number of moves were scored as correct. The main dependent variable was the total number of correctly solved problems.

The difficulty level for all tasks was constantly adapted for each participant over the course of the training program, because increasing the level of difficulty adaptively has been shown to be an important feature for effective training tasks (Klingberg et al., 2005). The difficulty level for verbal and visuospatial WM was adapted by increasing set size (number of items to be recalled) of the next trials by one item whenever the participant had two consecutive correct trials at the same difficulty level. If he/she only had one out of two trials of the same difficulty level correct, set size remained the same for the next two trials. If none of the trials were solved correctly, set size was decreased by one item on the next two trials. Similarly, the difficulty level for the Tower of London task was adapted by increasing set size (number of moves necessary to solve the problems) by one, whenever the participant solved four out of five trials (problems) of the same difficulty level correctly in the minimum number of moves. If the participant solved two or three out of the five problems correctly, the difficulty level remained the same. If he/she solved less than two problems correctly, the difficulty level was decreased by one move. This adaptive procedure attempted to keep all participants motivated by allowing them to experience periodic success while ensuring that participants regularly practiced at a level of difficulty that was at the limit of their current performance level. All tasks were administered in individual, face-to-face sessions. The tasks that were used in pre- and posttest sessions resembled those of the training sessions. To ensure that the exact same trials were not presented repeatedly, different (parallel) versions for trials on each difficulty level were constructed for all sessions.

5.2.3 Transfer tasks

To assess the first level of transfer (near transfer: within the same domain but to other stimuli) three different tasks were used that corresponded to each of the trained domains. The *Corsi Block Span* task, taken from the Wechsler Memory Scale (WMS-R, Wechsler, 2000), was used to assess visuospatial WM. The experimenter tapped a number of blocks on a board in sequences of increasing length. The participant had to reproduce the sequences by tapping immediately after the experimenter had finished. The sequence length (number of blocks tapped) was increased by one block if the participant was successful in completing at least one out of the two sequences of the same length. The dependent variable was the overall number of correctly reproduced sequences.

The *Letter-Span Plus* task (Verhaeghen & Marcoen, 1996) was used to measure verbal

WM capacity. The experimenter presented letter sequences of increasing length containing the letters A to I. The participant was asked to increase each presented letter in alphabetic order by one and repeat the (manipulated) sequence of letters. The sequence length (number of letters presented) was increased by one letter if the participant was successful in completing at least one out of the two sequences of the same length. The dependent variable was the overall number of correctly recalled sequences.

A computerized version of the *Tower of Hanoi* was used to assess executive control. The participants had to move an increasing number of discs of different sizes from a starting pole to an end pole while adhering to certain rules, e.g., only one disc can be moved at a time, a small disc can only be placed on a larger one, etc. The problem was counted as correctly solved if the participant solved the problem in the least possible moves. The difficulty of problems (number of discs) was increased by one disc if the participant solved at least one out of the two problems of equal difficulty. The main dependent variable was the sum of correctly solved problems.

To assess the second level of transfer to other cognitive constructs associated with WM capacity (far transfer), two tasks were used. In keeping with the literature, the *Raven Standard Progressive Matrices* (Raven, Court, & Raven, 1979) was used to assess nonverbal complex reasoning ability/fluid intelligence. The participant had to find logical patterns in an array of figures or patterns and choose the item that best fit in the blank space to complete the pattern. In the current study two parallel versions with 18 items each were constructed for the pretest and posttest sessions. The *Stroop interference* task (German version of the color-word-Stroop test taken from the Nürnberger Altersinventar, NAI, Oswald & Fleischmann, 1995) was used to measure inhibitory control. Here, the participant first had to read out loud color names (printed in black on a sheet) as fast as possible; in the second run the participant was to name color patches; in the last run he/she was to name the print color of color words printed in different colors. The main dependent variable was the difference in overall naming time between the third and the second run.

5.2.4 Procedure

Two to three days before and after training, the training group completed a pretraining and a posttraining assessment, respectively, with two sessions each. One session measured pre- and posttraining performance on the trained tasks to serve as baseline and outcome measure for the trained tasks. The other session included the non-trained transfer tasks to assess transfer on all three levels. The order of the tasks was the same in pre- and posttraining sessions and for all participants. Training was administered in nine sessions over three weeks. Each training sessions lasted 30 minutes in total, with about equal time (about 10 minutes) for each of the three training tasks. Difficulty levels were adapted individually within each session as described above. Participants started each session at the final difficulty level of the preceding session. The sequence of training tasks was counterbalanced over the sessions. Nine months after the posttraining assessment, 83 % of the training group (n = 33: 15 young-old and 18 old-old adults) participated in a follow-up session including trained tasks, and (due to time restrictions) a reduced set of transfer tasks (i.e., verbal and visuospatial WM and fluid intelligence).

The control group received no treatment, but was also tested in pre- and posttest assessments with the same time interval in between assessments as the training group. Similar to the training group, these assessments included two sessions: one for assessing performance on the transfer tasks and one for assessing performance on the training tasks. Twenty control participants were randomly selected for a follow-up testing session nine months later, and eighteen participated (45 % of the original control group): nine young-old and nine old-old adults.

5.3 Results

First, we tested for comparability in baseline performance between training and control group. Importantly, analyses indicated no significant differences at pretraining in any of the training or transfer tasks between training and control group suggesting that randomization had been successful.

5.3.1 WM training effects

To compare changes in performance on trained tasks from pre- to posttraining between groups, a two-factorial ANOVA was conducted with group (training vs. control) as a between-subjects factor and time of measurement (pretraining vs. posttraining) as a within-subject factor. Most importantly, there was an interaction for all three trained tasks between the time of measurement and the group indicating larger changes between the pre- and posttraining assessments for the trained group than for the control group (as can be seen in Figure 6): for the number of correctly repeated sequences in K-ABC Icons, $F(1, 78) = 20.1$, $p < .001$, partial $\eta^2 = .21$, for the number of correctly repeated sequences in Subtract-2 Span, $F(1, 78) = 32.7$, $p < .001$, partial $\eta^2 = .30$, and for the number of correctly solved problems in the Tower of London, $F(1,\ 78) = 13.0$, $p = .001$, partial $\eta^2 =.14$. Analyses also revealed a main effect of time, indicating gains from pre- to posttraining assessments for all trained tasks: for K-ABC Icons, $F(1,\ 78) = 7.4$, $p = .008$, partial $\eta^2 = .09$, for Subtract-2 Span, $F(1,\ 78) = 42.7$, $p < .001$, partial $\eta^2 =.35$, and for the Tower of London, $F(1,\ 78) = 12.6$, $p < .001$, partial $\eta^2 =.14$. There was also a main effect of group with the trained group performing significantly better than the control group for Subtract-2 Span, $F(1,\ 78) = 8.6$, $p = .004$, partial $\eta^2 =.10$, and for Tower of London, $F(1,\ 78) = 11.6$, $p = .001$, partial $\eta^2 =.13$, and a trend towards significance for K-ABC Icons, $F(1,\ 78) = 3.7$, $p = .06$, partial $\eta^2 =.05$.

