



Review

Boosting brain functions: Improving executive functions with behavioral training, neurostimulation, and neurofeedback

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ABSTRACT

Cognitive enhancement is a popular topic, attracting attention both from the general public and the scientific research community. Higher cognitive functions are involved in various aspects of everyday life and have been associated with manifest behavioral and psychiatric mental impairments when deteriorated. The improvement of these so-called executive functions (EFs) is of high individual, social, and economic relevances. This review provides a synopsis of two lines of research, investigating the enhancement of capabilities in executive functioning: a) computerized behavioral trainings, and b) approaches for direct neuromodulation (neurofeedback and transcranial electrostimulation). Task switching, memory updating, response inhibition, and dual task performance are addressed in terms of cognitive functions. It has been shown that behavioral cognitive training leads to enhanced performance in task switching, memory updating, and dual tasks. Similarly, direct neurocognitive modulation of brain regions that are crucially involved in specific EFs also leads to behavioral benefits in response inhibition, task switching, and memory updating. Response inhibition performance has been shown to be improved by neurostimulation of the right inferior frontal cortex, whereas neurostimulation of the dorsolateral prefrontal cortex exerts effects on task switching and memory updating. Due to a lack of consistency in experimental methods and findings, a comparison of different training approaches concerning their effectiveness is not yet possible. So far, current data suggest that training gains may indeed generalize to untrained tasks aiming at the same cognitive process, as well as across cognitive domains within executive control.

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1. Introduction

1.1. Theoretical justification for the training of executive functions

Within a very short time we are able to decide whether to follow the exit of a highway in order to avoid an upcoming traffic jam or to accept driving slowly and arriving at our destination late. In unfamiliar surroundings we can follow the instructions of a navigation system while also attending to traffic signs, thus avoiding accidents. In brief, we are able to define and update objectives, to flexibly adapt to our environment, and to guide appropriate behavior. Processes that enable the planning, control and monitoring of complex, goal-directed behavior and thoughts are often referred to as executive functions (EFs; Seiferth et al., 2007).

EFs are of relevance because they mediate learning processes (St. Clair-Thompson et al., 2010; Rabin et al., 2011) and the control of emotions (Fox and Calkin, 2003; Fikke et al., 2011). In preschool

children, EFs are more strongly linked to school readiness than intelligence or entry-level math skills (Blair and Razza, 2007; Diamond et al., 2007). Indeed, childhood EFs predict academic achievement and social functioning in adolescence (Biederman et al., 2004; Miller and Hinshaw, 2010). EFs are also important for successful aging because of their relevance to health behavior, stress regulation, and developmental trajectories of aging and mortality (Williams and Thayer, 2009). Moreover, disruptions of EFs are associated with various behavioral and neurocognitive impairments (e.g., Goldberg and Seidmann, 1991). It therefore is an important goal for public health research programs to discern ways of enhancing EFs through various methodological approaches. This requires a rigorous systematic investigation of putative training protocols in order to determine efficient and specific interventions for children, older adults, and patients.

This review provides an overview of current studies used to modify EFs. Here, we follow the framework of Miyake and colleagues, who define EFs as a collection of related yet separable higher order cognitive functions whose most important and independent representatives are task switching, memory updating, and response inhibition (Miyake et al., 2000; Miyake and Friedman, 2012; Fisk and Sharp, 2004). In addition, dual task processing will also be considered. While task switching describes the ability to shift between the

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processing of different (cognitive) tasks or their demands, memory updating is a sub-process within working memory (WM) that controls its contents and updates stored items with incoming information (Bledowski et al., 2009). Response inhibition is thought of as an active mechanism to stop or suppress responses within the motor domain. A more general inhibitory mechanism is believed to be of crucial importance in the cognitive or emotional domain as well. Coordination skills are suggested to underlie the concurrent performance of several tasks.

The relatively young research area on cognitive training shows a tendency to divide into two independent lines of research, one focusing on behavioral training procedures, the other on the up-regulation of the neural mechanisms enabling EFs by neurostimulation or neurofeedback. This review is the first to discuss both lines of research (see Fig. 1). Initially, brain networks implementing EFs are introduced. Then, the concept of plasticity, as well as training criteria, and principles are discussed. The main body of work, however, will be a synopsis of studies on the improvement of EFs by behavioral training on the one hand, and the improvement by neurostimulation and -feedback on the other. Finally, four key questions will be addressed based on our synopsis:

- 1) Is it possible to compare different behavioral training types concerning their effectiveness?
- 2) When do we expect transfer?
- 3) Do neurostimulation and neurofeedback techniques constitute neurocognitive interventions for the enhancement of executive functions? Last, but not least:

- 4) What do training-related neural correlates of enhanced executive functions tell us?

2. Neural networks implementing executive functions

By studying the basic neural mechanisms implementing EFs, it can be investigated whether cognitive trainings actually affect these mechanisms, and whether more neurocognitive approaches, such as neurostimulation and neurofeedback, can more directly modulate the activity profiles of relevant core regions, potentially leading to augmented EFs.

Historically, research on EFs has its roots in the examination of patients with frontal lobe lesions who exhibited severe problems in EFs (e.g., Duncan, 1986). Animal studies further supported the relevance of the prefrontal lobe for EFs (e.g., Fuster, 1990). Thus, the frontal cortex was initially seen as a discrete module where different EFs were thought to reside in isolation (e.g., Luria, 2002). Nowadays, it is becoming increasingly clear that EFs are supported by several brain areas forming complex functional networks. However, in a recent meta-analysis on 193 neuroimaging studies, it was demonstrated that the aforementioned EFs are supported by a common, distributed, super-ordinate network (see Fig. 2; Niendam et al., 2012). This so-called fronto-cingulo-parietal network consists of the dorsolateral prefrontal cortex (DLPFC; BA 9, 46), the frontopolar cortex (BA 10), the orbitofrontal cortex (BA 11), and the midcingulate cortex (MCC; BA 32). Additional network components are superior and inferior parietal (BA 7, 40), occipital (BA 19), and temporal (BAs, 13, 22, 37)

