# Cognitive Training Across the Adult Lifespan

**Sabrina Guye, Christina Röcke, Susan Mérillat, Claudia C. von Bastian, and Mike Martin**

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**Abstract** Normal aging is generally associated with deterioration in a number of cognitive abilities, although large individual differences in size and progression of age-related cognitive change exist. Cognitive training interventions have become an increasingly important object of research, aiming at the stabilization and improvement of cognitive abilities in old age. However, training gains tend to be of small to moderate magnitude compared to no training both on the behavioral and the brain level, but are small or disappear when compared to active control conditions. Across the different types of training interventions, mainly near transfer effects of small to moderate size have been documented. To gain further insights into the mechanism and boundaries of cognitive plasticity, we argue that future research should focus on

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S. Guye (✉) · C. Röcke · S. Mérillat
University Research Priority Program (URPP) "Dynamics of Healthy Aging", University of Zurich, Zurich, Switzerland
e-mail: sabrina.guye@uzh.ch

C. C. von Bastian
Department of Psychology, University Sheffield, Sheffield, UK

M. Martin
University Research Priority Program (URPP) "Dynamics of Healthy Aging", University of Zurich, Zurich, Switzerland

Department of Psychology, Division of Gerontopsychology and Gerontology and Gerontology Center, University of Zurich, Zurich, Switzerland



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investigating more thoroughly the cognitive processes involved in cognitive training, on identifying training contexts that may maximize training and transfer effects, and on quantifying potential impacts on meaningful real-life outcomes.

## Introduction

There is robust longitudinal evidence for age-related decline in cognitive abilities. Fluid abilities are affected earlier than crystallized abilities, but with varying onset and slope between individuals (e.g., Salthouse 2010). These negative age-related changes have sparked early interest in the possibility of preventing or counteracting this decline and thus maintaining cognitive health into later life with cognitive training interventions. In this chapter, we review the literature regarding training-induced plasticity in healthy older adults.

Many of the early training interventions focused on improving (episodic) memory ability, given that subjective changes in one's memory functioning are frequently voiced concerns from older adults (see also Wenger et al., this volume). Using a testing-the-limits paradigm, these training interventions typically instructed participants in a specific memory strategy, such as the Method of Loci, trying to uncover the strategy-independent latent performance potential and the boundary conditions for such latent reserve capacity of the aging cognitive system. The second generation of cognitive training interventions consisted of process-based approaches that focused on broader, more basic cognitive processes including working memory (see also Könen et al., this volume) or executive functions (see also Karbach and Kray, this volume). As a special form of process-based training, newer approaches target multiple cognitive domains simultaneously to achieve broader and larger transfer and greater ecological validity.

In the first part of this chapter, we review empirical evidence regarding the benefits of cognitive training interventions in healthy older adults separately for training gains, transfer, and their maintenance, as well as findings regarding brain structure and function. In the second part, we will outline the key points to consider in future research to design more effective training interventions for healthy older adults to help maintain cognitive functioning.

## Benefits of Cognitive Training Interventions

Cognitive training studies differ on a multitude of design choices (e.g., type of training and its administration, cognitive domain, setting, intensity and duration, type of control group, and type of outcome measure to assess training effectiveness; see Cochrane and Green, this volume). In addition, the systematic reviews and meta-analyses available also differ substantially in their scope and inclusion criteria, and whether they distinguish between training gain and transfer effects and between different types of control groups. Thus, conclusions from these overview analyses are not straightforward to compare.

## *Evidence for Training Effects*

***Training Gains: Passive vs. Active Controls*** Training effects are typically operationalized as pre to posttraining performance increases on the trained tasks compared to pre to posttraining performance changes in *passive* (i.e., with no instructed activity) or *active* control groups (i.e., with an instructed activity, but clear differentiation in the involved cognitive processes; Shipstead et al. 2012). Findings across different kinds of interventions indicate cognitive plasticity in terms of training gains (e.g., Baltes and Kliegl 1992). For example, in their meta-analysis on process-based working memory and executive functioning training, Karbach and Verhaeghen (2014) reported raw training gains of 0.9 *SD*, which remained almost equal in size when compared to passive controls (0.8 *SD*; see also Kelly et al. 2014 for similar effect sizes in working memory and speed training interventions). Interestingly, however, training gains were found as reduced to 0.5 *SD* (Karbach and Verhaeghen 2014) or even zero (Martin et al. 2011, see also Kelly et al. 2014 for replication) after comparing to active controls. Promising training gains emerge for multidomain training interventions (Park et al. 2014, see also Bediou et al., this volume).