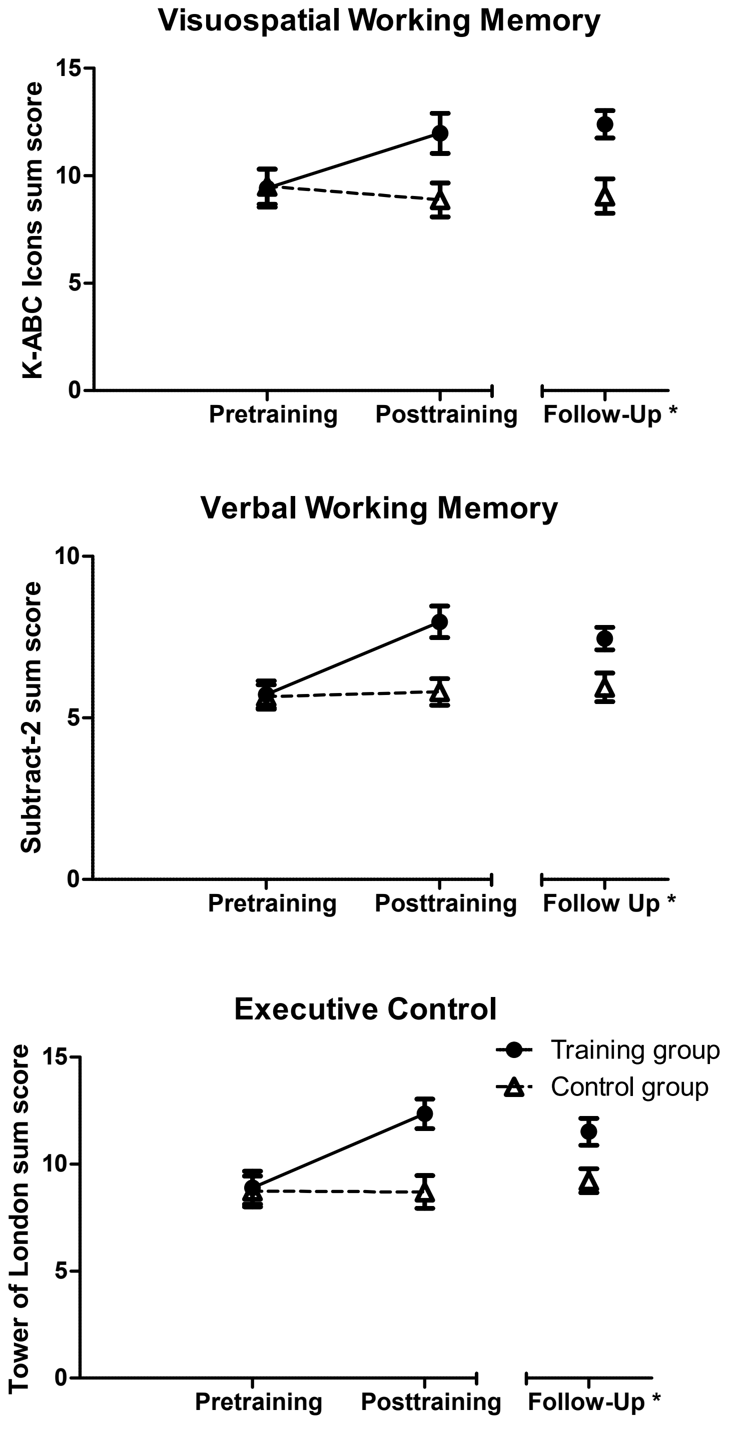
To explore the *stability* of the training effects, repeated measures ANOVAs with group as between-subjects factor and time of measurement (pretraining vs. follow-up) as a within-subject factor were conducted to compare differences between groups before training and at follow-up. Importantly, for all trained tasks the interaction term between time of measurement and group was still significant, indicating larger differences between pretraining and follow-up assessment for the trained group than for the control group (see Figure 6): for K-ABC Icons, $F(1,\ 49) = 14.5$, $p < .001$, partial $\eta^2 = .23$, for Subtract-2 Span, $F(1,\ 49) = 16.9$, $p < .001$, partial $\eta^2 = .26$, and for Tower of London, $F(1,\ 49) = 8.0$, $p = .007$, partial $\eta^2 = .14$.

To summarize the analyses on WM training effects, larger gains for the trained participants as compared to the control participants were revealed for all training tasks. Furthermore, the effects of training on performance on the trained tasks were still evident at the nine month follow-up.

5.3.2 Transfer effects

To explore possible group-level transfer effects of training, analyses were conducted analogous to the analyses of the training effects. A two-factorial ANOVA was used with group (training vs. control group) as a between-subjects factor and time of measurement as a within-subject factor. Means and SDs for pretraining, posttraining, and follow-up performance for the respective transfer tasks can be found in Table 8.

In the domain of near transfer, for the visuospatial WM transfer task (number of correctly repeated sequences in the Block Span task) there was a main effect of time, $F(1,\ 78) = 16.9$, $p = .003$, partial $\eta^2 = .11$, indicating general performance gains from pre- to post-training assessment. Neither main effect of group nor the two-way interaction between time and group was significant, indicating that groups neither differed overall nor in the pre- to posttraining gains on this task. For the verbal WM task (number of


Visuospatial Working Memory

Verbal Working Memory

Executive Control

* Follow-up for 64% of the sample:33 trained and 18 control participants

Figure 6: Training effects for all trained tasks (mean performance scores ± SE pretraining, posttraining and at follow-up) in the training and the control group: Visuospatial Working Memory (K-ABC Icons), Verbal Working Memory (Subtract-2-Span), Executive Control (Tower of London).

Table 8: Performance in transfer tasks in the training group and the control group

	Training group						Control group					
	Pretraining		Posttraining		Follow-up [a]		Pretraining		Posttraining		Follow-up [a]	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Near Transfer												
Block Span	6.62	1.68	7.58	2.00	7.09	1.31	6.40	2.02	6.75	1.81	6.56	1.92
Letter-Span	3.53	1.71	5.23	2.45	4.91	1.93	3.08	1.47	3.40	1.55	3.44	1.76
Tower of Hanoi	1.83	1.22	2.52	1.41	/		1.65	1.00	2.25	1.32	/	
Far Transfer												
Stroop	0.25	0.16	0.22	0.12	/		0.28	0.14	0.27	0.14	/	
Raven	11.02	4.32	12.08	2.75	10.85	4.03	10.50	3.79	9.98	2.50	10.17	3.42

[a] Follow-up for 64% of the sample: 33 from the training group and 18 from the control group. Note that due to time restrictions only three transfer tasks were assessed in the follow-up.

correctly repeated sequences in the Letter-Span Plus Task), there was a main effect of time indicating gains from pre- to posttraining assessment, $F(1, 78) = 33.8$, $p < .001$, partial $\eta^2 =.30$. There was also a significant main effect of group with the trained group performing significantly better than the control group, $F(1, 78) = 9.3$, $p = .003$, partial $\eta^2 =.11$. There was a significant effect for the crucial interaction between the time of measurement and the group, $F(1, 78) = 15.6$, $p < .001$, partial $\eta^2 =.17$, indicating transfer effects in the verbal WM task (see Table 8). For the executive transfer task (number of correctly solved problems in the Tower of Hanoi) there was a main effect of time indicating gains from pre- to posttraining assessments, $F(1, 78) = 16.9$, $p < .001$, partial $\eta^2 = .18$. Neither main effect of group nor the interaction between time and group was significant, indicating that groups neither differed overall nor in the pre- to posttest gains on this task.

In the domain of far transfer, for the inhibition task (interference score in the Stroop task) analyses revealed no significant main or interaction effects, indicating neither group differences nor changes from pre- to posttest. For the fluid intelligence task (Raven SPM), there was a significant effect for the crucial interaction between the time of measurement and the group, $F(1, 78) = 5.0$, $p = .03$, partial $\eta^2 = .06$, indicating larger changes in the trained group pre- vs. posttraining than in the control group.

Stability of the transfer effects was again analysed using repeated measures ANOVAs with group as between-subjects factor and time of measurement (pretraining vs. follow-up) as a within-subject factor were conducted to compare differences between groups before training and at follow-up. At follow-up, the crucial interaction between the time of measurement and the group was still significant for the verbal near transfer task (Letter-Span Plus), $F(1, 49) = 16.7$, $p < .001$, partial $\eta^2 = .25$, indicating larger changes from pretraining to follow-up in the trained compared to the control group. For the Raven SPM, the crucial Time x Group interaction term was not significant, $p > .1$, indicating no significant differences in changes from pretraining to follow-up between training and control group.

To summarize the analyses on transfer effects, near transfer (as indicated by larger pre- to posttest gains in the training group compared to the control group) was found for the verbal WM task, but not for the visuospatial WM task and the executive transfer task. Far transfer was found for the fluid intelligence task, but not for the inhibition task. Effects on transfer tasks were stable for the verbal WM task, but not for the fluid intelligence task.

5.3.3 Moderators of training and transfer gains

To explore possible moderating factors of individual differences in training and transfer gains, a set of analyses was conducted with only the trained individuals. The possible moderating factors we considered were age, crystallized ability, and baseline performance on trained tasks. Correlations between these factors and the training and transfer gains (differences between posttraining and pretraining performance) are presented in Table 9.