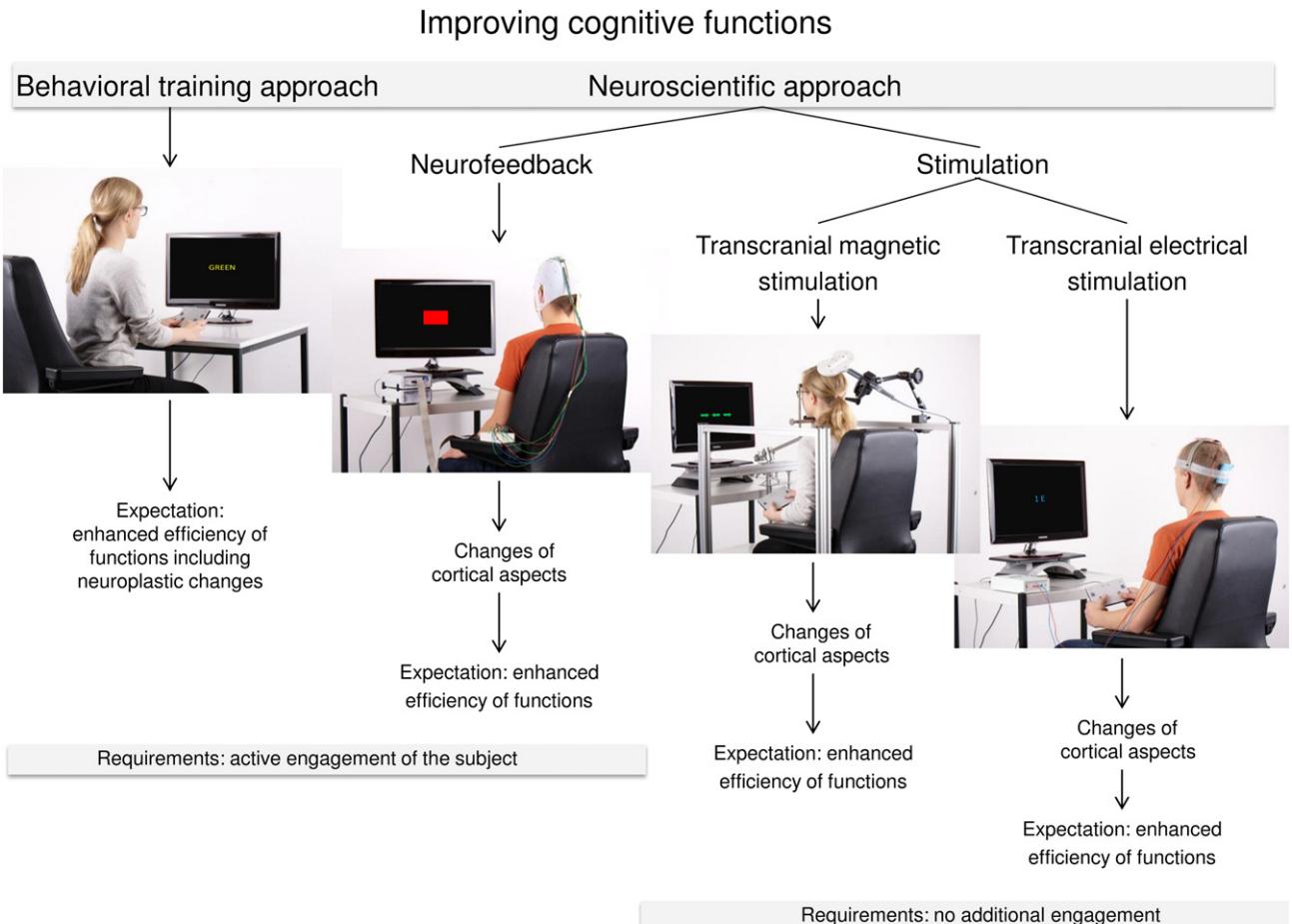


Fig. 1. Theoretical training approaches. To enhance cognitive functions behavioral training, neurostimulation and neurofeedback techniques can be differentiated. Behavioral-, and neurofeedback training all include the active engagement of the subjects, whereas neurostimulation does not.

Super-ordinate network underlying executive functions

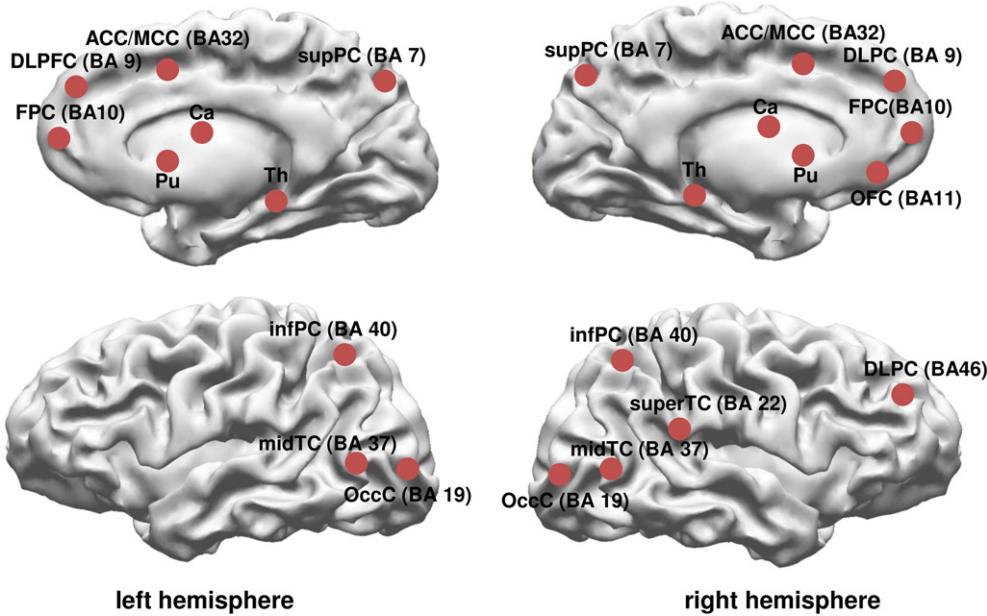


Fig. 2. Super-ordinate network underlying executive functions. This figure depicts the brain areas belonging to the super-ordinate fronto-cingulo-parietal network as suggested by the meta-analysis of Niendam et al. (2012). Abbreviations: Frontopolar C = frontopolar cortex; Th = thalamus; Pu = putamen; Ca = caudate; supPC = superior parietal cortex; OFC = orbitofrontal cortex; infPC = inferior parietal cortex; midTC = midtemporal cortex; OccC = occipital cortex.

areas, as well as subcortical areas such as the caudate, putamen, thalamus, and cerebellum. Besides this shared network, further domain specific regions were found for individual EFs in the anterior prefrontal cortex, anterior cingulate cortex (ACC; BA 24) and MCC (BA 32), as well as the basal ganglia, and the cerebellum.