***Age-Related Differences in Training Gains*** In contrast to findings from strategy-based training interventions indicating a magnification of age differences in cognitive performance and limits to training-induced plasticity in the very old (e.g., Verhaeghen and Marcoen 1996), no such age differences in training gains were observed for process-based working memory and executive functioning training interventions (Karbach and Verhaeghen 2014). The implementation of complex cognitive strategies may require a higher level of cognitive functioning than is true for the elementary cognitive processes targeted in process-based training interventions (Verhaeghen 2014). While research concerning multidomain training is still in its infancy, there is initial evidence for greater video game training benefits for older-old compared to younger-old adults, but the underlying reasons are yet poorly understood (see also Bediou et al., Strobach and Schubert, this volume).

***Moderators of Training Effectiveness*** Group-based lab settings show greater effects than home-based training interventions (Kelly et al. 2014; Lampit et al. 2014), but it remains unclear whether these differences are due to formal vs. informal instruction or to the social setting vs. being alone. The same is true for training frequency and duration, where there is conflicting evidence about whether shorter or longer duration is the most beneficial (Karbach and Verhaeghen 2014; Kelly et al. 2014).

### *Evidence for Transfer Effects*

As discussed in the paragraphs above, training interventions improve performance on the trained task, with greater gains compared to passive than active controls, and more robust effects for process- than strategy-based training interventions. Some of the training gains reported were of equivalent size as normal age-related declines across various cognitive domains, suggesting that training interventions likely help to reverse age-related declines and thus to stabilize cognitive functioning (Ball et al. 2002). The question is, however, if these improvements transfer to untrained tasks measuring either the same ability (i.e., near transfer) or to tasks measuring different abilities sharing underlying cognitive processes (i.e., far transfer; see e.g., Noack et al. 2009; Shipstead et al. 2012; see also Schmiedek, Taatgen, Chochrane and Green, this volume).

***Transfer to Other Cognitive Tasks Assessed in the Laboratory*** For strategy-based trainings, little to no transfer effects have been found (e.g., Martin et al. 2011). It has been argued, though, that in contrast to the acquisition of specific memory strategies, practice effects from process-based training would be more prone to induce transfer to other cognitive tasks sharing the same core processes as the ones targeted in the intervention (e.g., Shipstead et al. 2012). Indeed, some process-based cognitive training interventions have been shown to induce small to moderate near transfer effects when the intervention is adaptive and of longer duration (Kelly et al. 2014, but see Guye and von Bastian 2017; von Bastian et al. 2019). For training interventions targeting working memory and executive functioning, for example, Karbach and Verhaeghen's (2014) meta-analysis indicated a net gain in near transfer tasks compared to active controls of 0.5 *SD*. However, far transfer effects were very small (net far transfer effects 0.2 *SD* in Karbach and Verhaeghen 2014; see also Könen et al., Karbach and Kray, this volume). The few available multidomain training interventions including cognitively complex group activities (e.g., Park et al. 2014), problem-solving (Stine-Morrow et al. 2008), or video games (see Bediou et al., Strobach and Schubert, this volume) have also shown small to moderate transfer effects to some cognitive functions, including executive functioning, episodic memory or processing speed. However, in order to design effective training interventions in the future, the understanding of the underlying processes, the cognitive functions targeted, and a high degree of ecological validity are necessary (see also Binder et al. 2015).

***Transfer to Everyday Life*** Transfer to everyday life has been examined in only few studies, and some recent reviews have even excluded studies with everyday transfer from their analysis (e.g., Lampit et al. 2014). Studies in which everyday life was examined typically focused on self-reported basic or instrumental activities of daily living (BADL/IADL). However, these measures are designed to assess rather severe impairments in everyday life competence and, thus, are not necessarily optimal indicators of everyday functioning in healthy older adults due to ceiling effects. In the ACTIVE trial, the speed of information processing in everyday life was assessed by tasks such as looking up a telephone number, finding a respective food item on the supermarket shelf, identifying the ingredients on food labels, as well as self-reported driving ability. Not surprisingly, little to no evidence of transfer of the memory, reasoning, and processing speed training interventions to impairments in everyday functioning has been found immediately after training (Ball et al. 2002).

## *Evidence for Maintenance Effects*

Most studies assess pre and immediate posttest performance and transfer, but do not follow-up on these effects over extended periods of time. Many studies examine maintenance only across a few months, even though it has been proposed that a three-year interval provides a more sensitive test of maintenance, differential stability, and change (Salthouse 2006).