5.3.3.1 Moderators of training gains

To examine the unique contribution of factors that may moderate training and transfer effects, a series of hierarchical linear regression analyses were conducted. For each training gain age was included as a predictor in a first step, followed by crystallized abilities in a second step, and baseline performance in the respective training task in a third step (see Table 10 for a summary). Regression analyses revealed age to be a significant predictor for training gains in the visuospatial WM task, but not for training gains in the other training tasks. Older age was related to smaller training gains in the visuospatial WM task (negative bivariate correlation, Table 9). Crystallized abilities did not significantly add to the prediction of training gains when included in the second step. On the contrary, baseline performance on the respective trained tasks contributed significantly and substantially to the prediction of gains in all three training tasks. The bivariate correlations indicate that lower baseline levels in one specific training task were related to higher gains in this respective task.

Table 9: Correlation Matrix for Age, Crystallized Abilities, Baseline Performance Levels in Trained Tasks, Training and Transfer Gains.

		1	2	3	4	5	6	7	8	9	10	11	12	13
1	Age	–												
2	Crystallized abilities (MWT)	.02	–											
3	Baseline level visuospatial WM training (K-ABC)	-.27^t	.28^t	–										
4	Baseline level verbal WM training (Subtract-2)	**-.37***	.24	**.54***	–									
5	Baseline level executive control (Tower of London)	-.18	.23	.20	**.32***	–								
6	Training gain visuospatial WM (K-ABC)	**-.33***	-.18	**-.46***	-.19	-.10	–							
7	Training gain verbal WM (Subtract-2)	-.16	-.06	.13	**-.32***	-.21	.21	–						
8	Training gain executive control (Tower of London)	-.02	.06	.24	-.01	**-.64***	-.02	.24	–					
9	Transfer gain visuospatial WM (Block Span)	**-.40***	.11	-.17	.04	.07	.30^t	-.10	-.07	–				
10	Transfer gain verbal WM (Letter Span plus)	-.27^t	-.09	.03	.10	-.28^t	**.32***	**.36***	**.39***	.24	–			
11	Transfer gain executive control (Tower of Hanoi)	-.29^t	.19	.26	.18	-.30^t	.11	-.09	**.43***	.26^t	**.38***	–		
12	Transfer gain interference control (Stroop)	-.31^t	.26^t	.11	.20	**.39***	.00	-.15	-.14	.24	-.15	.18	–	
13	Transfer gain fluid intelligence (Raven)	**.42***	-.17	-.11	-.09	-.27^t	-.03	-.16	.11	-.03	.16	.15	-.13	–

$^*p < .05$, $^tp < .10$.

Table 10: Summary of Hierarchical Linear Regression Analysis for Variables Predicting Gains in Trained Tasks.

Training gain in	**Visuospatial WM task** (K-ABC Icons)		**Verbal WM task** (Subtract-2)		**Executive control task** (Tower of London)	
	ΔR^2	β	ΔR^2	β	ΔR^2	β
Step 1	**.11***		**.03**		**<.01**	
Age (in years)		-.49**		-.33*		-.15
Step 2	**.03**		**<.01**		**<.01**	
Crystallized abilities (MWT)		-.003		.06		.23^{t}
Step 3	**.30****		**.16***		**.47****	
Baseline performance in respective training task		-.59**		-.45**		-.72**
	$F(3, 36) = 9.1^{**}$		$F(3, 36) = 2.9^{*}$		$F(3, 36) = 10.9^{**}$	
Total R^2	.43		.19		.48	
Total corrected R^2	**.38**		**.13**		**.43**	

Note. β is based on the final regression model with all predictors. $^{**}p < .01$, $^{*}p < .05$, $^{t}p < .10$.

5.3.3.2 Moderators of transfer gains

For gains in near and far transfer tasks age was included as a predictor into the hierarchical linear regressions in a first step, followed by the inclusion of crystallized abilities in a second step and the gains in each of the trained tasks in a third step (see Table 11 for a summary). The analyses revealed that age explained a substantial amount of variance in the gains of all transfer tasks, which was significant for visuospatial WM, interference control, and fluid intelligence, and a trend towards significance for verbal WM and executive control. When considering the bivariate correlations, older age was related to lower transfer gains, with the exception of transfer gains in fluid intelligence where the opposite pattern emerged and older age was found to be correlated with higher gains. Crystallized abilities did not add to the prediction of transfer gains (except for a trend towards significance in the interference control task). Finally, even after controlling for age and crystallized abilities, the gains in the trained tasks contributed significantly and substantially to the prediction of transfer gains in verbal WM and executive control tasks when added to the regression in a third step. Bivariate correlations revealed higher training gains in the executive control task to be related to higher transfer gains in verbal WM and executive control tasks.

5.4 Discussion

The results of the current study provide the first evidence that, even with a relatively short training regimen of nine 30-minute sessions, training gains in three domains of WM (verbal, visuospatial and executive control) are possible in old age and transfer can be observed to near and far transfer tasks in older adults. Moreover, the current study is the first to provide evidence for stability of training effects (in comparison to non-trained controls) in participants well into the old-old range of adulthood for at least nine months. Remarkably, transfer to verbal WM was also stable nine months after training. Additionally, the current study provides evidence that different factors seem to moderate the amount of training and transfer effects. These findings may shed some light onto factors that might explain the mixed results on WM training and transfer effects in different studies as this is the first study to show that age and performance in WM and executive control tasks uniquely impact the extent to which individuals might benefit from WM training. Specifically, training gains were larger for individuals with lower baseline scores on WM and executive control, suggesting that lower ability older adults benefited most from the WM training program. Moreover, training gains

Table 11: Summary of Hierarchical Linear Regression Analysis for Variables Predicting Gains in Near and Far Transfer Tasks.

Transfer gain in	**Visuospatial WM** (Block span)		**Verbal WM** (Letter Span Plus)		**Executive control** (Tower of Hanoi)		**Interference control** (Stroop)		**Fluid intelligence** (Raven)	
	ΔR^2	β	ΔR^2	β	ΔR^2	β	ΔR^2	β	ΔR^2	β
Step 1	**.16***		**.07**^{t}		**.09**^{t}		**.10***		**.18***	
Age (in years)		-.35*		-.16		-.29^t		-.36*		.44**
Step 2	**.02**		**.01**		**.04**		**.07**^{t}		**.03**	
Crystallized abilities (MWT)		.16		-.06		.17		.26^t		-.17
Step 3	**.08**		**.25***		**.24***		**.05**		**.05**	
Training gains visuospatial WM		.25		.22		.11		-.04		.13
Training gains verbal WM		-.20		.20		-.27^t		-.16		-.17
Training gains executive control		-.03		.35*		.48**		-.13		.17
	$F(3, 34) = 2.3^t$		$F(3, 34) = 3.3^*$		$F(3, 34) = 3.9^{**}$		$F(3, 34) = 2.0$		$F(3, 34) = 2.4^t$	
Total R^2	.25		.32		.36		.22		.26	
Total corrected R^2	**.14**		**.22**		**.27**		**.11**		**.15**	

Note. β is based on the final regression model with all predictors. $^{**}p < .01$, $^*p < .05$, $^tp < .10$.

in visuospatial WM and transfer gains in all tasks were smaller for old-old adults, and the amount of training gains impacted the amount of transfer, to some extent.

5.4.1 Group-level WM training and transfer effects

Overall, the short-term, adaptive WM training program applied in this study proved to be effective in increasing older adults? performance on each of the three trained tasks relative to the control group. This was also true after nine months at the long-term follow-up assessment. These findings are in line with those of Dahlin, Nyberg, et al. (2008) who showed maintenance of training gains in young-old adults up to 18 months. The current results extend the finding of stable training effects to a considerably larger age range including old-old participants where such long-term training effects have not been found until now (see, e.g., Buschkuehl et al., 2008). These findings suggest that substantial and relatively stable training effects can be obtained for WM and executive control even with a total training time of only about four and a half hours spread over three weeks.