Further differentiating within the large super-ordinate network, Dosenbach et al. (2008) suggested a dual-network architecture distinguishing a fronto-parietal network, that initiates and adjusts control and maintains information over a shorter time, from a cingulo-opercular network (also known as fronto-executive network) that provides stable task sets by maintaining activity across a longer period of time.

Concerning the functional contribution of the previously specified brain areas, the association of the MCC (sometimes somewhat imprecisely also referred to as dorsal ACC) with pre-critical response conflicts is one of the best-established findings in cognitive neuroscience (Botvinick et al., 2001). Midcingulate conflict detection triggers strategic adjustments in the DLPFC to attenuate conflict and augments subsequent performance (e.g., Kerns, 2006). As summarized by Niendam et al. (2012), the DLPFC is predestined to shift attention according to task demands, to maintain action rules, and to select appropriate responses, whereas parietal regions provide the DLPFC with information about stimulus salience and learned stimulus-response associations.

All in all, enhanced executive functioning due to behavioral trainings or neuromodulatory approaches can be expected to alter activity profiles of regions of the super-ordinate network or domain specific networks.

3. Neural plasticity in the context of training

3.1. The concept of neural plasticity

The concept of neural plasticity refers to the brain's capacity for anatomically implementing reactive changes (Lövdén et al., 2010). Aside from a number of internal and external events such as

deprivation, maturation, brain injuries or regeneration, plasticity can also be induced by demands associated with training, practice or learning (e.g., Kolb and Whishaw, 1998), whenever these demands diverge from available capacities (e.g., Bäckman and Dixon, 1992; Lövdén et al., 2010). Plastic changes concern the modification of either knowledge (new skills, task strategies) and/or processes (efficiency of functions, e.g., EFs), manifesting in a change of behavioral performance. Following Lövdén et al. (2010), plasticity has to be differentiated from flexibility which denotes the range of performance within the limits of given functional capabilities, including the adaptation to environmental demands. In addition to behavioral performance changes, "functional brain data" can be used as an outcome measure to differentiate between plasticity and flexibility. Plastic changes in the brain can occur at various levels encompassing molecular, cellular, columnar, or systemic alterations and are referred to as structural plasticity (for more details see the reviews of Kelly and Garavan, 2005; Poldrack, 2000). Hence, different methods can be utilized to study plastic changes in the brain.

3.2. Training-related neural changes

Neuroimaging studies have become increasingly popular for addressing the neural correlates of training-induced changes. Here, three main patterns of changes in neural activity can be differentiated (Kelly and Garavan, 2005; Poldrack, 2000). First, decreases in activation or a reduced spatial extent of activations following training have been reported and have been suggested to indicate increased neural efficiency, corresponding to a sharpened neural network (Miller and Desimone, 1994). Second, spatial expansion or increases in activation strength are observed that most likely reflect the additional recruitment of cortical units (Karini et al., 1995). Third, functional restructuring has been found of which two subtypes can be differentiated: redistribution and reorganization of neural activations. Redistribution refers to changes in the relative contribution of specific areas while the overall pattern of activity stays largely unchanged

(e.g., Petersen et al., 1998). In contrast, shifts in the location of activations are believed to reflect a reorganization of cognitive processes underlying task performance (e.g., Bernstein et al., 2002).

However, neither changes in neural activity nor altered behavioral performance necessarily indicates an enhancement of the functions of interest. In the next section, criteria and training principles are presented that guide the design of trainings as well as their evaluation.

4. Criteria for training evaluation and basic principles of cognitive training

The goal of behavioral training is to induce an optimal and temporally stable increase in *specific skills* (e.g., learning a second language) or *cognitive functions* (e.g., EFs). However, short-term performance gains can be observed which do not necessarily reflect the facilitation of the ability of interest.

A prominent example is a reduction of reaction times (RTs) when the same stimuli are used repeatedly causing improved task performance that does not result from the targeted learning mechanisms. Rather, attenuated RTs may simply result from priming where the processing of a given stimulus becomes more effective due to contextual activation caused by earlier presented stimuli (Tulving and Schacter, 1990). Similarly, variations in RT can be induced by changes of arousal or attentional states during the course of training (e.g., Welford, 1980; Broadbent, 1971). Specifically, in the beginning of an experimental session subjects will usually exhibit higher arousal than in following sessions. Also, short-term performance gains can be caused by variations in motivation, adjustments of attention, automated processes, and task strategies that have to be distinguished from enhancements of the ability of interest. To increase the effectiveness of training procedures, and to adequately assess training effects, the following training principles and training criteria have been suggested.

4.1. Training principles

- 1) To prevent priming effects or the development of task strategies, non-predictability of training conditions, as well as a high degree of variability with respect to stimuli and response modalities should be achieved (*non-predictability*).
- 2) Training difficulty should be adapted individually during the entire training procedure to prevent premature automation of processes, or the development of task strategies. If automation of processes occurs, the cognitive function of interest will not be trained effectively because of a missing mismatch between task demands and cognitive capabilities (*task-difficulty adaptation*).
- 3) Using several training tasks for a specific cognitive function instead of only one also avoids the development of task strategies, thereby raising the probability of effectively training the targeted process (*training task variability*).

4.2. Criteria for the assessment of trainings

- 1) Random assignment of participants to the training and experimental group ensures that events between the test-sessions, that might have an effect, will be canceled out (e.g., Campbell and Stanley, 1963). Similarly, a random assignment will prevent effects like a regression to the mean (here participants with an extremely poor performance in the beginning will be better in the post test, while extremely good performers in the beginning will finally score less well).
- 2) To distinguish repetition-related and non-specific effects from true enhancements of cognitive functions, one criterion concerns the usage of a control group. Without control group neither repetition-related nor non-specific effects (that may arise from contact with the training instructor, lab visits, training-induced

time-management, received attention, or due to expectation...) can be controlled for. The comparison of the experimental group with a *passive group* only allows for the control of effects due to repeated skill assessments before and after training. However, a comparison with a randomly-assembled *active control group* that completes a plausible alternative training will account for both repetition-related and non-specific effects (Campbell and Stanley, 1963; Oken et al., 2008). In fact, Shipstead et al. (2010) call for replicating passive control group studies with a proper active control group to ensure internal validity.