***Maintenance of Training Gains*** Kelly et al. (2014) report maintenance effects examined after up to 6 months, indicating maintenance of training gains following executive functioning and memory training interventions. Longer follow-up intervals have been tested in selected studies, such as the ACTIVE trial (Rebok et al. 2014; Willis et al. 2006) that assessed maintenance effects 5 years and 10 years posttraining. In the ACTIVE study, training gains observed in each training group were maintained over 5 years, with positive additive effects through intermediate booster training (Willis et al. 2006). After 10 years, training effects were maintained in the reasoning and processing speed domains, but not in the episodic memory domain (Rebok et al. 2014).

***Maintenance of Transfer Effects*** Even though there were no immediate or shorter-term effects after 2 years in the ACTIVE trial (Ball et al. 2002), promising transfer effects to everyday functioning for particular training conditions and everyday outcomes were found after longer periods: (process-based) speed training was related to better driving performance and self-reported driving experience after up to 6-year intervals (Ball et al. 2010). In addition, there is evidence for effects of training on the slope of change trajectories in everyday functioning: Across a 5-year interval, participants in the (strategy-based) reasoning training group showed less steep declines in BADL/IADL competence and a 50% reduced risk of experiencing a car accident compared to the passive control participants (Willis et al. 2006). After an extended time period of 10 years, ACTIVE data showed transfer to everyday functioning in terms of BADL/IADL for all three training conditions, suggesting that trained individuals experienced fewer impairments in their independent functioning in everyday life. Interestingly, at the long term follow up and an average age of 82 years, 60% of the trained participants were at or above their baseline everyday competence level, which was true for only 50% of the passive control participants. Taken together, the findings suggest that transfer effects on the ability to live independently may be detectable only in the long run rather than immediately following the training intervention. Outcome measures assessing everyday performance above the impairment level or everyday cognitive activities instead of abilities have hardly been used in the literature so far, but may be more promising to detect transfer to real life.

## *Evidence for Effects on Brain Structure and Function*

Normal aging is accompanied by brain tissue loss and neurophysiological changes (Raz and Rodrigue 2006). While the loss of grey matter manifests itself as general volume decline and cortical thinning (Fjell and Walhovd 2010), the degradation of white matter is reflected in reduced integrity and the incidence of so-called white matter hyperintensities. With respect to brain function, aging has been linked with a complex pattern of local over- and under-recruitment of neural resources.

***Effects on Brain Structure*** A growing number of structural neuroimaging studies in healthy older adults provide evidence for beneficial effects of cognitive training on brain structure, especially for the domains of memory and working memory, where most of the work has been carried out (see Lustig et al. 2009 for a review, see also Oschwald et al. 2019). These effects (compared to a control group) comprise reduced decreases, maintenance or even increases in volume or cortical thickness of brain structures relevant for the trained function (e.g., Raz et al. 2013; Lövdén et al. 2012). The integrity of white matter, which can be qualified by different measures of water diffusion (e.g., Fractional Anisotropy, FA) on the basis of diffusion tensor imaging (DTI), can also be maintained or even increased by cognitive training interventions (e.g., Engvig et al. 2012). The reported effects reflect processes of structural neuroplasticity, which (partly) counteract the tissue degradation normally observed with aging. However, as most of the previous studies used passive control groups only, future studies including active control groups need to confirm the specificity of such effects.

***Effects on Brain Function*** The evidence emerging from studies investigating the effects of cognitive training interventions on brain function is less conclusive. On the one hand, studies adopting strategy-based training interventions report increased brain activity during posttraining task performance (e.g., Nyberg et al. 2003). Based on the observed correlations between neurophysiological and behavioral changes, the activation increase has been attributed to an enhanced recruitment of task-specific regions that enables behavioral gains. On the other hand, process-based training studies, particularly in the domains of working memory or executive functioning, showed decreased brain activity at the post- compared to pretraining assessment, indicating improved neural efficiency during posttraining task performance (e.g., Brehmer et al. 2011). This discrepancy in the pattern of activity might be due to the different neural mechanisms initiated by the different training types. However, there is evidence in younger adults, that the activity decrease seen at later phases of process-based training interventions is actually preceded by an increase of activity in early training phases (Hempel et al. 2004). Future studies need to confirm whether this trajectory holds for older adults and whether strategy-based training interventions would also lead to increased neural efficiency after an extended period of implementing the acquired strategies.

Using electroencephalography (EEG), recent studies in older adults have demonstrated facilitative effects of cognitive training on early electrophysiological markers of the trained cognitive function with the extent of the ERP change predicting posttraining performance (e.g., Berry et al. 2010).

## Future Directions

The central goal of cognitive training is to positively impact cognitive ability, cognitive plasticity, and ultimately functional ability in everyday life. Given the inconsistent findings with regard to training and transfer effects, as well as moderators thereof, we argue that future research should focus on three aspects (see also Guye 2018): (1) Investigate change in the cognitive processes involved in cognitive training to gain insights into the mechanism and boundaries of cognitive plasticity, (2) identify training contexts that maximize training and transfer effects, and (3) quantify the impact on meaningful real-life outcomes.