Furthermore, the current study aimed at exploring two levels of transfer from the WM training: (a) near transfer, i.e., transfer within the same domain but with different stimuli and response modes, and (b) far transfer, i.e., transfer to other cognitive constructs. According to models of neural plasticity one would expect transfer if training induces plasticity in a common neural network that is shared between the training and transfer tasks (Olesen et al., 2004), for example, in lateral prefrontal and parietal regions that is activated by both WM and fluid intelligence tasks (Gray et al., 2003; Olesen et al., 2004). If the current training program was able to induce such changes in common networks, one would expect transfer especially to other WM tasks (near transfer) and fluid intelligence task performance (far transfer).

For near transfer, transfer effects were found for the verbal WM task for the whole group (there were no differences between age groups). Moreover, this transfer effect seemed to be robust as it was stable at the nine month follow-up with substantial differences still present between the training and control group. This could suggest substantial training-induced plasticity in verbal WM processing regions in the brain. Future neuroimaging studies will have to directly test this hypothesis. For the visuospatial WM task and the executive control task, no transfer effects were found. This may suggest differential pathways of plasticity between WM domains and could constitute an important avenue for future research in this area. Far transfer was found for the fluid intelligence task. However, this benefit was not maintained at follow-up. Transfer to the interference control (Stroop) task was not significant. Thus, our WM training program produced transfer to a fluid intelligence task, which is methodologically quite different from the trained abilities, but may share similar underlying cognitive processes with WM performance. This is the first study to show far transfer to a fluid intelligence task in old-old adults, thereby extending results obtained with young adults (Jaeggi et al., 2008) and young-old adults (Borella et al., 2010).

5.4.2 Individual differences in training and transfer effects

The current study set out to delineate possible factors that may influence the amount of training-induced plasticity. The regression analyses revealed age was an important predictor of training and transfer gains in both the near and far transfer tasks. Specifically, older age was associated with smaller training gains in the visuospatial training task and smaller transfer gains in all three near transfer tasks and the interference control far transfer task. These findings suggest a reduction in the amount plasticity induced by cognitive training in old-old age, especially on the level of of training and transfer gains in old-old age. However, age was positively associated with the amount of transfer gained on the fluid intelligence task. One possibility is that older participants simply had more room for improvement on the Raven's task (young-old participants started out relatively high). Findings of transfer in the fluid intelligence task should be treated cautiously until further replication is provided, particularly given that the transfer effect was not maintained at follow-up.

Interestingly, baseline performance in trained tasks turned out to be the strongest predictor of training gains with lower baseline levels in a particular domain predicting higher training gains in this domain. This is in line with previous findings from our own research group that revealed the largest training gains for those individuals with initial low WM capacity (Zinke et al., 2012). These findings could be explained by the disuse hypothesis (Hultsch et al., 1999; Kliegel et al., 2004) which assumes that cognitive decline in old age may be associated with a reliance on automatic or habitual modes of cognitive processing as opposed to frequent engagement in cognitively demanding activities in daily life. The adaptive training regime used in the current study forced participants to continually adapt to increasing demands by engaging their cognitive resources ever more efficiently. Participants with higher baseline WM capacity who were already performing closer to optimal levels prior to training may not have profited as much from the type of WM training that we employed. This finding is important as it suggests that WM training does not simply result in the "rich getting richer." Rather, lower capacity participants were those that profited most from the training.

Additionally, the amount of training gains predicted the amount of gains in (some of) the near transfer tasks. Those individuals who showed higher increases in performance in the executive control training task showed higher increases in verbal WM and executive control transfer tasks. Our findings parallel similar findings from recent studies showing specific correlations between training gains and transfer gains (Chein & Morrison, 2010; Schmiedek et al., 2010) and a study that found transfer only in those who improved considerably in the trained task (Jaeggi et al., 2011). This is in line with the hypothesis that process-based training approaches lead to improvements in the trained processes that directly mediate improvements in (at least near) transfer tasks.

To summarize our findings, a rather short-term dose of WM training led to training and transfer effects in an age-diverse sample of old adults. This provides further evidence for cognitive plasticity through WM training interventions in old age and suggests that the capacity to modify cognition and brain health through the biological process of neuroplasticity is preserved, although the extent to which transfer effects may be obtained and upheld over time may be limited to some specific transfer tasks. The current study also highlights the importance of taking variables into account that may moderate the amount of training and transfer gains. Future research has to go beyond simply asking whether cognitive training can produce training and transfer effects or not, but rather differentiate between specific circumstances under which beneficial effects arise from cognitive training. Especially important in this regard seem to be baseline performance on the tasks that are trained and the amount of improvement in the trained tasks over the course of the intervention, with larger profits obtained by individuals with lower pre-training scores and by those who achieved greater training related gains. Additionally, age was revealed to be an important moderator of some of the training gains and all transfer gains, with old-old adults partly profiting less from the training than young-old adults. Future studies should consider these factors in more detail to further delineate the optimal conditions under which WM training can produce the largest training and transfer benefits. Another important aspect in this regard could be to systematically vary the duration and intensity of training. Further delineating all of these conditions would allow differentiating between training programs and specifically tailoring them to the needs of different subgroups, e.g., old-old participants or those with low baseline scores.

6 General Discussion

The current thesis aimed at elucidating several important questions concerning the plasticity of executive control functions induced by systematic cognitive training in different age groups. The three included studies were set up to investigate the amount, range, and stability of plasticity in adolescents and older adults. Secondly, studies explored if different training design and interindividual difference factors moderate the amount and range of changes after executive control training. Furthermore, the question of specific pathways between changes in training and changes in transfer tasks was explored. The following section will first summarize the empirical findings of the three studies. Afterwards, these findings will be discussed and integrated with a special focus on each major question outlined above. Closing the chapter is a conclusion and an outlook onto future avenues for research.

6.1 Summary of empirical findings

The first study was designed to explore, for the first time, if executive control can be trained with a process-based training approach in adolescents. Executive control functions are involved in a range of complex cognitive activities and have been shown to develop across adolescence. Therefore, exploring the plasticity of these functions in adolescents is highly relevant. In addition to training-induced plasticity of executive control in adolescents (10 to 14 years), the study explored what particular domains of executive control may underlie training and transfer effects, and if acute bouts of exercise directly prior to cognitive training enhance training effects. For that purpose, a task switching training and an acute exercise intervention were combined. Transfer was investigated systematically in all three domains of executive control, i.e., switching, updating, and inhibition. A group of adolescents that received a three-session task switching training was compared to a group that received the same task switching training but who exercised on a stationary bike before each training session. Additionally, a no-contact and an active control group (exercise-only) were included. Analyses indicated that both training groups significantly reduced their switching costs over the course of the training sessions for both reaction times and error rates. Furthermore, analyses indicated transfer to mixing costs in a switching task that was similar to the one used in training. Other findings of transfer were limited to a speed task and a tendency for faster reaction times in an updating task. Thus, findings indicate, for the first time, that executive control can be enhanced in adolescents through a short training. However, transfer was rather limited. Concerning the specific relationships between changes in trained and transfer tasks, analyses suggest that updating may be of particular relevance for the effects of task switching training. Analyses revealed no additional effects of the exercise intervention, that is, there was no indication of the hypothesized favorable effect of prior activation on cognitive training effects.

The second study set out to explore, for the first time, if executive control can be improved with a process-based training approach in old-old age (above 80 years). This is of particular relevance because this age range is associated with substantial cognitive decline and reduced plasticity. Hence, in the current study a training group was compared to a matched control group that did not participate in training. The training consisted of ten sessions of practice on verbal and visuospatial working memory tasks. The training group improved in four of the five trained tasks (medium to large effects). Training gains were significantly larger in the training group than in the control group in only two of those tasks. The training effects were largely driven by individuals of the training group who started out with a low capacity in the training tasks. No transfer effects were observed in this study, that included two far transfer tasks. Taken as a whole, findings suggest that positive effects can be achieved in the domains of verbal and visuospatial working memory with a short executive control training even in old-old age, particularly for low-capacity individuals. This emphasizes the potential for cognitive plasticity over the whole life-span. At the same time, the absence of transfer effects may point to the limits of plasticity in old-old adults.