- 3) One has to assess whether training gains affect the cognitive function of interest (in its broader, task-unspecific sense) and not only a single task-specific factor (see Lövdén et al., 2010). Thus, an optimal assessment of induced learning effects should be based on pre- and post-testing of *several non-trained heterogeneous transfer tasks*, thus probing if there is a specific relationship between training and functional improvements (in the sense of internal validity). A further reason for such transfer assessment might be to investigate whether only a specific ability or several domains are concurrently affected, thus testing also the generality of training gains. Four transfer levels can be differentiated: i) *modality transfer effects* test enhancements in the same task as used during training, but measured with new stimuli and/or another stimulus/response modality; ii) *near transfer effects* examine benefits observed in other tasks targeting the same domain/function that was trained; iii) *far transfer effects* capture improvements in another domain (e.g., on another EF); iv) *meta-cognitive transfer* means effects to everyday behavior, health, or overall quality of life.
Another way to disentangle task specific factors from the intended enhancement is the application of latent factor models to analyze common variance across transfer tasks thereby showing effects at the level of latent variables (e.g., Schmiedek et al., 2010).
- 4) Besides demonstrating intended improvements, an evaluation after longer time periods is needed to assess *long-term stability* of training effects.

In the next section, we present computerized paradigms targeting EFs and provide detailed descriptions of applied training protocols and principles.

5. Enhancing executive functions with task switching-, memory updating-, response inhibition, and dual task training

5.1. Task switching training

5.1.1. Experimental paradigms of task switching

In a typical task switching paradigm, participants work within so-called *mixed blocks* on two simple tasks and have to switch between processing in either a cued way or based on instructions given to them. Within cued mixed blocks, the specific task sequence can either include predictable or random switches. In contrast to mixed blocks, the processing of only one task is required in *pure blocks*. Typically, two kinds of costs emerge that constitute the dependent variables in training studies. First, within mixed blocks *switching costs* can be observed. These refer to prolonged RT and/or augmented error rates when switching from one task to the other compared to conditions without switching. Second, when comparing mixed and pure blocks *mixing costs* arise that are related to increased RT in non-switching trials of a mixed block compared to non-switching trials in a pure block.

5.1.2. Trainability and transferability of task switching

Kray and Lindenberger (2000) demonstrated a significant reduction of both switching and mixing costs as a result of a training consisting of four 45-minute sessions, realizing training task variability by using numerical, figural and verbal paradigms. Berryhill and Hughes (2009), as well as Strobach et al. (2012) have reported

extended trainability in a single task switching paradigm and thereby showed eliminated mixing but stable switching costs.

On top of that, Minear and Shah (2008) were the first to provide evidence for near transfer effects of training, thus revealing that improved performance was not only based on non-specific effects such as increased automaticity. Automation can arise within a single session (Meiran, 1996) or between identical sessions on different days (Cepeda et al., 2001). Minear and Shah, however, used a pre/post-test training design including one transfer task and a training implementing training task variability using three different tasks (simple number and letter discriminations). Two training types (predictable vs. random task-switching training) were compared to an active control group. After two training sessions both experimental groups showed reductions in mixing and switching costs in all training paradigms compared to the active control group. More importantly, only the random task switching training group showed transfer effects of mixing costs to untrained tasks.

Next, Karbach and Kray (2009) reported far transfer effects to another EF (conflict monitoring), to WM (reading span/counting span; symmetry span/navigation span), and to measures of fluid intelligence (figural reasoning/letter series and Raven's Standard Progressive Matrices) based on a pre/post-test training design. Their study included an active control group whose participants practiced each single component of the task switching composition in separate blocks. The first training group practiced both tasks in a typical task switching procedure; the second used additional self-instruction by repeatedly verbalizing actual task goals; whereas a third group was not only instructed to verbalize task goals, but these participants also received new tasks and stimuli on every session (training task variability). After training, all groups showed near transfer not only concerning mixing, but also concerning task-switching costs. The amount of near transfer was further modulated by the training type. Self-instruction did not lead to additional training benefits, but training task variability did.

Recently, Zinke et al. (2012) combined a training study with physical exercises. They instructed their participants to cycle for 20 min directly before the actual training sessions. Physical exercise, however, did not induce additional improvements. Zinke et al.'s study was based on three 20–25-minute sessions. Two training groups (task switching vs. combined task switching and physical training), both receiving feedback during training, were compared to two control groups (physical training only, and a passive control group). Near transfer was investigated with two new task switching paradigms, one assessing visual detection speed, and another assessing a simple decision making task. Far transfer was assessed on memory updating (making use of two-back- and a keep track task), and on conflict monitoring (by using a visual Flanker- and a Stroop task). Both training groups reduced switching costs concerning RT and accuracy during training. There were limited near transfer effects in only one of the two task switching transfer tasks; here the training group showed reduced RT mixing costs compared to the control groups.

5.1.3. Summary of task switching training

Regarding task switching, trainability was demonstrated by studies which differentiated between training principles (regarding training task variability and non-predictability of training conditions) and compared their training results to an active control group with rather short training durations of two to four sessions (total time: 1 to 1.5 h). Training led to near and far transfer effects (Minear and Shah, 2008; Karbach and Kray, 2009; Zinke et al., 2012). Additional self-instruction during performance, or physical exercise before a short training intervention, did not augment these effects (Karbach and Kray, 2009; Zinke et al., 2012).

5.2. Training of memory updating

5.2.1. Experimental paradigms of memory updating

With respect to memory updating, most often running-span, keep-track, and n-back tasks are utilized. With running-span tasks,

participants are confronted with lists of an unknown number of items consisting of objects such as letters, numbers, figures, or words. At the end of a list, participants are instructed to name the last, three, four, or five stimuli in the order of their presentation. Thus, the critical dependent variable is usually the participant's accuracy. With keep-track tasks, items of various semantic categories are also presented. However, only the last items which belong to a specific category have to be recalled. Thus, besides memory updating, the keep-track task also requires categorization and reorganization of items. With n-back tasks, participants are also confronted with stimulus lists (usually characters or digits) and are instructed to indicate whenever a stimulus was already presented two, three, or four trials before the current one. Although these tasks require typical WM processes such as maintenance and rehearsal, the most crucial cognitive function is the updating of information in WM.

5.2.2. Trainability and transferability of memory updating

Training studies on WM have already demonstrated that the number of active representations in WM can be increased over a short period of time (see reviews of e.g., Klingberg, 2010; Morrison and Chein, 2011). Despite this, a further question is whether sub-processes within WM can be trained, and whether training gains can be maintained over a longer period of time.