### *Cognitive Processes During Cognitive Training*

The basic assumption underlying cognitive training is that repeated practice of cognitively challenging tasks expands the cognitive capacity (i.e., cognitive plasticity). However, the limited evidence for both near and far transfer after intensive cognitive training challenges this basic assumption. We argue that a better understanding of the changes occurring in the cognitive processes involved in training is needed to identify the potential mechanisms that could drive cognitive plasticity. Oberauer and Lewandowsky (2019) have recently presented measurement models for working memory tasks that assume two dimensions contributing to working memory performance: memory for individual elements (e.g., single digits) and memory for relations (e.g., the temporary binding of a digit to its position in a list of digits). The authors found evidence that, relative to younger adults, older adults showed specific deficits in memory for relations but not in memory for individual elements. Thus, directly targeting memory for relations as a cognitive process that deteriorates in old age could be a potential way to boost training and transfer gains.

## *Optimal Training Contexts*

Understanding the parameters of the individually optimal training context (e.g., location, social setting, psychological state and training schedule) may direct us towards better tailoring cognitive training to the individual needs and preferences. Therefore, in addition to focusing on between-person factors associated with cognitive performance (see Katz et al., this volume; Guye et al. 2017; and for review see von Bastian and Oberauer 2014), we and others (e.g., Könen and Karbach 2015) argue that future research efforts should aim towards a better understanding of the influence of within-person covariates and environmental factors on cognitive training and transfer performance. Assessing those variables in naturalistic settings has become easier than ever given the technological advancements in recent years.

There is accumulating research showing within-person associations between cognitive performance and other factors including stress (Sliwinski et al. 2006; Stawski et al. 2011), both positive and negative affect, as well as motivation (Brose et al. 2012; Brose et al. 2014), sleep (Könen et al. 2015), and social activity (Bielak et al. 2019). The assessment of such contextual factors could be integrated in cognitive training studies to provide real-time feedback to participants on which factors are positively or negatively associated with the current training performance. Based on such just-in-time information (Nahum-Shani et al. 2018), participants would then be able to dynamically adapt their training regime to match the personally most beneficial training context, potentially maximizing the overall longer-term training benefit. Thus, a comprehensive assessment of daily personal and environmental factors, which are theoretically assumed to co-vary with daily cognitive performance, may further contribute to understand how daily training performance can be boosted.

Given the technological developments in the field of mobile sensing, ambulatory assessments to collect self-reported outcomes can easily be complemented with other tracking technologies to objectively assess further contextual parameters such as physical activity (e.g., GPS and accelerometer), physiological parameters (e.g., sleep and heart rate), or social interactions (e.g., Brose and Ebner-Priemer 2015, Mehl et al. 2001; see also Cochrane and Green, Colzato and Hommel, this volume).

## *Meaningful Real-Life Outcomes*

One of the main goals of cognitive training interventions is to enhance cognitive performance in real-life settings and functional ability in everyday life. Although research has shown that specific aspects of cognitive ability, engaged lifestyle, and functional ability are associated (Guye et al. 2019), cognitive training studies have primarily focused on lab-based cognitive transfer tasks. Ecologically valid assessments of transfer to measure functional ability or everyday cognition are scarce (but see Ball et al. 2010; Cantarella et al. 2017; Willis et al. 2006 for exceptions).

Especially in older adults, it may come as a surprising observation that age-related decline in basic cognitive functions measured with lab-based cognitive tasks can go hand in hand with high levels of life satisfaction (e.g., Lachman et al. 2008; Scheibe and Carstensen 2010), and the ability to clearly manage tasks and activities in real-life successfully (Salthouse 2011). Thus, in order to understand whether cognitive training is beneficial for older adults beyond lab-based measures of cognition, it is crucial to embed the evaluation of cognitive training into real-life settings and measure everyday cognition (Bielak et al. 2017; Verhaeghen et al. 2012). Some studies have used self-reported measures (e.g., IADL; Lawton and Brody 1969; CFQ; Broadbent et al. 1982), and performance-based measures of everyday cognition in the lab (EPT; Willis and Marsiske 1993). However, in addition to the potential ceiling effects discussed above, these efforts do not capture the complexity and richness of real-life activities under natural circumstances. Thus, to quantify the real-life impact of cognitive training interventions, the development of objective, ecologically valid and comprehensive measures of cognitive functional ability are needed (see Mazurek et al. 2015 for an exception).

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