The third study aimed at further elucidating the mixed findings regarding the amounts of training and transfer effects induced by executive control training in older adults. For that purpose, a larger sample of older adults was included covering a wide range from young-old to old-old age (65 to 95 years). Furthermore, possible individual differences that may influence the amount of training and transfer effects were investigated. Half of the sample of older adults were trained for nine sessions on a visuospatial and a verbal working memory as well as an executive control task; the other half did not receive training. Additionally, performance on trained and transfer tasks was assessed before and after training, as well as nine months later to assess the range and the stability of possible training and transfer effects. Analyses revealed significant training effects in all three trained tasks, as well as near transfer to verbal working memory and far transfer to a nonverbal reasoning task. Remarkably, all training effects and the transfer effect to verbal working memory were stable at the nine-month follow-up. Further analyses revealed that training gains were predicted by baseline performance in training tasks and (to a lesser extent) by age. Transfer gains on the other hand, were predicted by age and, additionally, by the amount of improvement in the trained tasks. These findings suggest that cognitive plasticity is preserved over a large range of old age and that even a rather short training regimen can lead to (partly specific) training and transfer effects. However, there are a range of factors that may limit the amount of plasticity, e.g., age and baseline performance in the training domain.

6.2 Integration of the main empirical findings

The studies of the current thesis explored the effects of short executive control trainings (varying in procedure and domain) on cognitive functions in populations of adolescents and older adults. These studies add to the growing literature on plasticity of executive control that is induced by process-based training. The findings, first of all, highlight the potential for intraindividual variability that seems to be maintained across the whole life-span. Secondly, the studies were set up to investigate central questions: the trainability of executive control as well as transferability and stability of executive control training effects, possible moderators of training effects and pathways of training and transfer effects. Following up on these issues, the next sections will discuss in detail how the current findings relate to the central research questions of this thesis.

6.2.1 Amount of plasticity induced by executive control training in different age groups

The first major question of the thesis concerned the amount and range of plasticity that can be achieved by executive control training in adolescents and older adults. Concerning *trainability* as one aspect of plasticity, all studies provide evidence for substantial gains in all trained tasks over the course of training. Specifically, task switching performance improved with training in adolescents (study one); performance on verbal, visuospatial, and executive working memory was shown to improve with training in older adults (study two and three). To rule out simple retest effects, these improvements were compared to pre-posttest gains in a control group that was not trained. Importantly, the gains in trained tasks were significantly larger than in controls in almost all of the tasks, except for study two where gains were reliably larger for only two of the trained tasks. The current studies are the first to demonstrate plasticity of executive control in a group of adolescents and preserved plasticity in adults that are well within their old-old age. Importantly, from a life-span perspective, the targeted age groups fill gaps in the growing literature on plasticity of executive control in nonclinical participants (e.g., Dahlin, Nyberg, et al., 2008; Jaeggi et al., 2008; Karbach & Kray, 2009; Loosli et al., 2012). The findings underline that executive control is not static, but rather can be improved in participants across the whole life-span.

Concerning the amount and range of transfer effects after executive control training (*transferability*), current findings are somewhat mixed. Study one and three were able to demonstrate near transfer as well as some far transfer effects, whereas study two did not provide evidence for transfer (however, note that this study did not include near transfer assessments). Specifically, near transfer was demonstrated for tasks that were similar to the ones trained with regard to structure and required processes, i.e., training on task switching transferred to a similar switching task; training on working memory transferred to verbal working memory tasks. This is in line with other studies showing mostly near transfer to tasks that are similar to trained tasks in cognitive domain, type of stored information, or involved processes (Buschkuehl et al., 2008; Dahlin, Nyberg, et al., 2008; Li et al., 2008). In addition to near transfer effects, the present studies provide evidence for far transfer to tasks measuring different cognitive functions. Better performance was found in a speed task and an updating task (tendency) after task switching training in study one, as well as better performance in a nonverbal reasoning task after working memory training in study three. These tasks are structurally quite different from the tasks trained, but may share similar underlying cognitive processes. Study three is the first to show far transfer of an executive control training to a nonverbal reasoning task in old-old adults, thereby extending results obtained with young adults (Jaeggi et al., 2008) and young-old adults (Borella et al., 2010). This is a remarkable indication of substantial plasticity at this very old age.

However, in general, findings of transfer were more limited than in some other studies (e.g., Karbach & Kray, 2009; Klingberg et al., 2005, but see, e.g., Dowsett & Livesey, 2000; Li et al., 2008; Strobach et al., in press for findings of limited transfer). Transfer was neither found reliably for some of the near transfer tasks (e.g., not for another switching task in study one) nor for a range of far transfer tasks (e.g., inhibition tasks in all studies). Additionally, transfer to a nonverbal reasoning task (as was demonstrated in study three) was not found in study two although the training regimen was rather similar. This may be due to different factors. First of all, the target age group may have played a role with transfer being more difficult to demonstrate especially in old-old age. This has been suggested in studies investigating strategy-based trainings (Brehmer et al., 2008; Singer et al., 2003) and in our own investigation of the possible influence of age (study three). Furthermore, different domains of executive control may differ in their plasticity induced by training. Also, the short duration of training may not have been enough to produce reliable and substantial transfer effects, especially in the old-old adults of study two. The possible influences of these factors will be discussed in more detail in section 6.2.3.

To summarize the empirical findings on the plasticity of executive control, the studies of the current thesis show substantial amounts of plasticity over the whole life span as evidenced by significant training gains and some findings of transfer effects in adolescents and older adults. The findings on transfer varied in amount and range across studies. In general, transfer was mostly found for tasks that were rather similar to the trained tasks (near transfer), with only some evidence for transfer to tasks measuring other cognitive abilities (far transfer). Thus, although training-induced plasticity of executive control was evidenced, the amount and range of transfer was more limited than would be expected from impressive findings by Karbach and Kray (2009) or Jaeggi et al. (2008; but see, e.g., Li et al., 2008; Strobach et al., in press, for findings of limited transfer). This, again, highlights that there may be moderating factors of the amount and range of plasticity.

6.2.2 Maintenance of training and transfer effects of executive control training

Whereas the range of transfer effects was found to be somewhat limited, especially in old-old adults, maintenance of training and transfer effects was revealed in study three. The study is the first to provide evidence for *stability* of training effects for at least nine months in participants well into old-old age. Remarkably, transfer to verbal working memory was also stable nine months after training. This is in line with findings by Dahlin, Nyberg, et al. (2008) showing maintenance of training gains for as long as 18 months in young-old adults. The current results extend the findings of stable training effects to a considerably older age range where stability of training effects had not been found until now (see, e.g., Buschkuehl et al., 2008). These findings suggest that substantial and relatively stable training effects can be obtained for working memory and executive control even with a total training time of only about four and a half hours distributed over three weeks. One has to note, however, that the far transfer effect to nonverbal reasoning that was evident immediately after training was no longer found after nine months, suggesting no stability of this effect. It is reasonable to assume that such far transfer effects would require more substantial changes or possibly reactivation sessions in order to be maintained. It would be interesting to investigate the stability of such effects for even longer periods of time and explore if these effects may even be able to prevent, slow down, or postpone cognitive decline in old age.

To summarize, maintenance of training and near transfer effects as another aspect of plasticity was found nine months after training. This is impressive in its own regard considering that tasks were trained within a short time span of only three weeks with no further training or booster sessions for the following months. Thus, the hypothesis that training and transfer effects remain stable over time was supported.

6.2.3 Factors moderating the amount and range of plasticity

Both from a theoretical and from an applied perspective it is important to explore factors that may influence the amount and range of plasticity induced by executive control training. From a theoretical perspective, this may shed more light on the question why some training studies find a range of training and transfer effects while others show very limited transfer of the training. From an applied perspective, exploring these possible factors may help to tailor efficient executive control trainings specifically for a certain target population. For these reasons, the second major aim of the current thesis was to explore whether aspects of the training design, age, and interindividual differences moderate the amount and range of changes after executive control training.

6.2.3.1 Training design factors

An issue currently under debate in the executive control training literature is the target domain of the training. Are the different components of executive control trainable to the same extent? All of the current studies employed a process-based executive control training consisting of several sessions of repeated performance on executive control tasks. The target domain differed, however: Study one targeted switching and maintenance of task sets, whereas studies two and three targeted different domains of working memory.

Different components of executive control processes may be more or less susceptible to training-induced changes. The current studies do not allow to draw specific conclusions about this issue because trainings targeting different executive control domains were not directly compared in one study. However, in line with other training studies using updating or switching tasks (e.g., Jaeggi et al., 2008; Karbach & Kray, 2009; Klingberg et al., 2005), the current studies add to the empirical evidence that the executive control components switching and updating are trainable.