One of the few studies addressing the issue of the persistence of beneficial training effects and transferability was conducted by Dahlin et al. (2008a). They demonstrated enhanced memory updating performance which remained stable over a period of 18 months. The authors also reported near transfer to an untrained updating task (the three-back task) as well as far transfer regarding episodic memory; all compared to a passive control group and based on a pre/post-test training design. Their training program, lasting five weeks in total, was set up on the basis of three sessions per week with a duration of 45 min for each session. Training aspects included the utilization of training task variability (running span and keep-track tasks consisting of different stimuli), and the adaptation of task difficulty. Their cognitive test battery included the three-back task for assessment of near transfer and tests of perceptual processing speed, episodic and semantic memories, and WM for far transfer (tested with computerized span- and digit span tasks).

Using a slightly different approach, Jaeggi et al. (2008) even reported far transfer effects on WM and fluid intelligence. Participants were trained on n-back tasks with one 25-minute training session per day; task difficulty was also adapted. Across groups, training duration was varied, ranging from 8 to 19 days. Auditory and visual stimuli were presented simultaneously and had to be processed concurrently. Hence, memory updating and dual task capabilities were trained at the same time. Performance increases were superior in the training compared to a passive control group in one of the tested WM tasks (the digit-span task), and the short version of the Bochumer Matrizen-Test (BOMAT, a single standardized test of fluid intelligence, Hossiep et al., 1999), which yielded highest scores between the 12th and 17th day of training. In 2010, Jaeggi et al. demonstrated that this far transfer effect did not depend on the dual-task approach; comparable effectiveness was also shown with the single n-back training. In addition, training gain transferred to two tests measuring intelligence (the BOMAT and the Raven's Advanced Progressive Matrices, APM, Raven, 1990). However, neither group showed transfer effects to a WM-capacity test (operation span task).

By means of a similar difficulty-adapted dual n-back training of an audio-visual task, Salminen et al. (2012) investigated the extent of transfer on other EFs. They let their participants train for 14 sessions during three weeks and compared results to a passive control group with a pre/post-test training design. Transfer tasks consisted of two other updating tasks (a visual and an auditory running span task), two tasks on task switching (with visual and auditory stimuli), a simple dual task (a combination of an auditory and visual task), an attention task, and a task measuring fluid intelligence (APM, Raven, 1990).

After training, near transfer was observed for the auditory running span task, and far transfer for task switching, and the attention tasks. However, no transfer was observed for visual running span, dual task processing, and fluid intelligence.

Recently, training studies on memory updating using passive control groups and single transfer tests have received a lot of criticism (e.g., Shipstead et al., 2010). As a result, Redick et al. (2012) conducted a dual n-back task comparable to Jaeggi et al.'s adaptive procedure, but lasting for 20 sessions spread over three to four weeks in total. Redick et al. included an active control group that received adaptive training on visual search. Their design additionally comprised pre-, mid-, and post-tests based on 17 transfer tasks divided into measures of fluid and crystallized intelligence, multitasking, WM capacity, and perceptual speed (incorporating verbal and nonverbal measures). In addition, participants were not informed that they were taking part in a training study. However, they were asked about their own assessment of perceived improvements during the course of training. Although the experimental and active control groups significantly increased performance during training, thus again showing trainability, no transfer effects were reported. Interestingly, despite these effects being objectively missing, participants of the dual n-back training reported subjective benefits. Redick et al. interpreted this as illusory placebo effect, potentially arising due to changes in motivation and self-efficacy. Nevertheless, by using an active control group they clearly demonstrated trainability of memory updating.

Similarly, Lilienthal et al. (2012) investigated effects of an eight session dual n-back training based on Jaeggi et al.'s study (2008) on several transfer tasks such as the cued recall span, focus-switching, grid span, operation span and a running span task. They compared the results of adaptive training to a passive and an active control group involving non-adaptive training. The adaptive training group improved more than the active control group during training and transferred training gains to the running span task.

5.2.3. Neural correlates of memory updating

One of the research questions for which the neural correlates of memory updating may be of relevance refers to the prerequisites for far transfer effects. Dahlin et al., 2008b hypothesized that transfer depends on the engagement of overlapping brain networks in trained and transfer tasks. To address this notion, Dahlin and colleagues conducted a study testing transfer effects while collecting fMRI data. In addition to the actual training task, participants also processed a non-trained memory updating- and a Stroop task in a pre/post-test training design. Trained and non-trained memory updating tasks, but not the Stroop task, recruited common brain regions including the left striatum and fronto-parietal regions. After training, enhanced activations of the left striatum and decreased activations in fronto-parietal regions were observed with trained and non-trained memory updating tasks, while there were no significant changes of activity patterns with the Stroop task.

Although several studies use visual and auditory training n-back tasks, few studies directly compared modality effects. Schneiders et al. (2011) did so by conducting a study including fMRI measurements showing that modality-specific and cross-modal effects can result from training. Within two weeks, with a total of eight to ten training sessions, a visual and an auditory training group received an individualized training with adaptation of task difficulty. Both groups were compared to a passive control group. A visual two-back task with new sets of stimuli (compared to the tasks in the visual training) was used in pre- and post-training fMRI sessions. Thus, intra-modal effects could be investigated by means of the visual training group, whereas cross-modal transfer was assessed via the auditory training group. Training resulted in improved performance in both groups. However, higher performance increases were found with the visual group compared to the auditory training group. After training, the visual training group showed decreased activity in the right middle

frontal gyrus. Both training groups demonstrated decreased activations in the right superior middle frontal gyrus, as well as in the posterior parietal region, compared to the passive control group.

Most studies do not assess changes of neural activity profiles throughout the whole course of training, but rather assess direct pre-to-post effects only. However, when done, this can provide interesting insights. Hempel et al. (2004), for example, were the first to measure fMRI on more than two occasions and reported an inverse U-shaped activation function over the course of their training. They investigated training-induced changes before training, after four weeks (of practicing zero-, one-, and two-back tasks), and after completion of the training. During the course of the training, error rates decreased from the first to the second session and remained stable until the third session. Similarly, fMRI activations increased from the first to the second session, but decreased from the second to the third. This inverse U-shaped function was specific for the rIFC and the right intraparietal sulcus. The initial increase of activations was observed with optimized performance, but was followed by a decrease when performance improvements stabilized.

In a more recent study, such U-shaped activation changes were also observed within the striatum. Kühn et al. (2012) performed fMRI measures over a long training period: right before training, after five training days, and at the end of 54 days of training. Participants were trained with two memory updating tasks (a numerical and a spatial n-back task), each applying different difficulty levels. The authors compared performance changes in the actual training tasks, in near (numerical n-back), as well as in far transfer tasks (a test on intelligence) relative to changes in an active control group that underwent training with easier tasks, omitting difficulty adaptations in shorter sessions. Although both groups exhibited performance benefits in the trained tasks, those of the actual training group were more pronounced. Similar performance increases were found for the near transfer task, as well as on two subtests of the Berlin Intelligence Structure Test (Jäger et al., 1997). Here, groups did not differ significantly with respect to their gains. Activation in the striatum increased early in training. However, as the training continued, the initial increase in regional activation was followed by decreases in the right striatum only for the experimental group.

It can easily be argued that behavioral improvements and neurofunctional changes may result from alterations in brain structure, such as altered conduction velocity and synchronization of signal transmission (Fields, 2008). The first study to investigate training-induced white matter plasticity via diffusion tensor imaging (DTI) was undertaken by Takeuchi et al. (2010). DTI is a method sensitive to the hindrance of water diffusion resulting from local tissue boundaries. As a quantitative measure, fractional anisotropy (FA; derived from DTI) provides information about anatomical features (e.g., axon caliber, fiber density and myelination). Thus, Takeuchi et al. (2010) were interested in whether or not two months of training lead to white matter changes, as reflected by FA differences. Their training procedure incorporated training task variability by using a visuo-spatial WM task and two memory updating tasks (an n-back- and a dual n-back task), based on the adaptation of task difficulty. After training, FA was indeed increased as compared to the measurement before training. Augmented values were observed in two white matter regions encompassing fiber tracts near the intra-parietal sulcus and adjacent to the anterior part of the body of the corpus callosum connecting bilateral DLPFCs. Although no control group was included, correlations of FA increases with training duration argue in favor of training-induced plasticity.

5.2.4. Summary of memory updating training

Usually, memory updating tasks feature the adaptation of task difficulty and/or training task variability. Compared to task switching, these trainings are rather extensive and usually include eight to twenty sessions. Here, beneficial training effects have primarily been compared to a passive control group and were shown to transfer

to other non-trained memory updating tasks. With respect to far transfer, effects are found for intelligence measures (Jaeggi et al., 2008) and task switching (Salmi et al., 2012). However, the study by Redick et al. (2012) challenged earlier results on transfer to intelligence by incorporating an active control group and showing a lack of transfer to other domains such as WM.

Functional imaging shows that training gains are accompanied by an inverse U-shaped activation function in parietal regions (Hempel et al., 2004) and the striatum (Kühn et al., 2012). Indeed, parietal activations were attenuated in all studies after training (Dahlin et al., 2008b; Schneiders et al., 2011). Similarly, Takeuchi et al. (2010) demonstrated increased FA values in white matter regions near to the intra-parietal sulcus, and also within the white matter tract connecting both DLPFCs. In addition, Dahlin et al. (2008b) reported transfer effects to be mediated by striatal activity (left putamen). That is, the authors concluded that transfer effects rely on the recruitment of overlapping neural systems active in the trained and transfer tasks. The studies of Kühn et al. (2012) and Hempel et al. (2004) stress the importance of repeated fMRI measurements when investigating the temporal dynamics of activation changes associated with training related effects.

5.3. Training of response inhibition

5.3.1. Experimental paradigms of response inhibition

Typical paradigms for the investigation of response inhibition are the go/no-go, the stop-signal, and the anti-saccade tasks. With the first two tasks, the majority of trials require participants to react as fast and as accurately as possible to the go-stimulus, whereas in the remaining trials they have to suppress their reaction when a stimulus different from the go-signal is presented (no-go trials in go/no-go tasks), or to abort an already initiated response when the go-stimulus is followed by a stop-signal (stop trials in stop-signal tasks, e.g., Enriquez-Geppert et al., 2010). In the anti-saccade task, subjects have to suppress the reflex to look at a visual target appearing suddenly in the peripheral visual field. Instead, they are instructed to look in the opposite direction of the target.

Although commercial training interventions for response inhibition are available, scientific studies assessing the trainability of response inhibition are still sparse. Apart from Dowsett and Livesesy's (2000) study with pre-school children, one of the few scientific studies available was performed by Thorell et al. (2009) who demonstrated training gains in young children at the age of four and six years due to a combined training of WM and response inhibition. After a training of five weeks (daily sessions of 15 min for five days a week), effects were shown in all trained WM-tasks; transfer effects to non-trained WM tasks were also observed. Furthermore, training benefits in all trained tasks, but no transfer, were found for response inhibition. Although this effect seems to be limited regarding transfer, the training results on their own are interesting because complex self-regulation functions (such as response inhibition) are believed to develop only until early adolescence (Levin et al., 1991; Jones et al., 2003). The trainability and transferability of response inhibition were also investigated by an unpublished study conducted by Thummala and Satpathy (2009). The authors trained eight students with Attention Deficit Hyperactivity Disorder (ADHD) using eight different tasks (training task variability), and investigated both near and far transfer effects in untrained response inhibition, in task switching, and in interference control tasks. Effects in the experimental group were compared to those of an active control group. Thummala and Satpathy not only reported performance increases in response inhibition, but also transfer to other EF tasks.

5.4. Dual-task training

5.4.1. Experimental paradigms and training types for dual task processing

Dual-task paradigms require the simultaneous performance of two choice reaction tasks, whereby so-called *dual-task costs* arise

such that the simultaneous processing of choice reaction tasks leads to a dramatic slowing and/or reduced accuracy of responses in either task compared to the performance on one task alone. In contrast, *task-set costs* are defined as the difference in behavioral performance for single task processing in different contexts, once in a block containing both single-task- and dual-task trials (mixed trial block), another time in a block purely consisting of single task trials.

The exact nature of relevant cost effects, as well as the exact timing of their onset, has been differently specified by diverse models (e.g., Pashler, 1994; Meyer and Kieras, 1997). The adaptive executive control model (ACE), for instance, assumes that two tasks can in principle be performed simultaneously. For optimal coordination and selection of concurrently processed actions this model states three prerequisites. First, simultaneously processed tasks should engage different motor effectors to prevent limitations in response initiation at the motor stage. Second, a sufficient amount of training is essential. Third, both tasks should have the same priority.