Adjusting the difficulty of training tasks has been discussed to be an important feature of process-based training approaches (e.g., Dahlin, Bäckman, Stigsdotter Neely, & Nyberg, 2009; Klingberg, 2010; Morrison & Chein, 2011), however, not all of the recent training studies reporting training and transfer effects have used an adaptive procedure (e.g., Karbach & Kray, 2009; Li et al., 2008). Is adapting difficulty of tasks during training really a necessary feature of successful training designs? In studies two and three, the difficulty of the working memory tasks was continuously adapted to the individual performance during training (e.g., by varying the amount of information to maintain). In study one, the task switching training procedure was closely modelled after the one used by Karbach and Kray (2009), i.e., task difficulty was not changed over the course of the training. Because study one also found training and (some) transfer effects, adapting task difficulty does not seem to be essential (at least) for effects of this particular task switching training. Here, it seems to have been sufficient to ask participants to try to perform faster and more accurate over the course of training.

However, more substantial and broader effects may depend on additional adaptive procedures. To test this prediction for the task switching training employed in the current study one, the difficulty of the training task would have to be adapted. This may be achieved by varying the sequence of tasks to be executed (e.g., performing task A three times in a row, then performing task B two times, etc.), increasing the number of tasks to switch between or changing the contents of the tasks. Regarding the last point, which can also be termed variability of training, the study by Karbach and Kray (2009) provides initial evidence that variable training may promote more general transfer. However, importantly, in children contrary effects were found with less transfer after variable training, possibly because the increased cognitive load did not leave children with enough processing capacity to improve in trained task abilities (Karbach & Kray, 2009). This may also be true for adolescents or old-old adults. Thus, in exploring effects of adaptivity one has to consider the possibility of age-dependent effects of adaptivity manipulations.

Another possible moderator of training effects is the duration of training. Is an extensive training regimen necessary to achieve effects or is it possible to obtain comparable outcomes with shorter training regimen? All of the current studies applied a rather short duration training with only three sessions over three weeks (study one), ten sessions over two weeks (study two), and nine sessions over three weeks (study three). The findings of significant training effects in all studies and transfer effects in two of the studies exemplify that even with short durations of cognitive training substantial amounts of plasticity are possible. Interesting to note is that training gains in study one were comparable in size to a task switching training study with a similar short duration (Karbach & Kray, 2009) and training gains in study two were comparable in size (or even larger in low-capacity individuals) to a more extensive training regimen in the study by Buschkuehl et al. (2008) with more than twice as many training sessions.

However, findings of rather limited transfer effects in the current studies (especially in study one and two), may be related to the rather short training durations. It may be that the training dose was not enough to produce robust transfer effects. That is a possible explanation, especially when comparing current training regimen with considerably more extensive training regimen that find relatively broad transfer like the ones used by Klingberg and colleagues (2005, with 25 sessions) and a recent study that even included as many as 100 training sessions (Schmiedek et al., 2010). It is reasonable to assume that a certain amount or intensity of executive control training may be a prerequisite for substantial changes to occur (see, e.g., Hertzog et al., 2009; Klingberg, 2010). Broader transfer effects may be found with a larger amount of training. Considering plasticity as the potential of brain and behavior to change in response to environmental challenges (e.g., cognitive demands of an executive control training Hertzog et al., 2009), the amount of plastic changes and therefore the amount of transfer may strongly depend on the intensity and duration of the challenge. This may be especially true for older adults because of their reduced plasticity. This hypothesis is in line with the findings of study two. Here, training gains were mainly observed in tasks focusing on the storage of information and were just starting to evolve in the second training week for training tasks requiring processing of the stored information to a larger degree. Because processing of information may be especially relevant for transfer effects, a longer training period may have been needed to observe far transfer. As Dahlin, Nyberg, et al. (2008) - who also did not find transfer to executive control tasks in young and young-old adults with an even longer training (15 sessions) - pointed out, a high level of skill in the trained task may be required for the occurrence of such far transfer.

In addition to the overall duration of training (for example hours of training on a particular task), the spacing of the cognitive training sessions may play a role. Is a concentrated training over a short period of time (e.g., daily sessions like in the study by Jaeggi et al., 2008 or in study two) better than several short training sessions distributed over a longer period of time (e.g., weekly sessions like in study one)? No previous study allows to come to a conclusion about this question because the overall amount and/or spacing of the training sessions was not varied systematically within one study. This would be an important avenue for future studies to explore.

With regard to optimal training conditions, study one explored the role of activation prior to cognitive training for the first time. Results from the current study did not lend empirical support for the hypothesized additional benefit of acute exercise directly before cognitive training. This may be due to the rather mixed findings of acute exercise effects on cognitive functions (Hillman et al., 2009; Stroth et al., 2009; Yanagisawa et al., 2010). It is not clear yet what particular aspects of cognition may be reliably influenced by what particular exercise (see, e.g., Budde et al., 2008, for possibly varying effects of aerobic exercise vs. coordination exercise). Most importantly, possible pathways of how cognitive training leads to plastic changes are also not well understood. After future research has made these issues clearer, it will be easier to specifically pinpoint if and how cognitive and exercise interventions may have an added value.

Summarizing the integrated discussion of training design factors possibly modifying the amount and range of plasticity achieved by executive control training, a range of points remain to be tested empirically. However, factors that emerged from the discussion as being especially important in explaining the mixed findings of training studies include the adaptivity of the training regimen as well as timing aspects (e.g., overall duration and spacing of training sessions). Systematic variation of these aspects within one study would further help to delineate essential features of an efficient training design.

6.2.3.2 Age and interindividual differences

A central factor that emerged as possibly moderating the amount of plasticity and has been implied by findings from previous studies (e.g., Brehmer et al., 2008; Karbach & Kray, 2009) is age. Thus, the current thesis tried to answer the question if age influences the amount of training and transfer gains. Incorporating findings from all three studies of the current thesis, behavioral plasticity was shown in adolescents as well as older adults. This is in line with research showing that humans maintain their potential for plastic changes in response to environmental demands across the whole life-span (P. B. Baltes &

Singer, 2001; Li, 2003). However, in old-old adults in study two, training effects were not as reliable and transfer was not found. This may suggest reduced plasticity in this age group. In line with this suggestion, directly investigating the factor age within a single sample (study three), regression analyses revealed that age was a significant predictor of training gains in the visuospatial working memory task with older age being associated with smaller gains in these domains. This finding is paralleled by a negative influence of age on transfer gains in almost all tasks. These findings may, again, suggest reduced plasticity through process-based training with advancing age, especially on the level of transfer. They are consistent with strategy-based training studies showing the potential for plasticity to be smaller in older adults as compared to children and younger adults (P. B. Baltes & Kliegl, 1992; Brehmer et al., 2008; Singer et al., 2003). However, training gains for verbal working memory and the executive control tasks were not predicted by age. This may suggest that it is more difficult to train some aspects of working memory (visuospatial) in old-old age, whereas other aspects of working memory are trainable regardless of age.

To summarize, reduced plasticity with advancing age was revealed for some aspects of executive control (especially on the level of transfer) but not for others (especially on the level of trainability). Future studies will have to further explore possible differences in the plasticity of different executive control aspects across old age. Furthermore, it would be interesting to compare the potential for plasticity in these domains directly across a larger age range, possibly covering the whole life-span. Although both adolescents and older adults are not (yet or any more) at the peak of their cognitive performance level, their potential to improve seems to differ greatly. Intraindividual change (at least on a more general level) seems to be more difficult to achieve in old-old adults. This may be rooted in differences in neuronal plasticity between young and older brains, e.g., reduced potential for synaptogenesis (Kempermann, 2008; van Praag et al., 2000).