Concerning dual task training, three training types have to be distinguished. First, with *part-task training* each task is practiced in separate blocks. However, the drawback is that dual-task processing requires more than completing either task alone (e.g., Damos and Wickens, 1980). Second, with *whole task training*, on the other hand, both tasks are trained under dual task conditions. Here, high processing demands might impede learning (e.g., Nissen and Bullemer, 1987). Third, as a result, *hybrid-training* procedures were suggested as being optimal for facilitating dual-task capabilities as they combine both above mentioned training types in a sequence.

Importantly, task combinations in dual-task settings are composed of a variety of task types, differing in complexity and stimulus/response modality combinations. Transfer effects are most often investigated with respect to the modality (modality transfer) and not regarding other tasks and/or other cognitive functions. Near modality – or *within modality* – transfer is differentiated from far modality or *cross modality* transfer. While the former type refers to new stimuli sets, but maintaining the same stimulus and response modality, the latter is related to tasks involving a different stimulus modality (auditory vs. visual tasks) and/or a different response modality (verbal vs. manual responses) for transfer. Further, dual-task trainings can be differentiated concerning the complexity of tasks.

5.4.2. Trainability and cross modal transfer

Compared to task switching, memory updating, and response inhibition, dual-task training has been a more active field of research. Specialized reviews already exist addressing whether two tasks can be performed simultaneously and which mechanisms enable dual-task performance (e.g., Schneider and Detweiler, 1988). More recent key findings and newer developments will be discussed here.

First, based on the hybrid training rational, McDowd (1986) showed training-induced increases of dual-task performance. He had subjects perform 1-hour training sessions once a week for six weeks in total. However, single-task performance was still superior to dual-task performance. To test whether the simultaneous performance of two tasks is nevertheless compatible with a perfect sharing of resources, Schumacher et al. (2001) developed an interesting study design. To prevent task interference due to limited perceptual-motor resources, two simple reaction tasks with different stimulus and response modalities were utilized (auditory-vocal, and visual-manual combinations), thus the first criterion by the ACE model was met. By using a complex hybrid-training with balanced task priority and money as incentives, dual-task costs were dramatically reduced. After five sessions, RT differences between dual-task and single-task performances were extenuated. Hazeltine et al. (2002) extended Schumacher et al.'s results by demonstrating stable training gains even when introducing new stimulus pairings, stimulus onsets and durations, which were not present during training.

Further comparing hybrid dual-task training with part-task training, Liepelt et al. (2011a) used a visual and auditory dual-task combination with manual and pedal responses. Although the mapping of stimulus and response modalities were different, rest costs remained stable after training that were not expected by the ACE model. The specific response combination in Liepelt et al.'s (2011a) dual-task combination might have led to a common spatial dimensional compatibility effect of left hand and left foot in one situation, compared to right hand and right foot responses in the other. This cross-talk likely interfered with perfect dual-task performance. Thus, the crucial criterion for the total reduction of rest costs might not simply be the requirement of different response modalities, but the different spatial dimension of the effectors.

Focusing on the dissociation of coordination skills from automation of stimulus-response assignments, Liepelt et al. (2011b) designed a study which incorporated a series of experiments based on the hybrid training of Schumacher et al. (2001). Their training incorporated equal task priority instructions during dual-task processing (of a visual and an auditory task), all of which were compared to a simple single-task training. To test if coordination skills were indeed enhanced and to exclude automation of stimulus-response assignments, transfer was tested by changing characteristics of one task of the dual-task combination. Stimuli and the stimulus-response mapping of the visual task were changed while keeping the auditory task identical to training. Their data showed dual-task training advantages in all training experiments as well as in the transfer tasks. This might suggest optimized coordination skills due to hybrid training, while part-task training might augment automation.

Strobach et al. (2011) continued to investigate the extent of the transfer of task coordination skills, but encountered strong limitations. Similar to Liepelt et al.'s (2011b) study they used also the design of Schumacher et al.'s (2001) which included hybrid vs. part task training. However instead of changing only one of the dual tasks, they tested for transfer in a dual-task combination including changes in both tasks. A further condition included a dual-task combination that remained constant, while far transfer effects were tested by a task-switching paradigm. Concerning near modality transfer to a changed dual-task composition, hybrid training only showed a benefit concerning error rates but not RT compared to part-task training. Regarding far transfer, both groups showed improved mixing costs in task switching.

Lussier et al. (2012) investigated the extent of modality transfer in a more systematic fashion. By means of a pre/post-test training design with five training sessions, they compared an experimental to a passive control group concerning the performance on a simple visual dual-task combination calling for different manual responses. Lussier and colleagues made use of three transfer conditions: implementing tasks that differed with respect to the stimuli used in training (visual vs. auditory), the response modality (key pressing vs. wheel turning), or both. Larger improvements were shown for the training group in all three task conditions. However, reduced dual-task costs were only reported when either stimuli or response modality were changed, but not both. Given that only dual-task-, but not task-set costs, were affected, these transfer effects were interpreted as facilitated executive task coordination skills, and not as enhanced preparation of stimulus-response mappings. All in all, modality transfer of dual-task coordination indeed seems to be moderately tied to the modality used during training as it is only observed when either the stimuli or response modality is changed in the transfer task.

The efficiency of fixed- and variable-priority training is a further aspect of dual task training procedures that needs further clarification. This aspect was in focus of Kramer et al. (1985), who used a six session training of a complex dual task design. While fixed priority training emphasized comparable performance in both complex tasks (a visual monitoring- and an alphabet-arithmetic task), variable priority training relied on differentially adjusting performance priorities.

More pronounced behavioral benefits resulted from the variable priority training. Performance increases were found with the trained as well as with untrained transfer tasks (a visual scheduling and a paired-associates running memory task). These findings were shown to persist up to two months in a conceptually similar follow-up study (Kramer et al., 1999).

Bherer et al. (2005) also compared fixed- and variable-priority training procedures, including an additional passive control group. In contrast to earlier studies, simple instead of complex tasks were used. With this type of task, training procedures did not lead to differential effects when comparing both priority training procedures. Hence, variable-priority training seems to be especially beneficial in cases when tasks involve a variety of perceptual, memory, and motor processes.

5.4.3. Training-induced neural changes

Erickson et al. (2007) compared performance of an active training group with that of a passive control group utilizing a simple letter discrimination task with fMRI and a pre/post-test training design. Training consisted of five 1-hour sessions during the course of two to three weeks. Greater changes were observed in the experimental group compared to the passive control group. Reduced activations in the right ventral IFC, right superior parietal regions, and right dorsal IFC were shown. Moreover, these observed activation reductions and the increased activation seen in the DLPFC were correlated with performance increases.