Another factor that may moderate training and transfer effects is baseline performance of the participants. Both studies two and three show that within the training group, training gains were larger for individuals with lower baseline scores on trained tasks. This suggests that lower ability older adults benefited more from working memory training. Thus, the training helped to compensate instead of amplify pre-existing differences between individuals (see, e.g., Kramer et al., 1999 for similar findings of a compensatory effect). In fact, in study two only the lower ability older adults were driving the reported training effects, i.e., significant training effects were found in all tasks for this subgroup only. On the contrary, virtually no training effects were found for the old-old high-capacity individuals. Thus the training regimen in this study did not seem to be suitable for high functioning old-old adults. Conceptually, the finding of larger training gains in the low- compared to the high-capacity individuals is consistent with the disuse hypothesis (Gatz et al., 2001; Hultsch et al., 1999; Kliegel et al., 2004). The disuse hypothesis assumes that cognitive decline in old age may be due to suboptimal use of cognitive resources. Frequent use of cognitive resources is thought to help maintain high performance levels, whereas lack of practice is thought to lead to low performance levels. In the current studies the individuals with low baseline working memory capacity may have lacked frequent practice of working memory tasks. When challenged in an adaptive training regime they seemed to be able to reactivate some of their potential. Participants with high baseline capacity may have maintained their ability through frequent use of executive control processes and therefore might not have profited as much from the applied working memory training. However, the current findings are in contrast to previous data showing greater training gains for individuals with higher baseline capacity (Bissig & Lustig, 2007; M. Baltes et al., 1995; Yesavage et al., 1990). These divergent findings could be explained by different factors, e.g., by different training approaches (strategy training vs. process-based training). Methodologically, studies differ in how they define high and low capacity - either by general measures (e.g., crystallized abilities) or more directly by baseline performance in trained tasks as in the current studies. Study three directly compared both types of measures and was able to show that baseline performance on trained tasks differentially predicted training effects whereas general crystallized abilities were less predictive.

To summarize this section, intraindividual differences in age and baseline performance were found to moderate training benefits. These findings may explain why findings of transfer effects have been more limited in studies with old-old participants (e.g., Buschkuehl et al., 2008 or study two). Closely related to this issue, studies may have produced mixed results because of varying degrees of baseline performance in their participants.

6.2.4 Relationships between changes in training and transfer tasks

As the fourth central question of this thesis, possible pathways between changes in training and changes in transfer tasks were explored. The findings from studies one and three suggest that the amount of training gains predicted the amount of gains in (some) transfer tasks. Specifically, those adolescents who improved more in the task switching training in study one also improved more in an updating transfer task. In study three, those older adults who showed higher increases in performance in the planning training task showed higher increases in verbal working memory and planning transfer tasks. Thus, there were specific relationships between changes in training and transfer tasks supporting the claim that process-based training approaches lead to general improvements in the trained processes (executive control) that directly mediate improvements in transfer tasks (that rely on executive control). These findings are in line with other recent studies showing specific correlations between training gains and transfer gains (Chein & Morrison, 2010; Schmiedek et al., 2010). Additionally, the study by Jaeggi et al. (2008) found a specific relationship between the number of training sessions and the amount of transfer. Note that this aspect is closely linked to the possible influence of training duration. If the amount of training gains is related to the duration of training, larger amounts and range of transfer would be expected after longer training duration.

When considering the components of executive control, updating played a very important role in the cognitive trainings of the current thesis. First of all, training tasks of studies two and three directly targeted working memory functions and transfer was found in study three for verbal working memory. Furthermore, the specific task switching training in study one also emphasized updating processes because there were no external task cues to help maintain the sequence of tasks (Karbach & Kray, 2009, see also Allen & Martin, 2010; Karbach & Brieber, 2011, September; Kray et al., 2010, for involvement of updating in self-cued task switching). Furthermore, in study one, near transfer was shown for mixing costs in a similar switching task. Because mixing costs represent the more general ability to maintain several task sets (Kray & Lindenberger, 2000), this finding suggests that the specific switching training may have indeed trained aspects of updating. This is paralleled by a finding of trend for a transfer effect to an updating task and the finding that training gains were related to transfer gains in this same updating task. Thus, in all of the trainings of the current thesis updating seems to have been a crucial aspect. The importance of updating processes is in line with a range of cognitive training studies that have used updating and working memory tasks and have been able to show robust training and transfer effects (e.g., Dahlin, Nyberg, et al., 2008; Jaeggi et al., 2008, 2011; Klingberg et al., 2005). This is especially interesting because updating is the component of the executive control model by Miyake et al. (2000) that was found to be most closely related to intelligence (Friedman et al., 2006). Future studies should specifically investigate the tentative suggestion that updating may be the executive control component that is most susceptible to training-induced plasticity and may underlie transfer effects by directly comparing cognitive trainings that target different executive control components.

Concerning the specific pathways that may lead to transfer of executive control trainings, the current thesis underlines the importance of exploring relationships between cognitive performance gains during training and the observed transfer effects. Specific relations were found that link training gains to transfer effects. Promising candidates for further exploration in this regard seem to be updating processes. It is important for future studies to explore the nature of transfer effects and specifically what aspects of training may underlie transfer. Fruitful in this regard could be studies employing neuroimaging techniques. This may help to delineate regions and processes of the brain that are involved in task execution. For example, according to models of neuronal plasticity one would expect transfer if training induces plasticity in a common neuronal network that is shared between the training and transfer tasks (Olesen et al., 2004). Studies suggest that different working memory and nonverbal reasoning tasks activate overlapping neural regions, mostly lateral prefrontal and parietal regions (Gray et al., 2003; Olesen et al., 2004). If a training program is able to induce changes in these common networks, one would expect transfer especially to other working memory and nonverbal reasoning task performance that rely on the same networks.

6.3 Conclusion and Outlook

The current thesis adds important findings to the developing field of research on the possibility of enhancing executive control functions with the help of systematic cognitive trainings. Potentials for plastic changes were shown in different age groups including adolescents and old-old adults. At the same time important limitations of the amount and range of transfer became evident. As a novel aspect, the current studies exemplified factors that seem to influence and mediate the effects of cognitive training.

A range of open questions and implications for future research may follow up on the current work. Especially relevant for delineating the specific influences and pathways of different executive control trainings would be a study that systematically compares training regimen targeting different components of executive control (e.g., Miyake et al., 2000). For this purpose, a study would need to include at least three different training groups that are trained on tasks either targeting updating, shifting, or inhibition. As has been discussed, the switching tasks used for training in study one may have targeted more than ”just” the switching component of executive control. This type of task switching may have put a strong emphasis on updating requirements also, because the participants had to maintain task sets and the sequence of tasks on their own. A switching task that more purely requires shifting (for example with a paradigm that cues the respective tasks to be executed) may be more suitable to delineate the trainability of the shifting component. In a study comparing training effects of the different executive control components, the procedure, mode, and amount of training should be comparable. A systematic variation and combination of these single training interventions would also be interesting in order to explore simple and combined effects of these interventions. In addition to exploring training effects, it is necessary to systematically evaluate transfer on different levels (near and far transfer). Tasks that cover all components of executive control will have to be included for this purpose, as has been done for example in study one. Such studies would allow to investigate the potentials and boundaries of trainability and transfer across the major components of executive control (as has also been proposed by Dahlin et al., 2009).

None of the previous training studies, including the studies of the current thesis, have specifically investigated the influence of training duration, intensity, and spacing. Reviews that try to compare different studies with longer and shorter periods of training indicate that changes in behavior and neural correlates may vary for different amounts of training (see, e.g., Dahlin et al., 2009; Klingberg, 2010). However, directly comparing findings from different studies is complicated because they differ in other important aspects of training regimen (training task, adaptivity, etc.) and dependent measures. Thus, future studies will need to directly compare different amounts and spacing of training sessions with the same training task, to draw conclusions about dose-dependent effects of executive control training. Conclusions about optimal or rather most efficient training time may differ for different target domains and target populations.

A methodological question that arises in cognitive training research is the choice of an appropriate control group. Including a control group, as has been done in all of the current studies, is essential to rule out that simple retest effects may underlie the observed gains in training and/or transfer tasks. However, a no-contact control group like in studies two and three and a range of other studies on executive control training (e.g., Dahlin, Nyberg, et al., 2008; Li et al., 2008; Schmiedek et al., 2010) can not completely rule out other possible influencing factors. For example, it could be that being in the training group, having several one-on-one sessions with an experimenter, and possibly gaining general experience with cognitive tasks may produce (some of) the observed effects. Social interaction has indeed been found to increase performance in cognitive tasks (e.g., Ybarra et al., 2008). This may be especially true for older adults (see, e.g., Hertzog et al., 2009). In study one with adolescents, an active control group (exercise only) was included in addition to a no-contact control group. This active control group had the same amount of sessions in the laboratory, interacting with the experimenter. In this study, there was no clear indication of differences between the no-contact and the active control group (as has been found in a study by Mahncke et al., 2006). Thus, in some cases including an active control group may not necessarily lead to different conclusions about observed training and transfer effects. However, the current active control group did not control for the amount of experience the training group gained with computerized tasks. Consequently, future studies should carefully consider the choice of (active) control groups despite its costs and efforts. An example for a rather strict active control group can be found in the studies by Klingberg et al. (2005) or Karbach and Kray (2009). Here, control participants trained on nonadaptive versions of the same tasks as the participants of the training group, thus receiving the same amount of experience with the tasks and computerized task execution as the training participants.

From an applied perspective, the findings of substantial effects for trainings with a rather short training duration seem very promising. Shorter trainings are easier to implement into daily lives of adolescents as well as older adults than extensive training procedures over several months. Additionally, a specific feature of the current studies with older adults should be noted. In order to accommodate the special age group of older adults, a mode of training was chosen that may be more suitable and motivating for older adults without computer experience. That is, participants were trained face-to-face with more liberal reaction time limits as opposed to using a computerized training program like in study one and most of the other cognitive training studies so far (e.g., Dahlin, Nyberg, et al., 2008; Jaeggi et al., 2008; Klingberg, 2010). The findings suggest that training effects can also be obtained in this setting, that may be particularly motivating for the old-old adults as is suggested by the high compliance rate in study two for example.

The findings of specific influences of baseline performance on trained tasks in older adults are interesting because they suggest that executive control training does not simply result in the ”rich getting richer”. Rather, lower capacity participants were those that profited most from the training. While this may be good news for the lower functioning, current training regimen of studies two and three did not seem to be particular beneficial for high functioning older adults. This again highlights the importance of exploring interindividual difference factors, specifically, to adapt training to individual resources and needs. From an applied perspective, training interventions should benefit participants in important aspects of their cognitive functioning. However, transfer to real-world tasks and skills has not been shown in the current studies, which is also true for most of the other training research. Thus, the ”gold standard” of applied training interventions may be very hard to achieve and awaits further investigation.

To achieve these goals, it is necessary to continue to pursue the exploration of individual differences that may influence the amount of benefit from cognitive training interventions. In addition to age or baseline performance in the training domain other factors could play a role, for example proficiency in working with a computer, general health, or current mood. Furthermore, motivational issues may be of importance as was indicated by personal observations during the studies. For example, in study one some adolescents seemed to become less motivated over the course of the training (and in posttraining assessments) to perform the same tasks over and over again. An indication for this loss of motivation may be that error rates in nonswitch trials increased over the course of the training sessions in this study. On the contrary, in the studies with the older adults, the one-on-one setting seemed to have been very positive for the participants because it also provided the opportunity for social contact. That is, different aspects of motivation and interindividual differences in these aspects may influence the effects of cognitive trainings and thus should be explored further.

6.4 Summary

The current thesis explored effects of short executive control trainings on cognition in adolescents and older adults. The findings suggest a high potential for intraindividual variability across the whole life-span. Plasticity was shown on the level of training and transfer tasks, as well as on the level of stability of effects. Furthermore, results support the notion that process-based training approaches do indeed improve executive control processes that in turn lead to improvements in tasks that rely on these processes.

The current thesis makes important contributions to the conceptual debate about the potentials and limits of training-induced plasticity across the life-span. It benefits the debate in that it delineates factors that moderate the obtained effects. Further exploring these factors may make it possible to specifically tailor executive control training to the specific predispositions of different individuals. The main question for future studies should no longer be *if* executive control training leads to training and transfer effects but rather *under what circumstances.*

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Appendix

Supplementary Tables for Study 1

Table A1: Mean RT data for transfer task switching and inhibition tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact)

Training groups	**COMBINED TRAINING**				**COGNITIVE TRAINING**			
	Pretraining		Posttraining		Pretraining		Posttraining	
	M	(*SD*)	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)
Food/Size Switching Task (mean RT in ms)								
Single Trials	684	(109)	611	(100)	686	(171)	612	(180)
Nonswitch Trials	789	(166)	642	(103)	774	(188)	621	(180)
Switch Trials	1010	(263)	778	(180)	1016	(252)	735	(260)
Number Switching Task (mean RT in ms)								
Single Trials	656	(85)	636	(104)	661	(118)	633	(171)
Nonswitch Trials	1285	(246)	1135	(223)	1329	(293)	1135	(314)
Switch Trials	1484	(276)	1216	(280)	1450	(364)	1258	(313)
Flanker Inhibition Task (mean RT in ms)								
Congruent Trials	554	(60)	507	(59)	559	(99)	515	(100)
Incongruent Trials	573	(58)	518	(65)	582	(104)	535	(93)
Stroop Inhibition Task (overall time in s)								
2nd run (color patches)	26	(7)	24	(5)	25	(5)	24	(5)
3nd run (color names)	44	(10)	39	(12)	44	(10)	42	(11)
Control groups	**EXERCISE ONLY**				**NO-CONTACT**			
Food/Size Switching Task (mean RT in ms)								
Single Trials	691	(133)	641	(123)	726	(147)	650	(117)
Nonswitch Trials	783	(186)	707	(169)	816	(175)	745	(138)
Switch Trials	1002	(273)	843	(225)	1125	(301)	908	(189)
Number Switching Task (mean RT in ms)								
Single Trials	678	(132)	659	(111)	671	(92)	621	(87)
Nonswitch Trials	1279	(367)	1147	(266)	1420	(277)	1244	(183)
Switch Trials	1427	(450)	1269	(326)	1586	(257)	1371	(245)
Flanker Inhibition Task (mean RT in ms)								
Congruent Trials	559	(87)	537	(63)	539	(64)	523	(79)
Incongruent Trials	575	(96)	558	(71)	548	(63)	532	(70)
Stroop Inhibition Task (overall time in s)								
2nd run (color patches)	26	(5)	26	(6)	27	(6)	26	(6)
3nd run (color names)	43	(11)	38	(6)	45	(16)	41	(9)

Table A2: Mean error data for transfer task switching tasks in the training groups (combined and cognitive training only) and control groups (exercise only and no-contact)

Training groups	**COMBINED TRAINING**				**COGNITIVE TRAINING**			
	Pretraining		Posttraining		Pretraining		Posttraining	
	M	(*SD*)	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)
Food/Size Switching Task (mean error rate in %)								
Single Trials	8.2	(5.0)	13.2	(10.3)	8.9	(6.2)	16.4	(10.0)
Nonswitch Trials	10.5	(6.7)	16.1	(12.1)	9.5	(6.3)	19.2	(14.4)
Switch Trials	13.6	(8.0)	19.1	(12.7)	14.2	(7.5)	23.9	(12.5)
Number Switching Task (mean error rate in %)								
Single Trials	9.3	(11.2)	8.8	(4.4)	8.4	(7.0)	11.6	(7.2)
Nonswitch Trials	10.3	(8.1)	11.4	(11.4)	11.3	(13.2)	12.4	(9.0)
Switch Trials	12.9	(7.2)	17.9	(13.2)	16.3	(11.9)	17.1	(11.6)
Control groups	**EXERCISE ONLY**				**NO-CONTACT**			
Food/Size Switching Task (mean error rate in %)								
Single Trials	7.4	(4.2)	8.5	(5.7)	6.4	(4.2)	8.4	(6.3)
Nonswitch Trials	6.7	(4.1)	8.9	(5.9)	6.3	(4.0)	9.3	(6.4)
Switch Trials	11.3	(5.7)	10.8	(8.9)	9.7	(5.7)	12.7	(6.2)
Number Switching Task (mean error rate in %)								
Single Trials	7.5	(10.1)	7.9	(6.2)	5.7	(4.6)	10.1	(9.4)
Nonswitch Trials	10.5	(10.7)	11.2	(11.5)	7.9	(5.3)	7.1	(5.3)
Switch Trials	11.7	(10.7)	14.4	(12.6)	12.2	(8.0)	12.6	(7.7)