5.4.4. Summary

Studies concerning the conditions of the ACE model, and using a hybrid training paradigm, revealed trainability (e.g., Schumacher et al., 2001) effects that may even last up to two months (Kramer et al., 1999). Achieved training benefits can transfer to tasks using different modalities (e.g., Hazeltine et al., 2002; Lussier et al., 2012). However, such modality transfer seems to be strongly limited and dependent on continuous characteristics of training and transfer tasks (Liepelt et al., 2011b; Strobach et al., 2011; Lussier et al., 2012). Dual-task training studies did not apply training task variability nor was task difficulty adapted. Also, neural correlates of training gains with dual task training so far have rarely been assessed (but see Erickson et al., 2007).

5.5. Summary of behavioral training procedures

It seems clear that beneficial training effects can be observed for task switching (Cepeda et al., 2001; Meiran, 1996; Minear and Shah, 2008; Karbach and Kray, 2009), memory updating (Dahlin et al., 2008a,b; Jaeggi et al., 2008, 2010; Kühn et al., 2012; Salminen et al., 2012), and dual task processing (e.g., Schumacher et al., 2001; Hazeltine et al., 2002; Liepelt et al., 2011b; Lussier et al., 2012). With respect to response inhibition, there seems to be no published behavioral training study involving healthy adults. Hence, it is currently not possible to clearly state the extent to which response inhibition can be optimized or whether improvements are possible at all. It is furthermore not clear whether studies have been conducted without subsequent publication or if behavioral response inhibition training studies have actually not been conducted.

Transferability of training gains, on the other hand, is of specific interest to test whether performance increments actually derive from the targeted cognitive function or whether they merely reflect task-specific adaptations of processing strategies. With task switching and memory updating, near transfer effects were reported for non-trained task switching and memory updating tasks (Minear and Shah, 2008; Karbach and Kray, 2009; Zinke et al., 2012; Dahlin et al., 2008a,b; Jaeggi et al., 2010; Schneiders et al., 2011; Kühn et al., 2012). However, with respect to dual-task training, transfer to other tasks or even other functions has only rarely been investigated (but see Strobach et al., 2011) and the suggested training principles were most often not followed. Based on current training studies, the rather

limited degree of modality transfer does not speak in favor of enhanced task coordination skills between tasks.

6. Enhancing executive functioning with neurostimulation and neurofeedback

6.1. Neurostimulation and neurofeedback

Apart from behavioral training procedures, other approaches take a more neuroscientific perspective and try to induce performance increases by means of neurostimulation or neurofeedback (see Fig. 1). Both approaches aim to modify neural activity, with most studies trying to augment the amplitude of certain EEG oscillations. It has been shown that a large spectrum of cognitive functions is related to such synchronous neuronal processes reflected in EEG oscillations at specific frequencies (Basar and Güntekin, 2008; Basar et al., 2000; Herrmann and Knight, 2001; Herrmann et al., 2004). It has been shown that both neurostimulation and neurofeedback affect the amplitude of such EEG oscillations (e.g., Egner et al., 2002; Enriquez-Geppert et al., submitted for publication; Demos, 2004; Hanslmayr et al., 2005; Zaehle et al., 2010; Zoefel et al., 2010).

Concerning neurostimulation, different procedures exist including transcranial magnetic stimulation (TMS), transcranial direct current stimulation (tDCS), and transcranial alternating current stimulation (tACS). These approaches directly stimulate the brain via electrodes that are mounted on the scalp in the case of tACS/tDCS, or via a magnetic field delivered by a coil in the case of TMS. Recently, modeling studies have demonstrated that it is possible to predict which brain regions will be stimulated by specific montages of stimulation electrodes (Neuling et al., 2012). Neurofeedback approaches, on the other hand, apply the principles of operant conditioning and require, as does behavioral training, the active engagement of the participants. In contrast to TMS/tDCS/tACS, participants do not just assume a passive role. Instead, their active engagement might have additional effects on long-term retention, as has been suggested for constructivist learning in school environments (e.g., Narli, 2011). Interestingly, neurofeedback significantly influences cortical neuroplasticity as shown by applying TMS after neurofeedback (Ros et al., 2010). Furthermore, criteria for enhancing self-efficacy are specifically met with neurofeedback training as already suggested by Carlson-Catalano and Ferreira (2001), and by Linden et al. (2012). Self-efficacy is defined as judgment about one's own capabilities to execute actions required to attain designated performance types. Thus, neurofeedback provides direct and continuous feedback, thereby fostering the participant's experience of self-regulating specific brain aspects. This in turn is specifically important for self-efficacious behavior (e.g., Bandura, 1997). With neurofeedback, it is possible to influence certain aspects of the brain's activity, which in turn affects an individual's behavior. Typically in this context the brain's activity is measured via EEG. However, it is also possible to perform real-time fMRI feedback, thereby up- or down-regulating activation in certain target brain areas (e.g., Weiskopf et al., 2005; Johnston et al., 2009).

6.2. Application of neurostimulation to enhance executive functions

Up to now, most studies applying neurostimulation techniques such as TMS or tDCS/tACS focus on modulating very specific cognitive functions that have been associated with certain EEG oscillations but are only indirectly linked to EFs, such as attention (e.g., Taylor and Thut, 2012) or memory (e.g., Zaehle et al., 2011). A few studies, however, have more directly addressed how neurostimulation can affect EFs, mainly using tDCS.

6.2.1. Enhancement of task switching by tDCS

For example, tDCS has already been used with task switching. Leite et al. (2011) were able to demonstrate that anodal tDCS applied over the DLPFC and the primary motor cortex (M1) increased performance

in task switching (reduced task switching costs) compared to a sham condition. Interestingly, anodal and cathodal stimulations had opposite effects, confirming the notion that anodal tDCS enhances cortical activity while cathodal tDCS suppresses it (Nitsche and Paulus, 2000).

6.2.2. Enhancement of memory updating by tDCS

Memory updating has also been enhanced with anodal tDCS in several studies. Fregni et al. (2005) applied anodal tDCS over the left DLPFC. tDCS (1 mA) was applied for 10 min, and a three-back task was performed in the second half of the stimulation. As control conditions, cathodal stimulation of the left DLPFC, as well as anodal stimulation of the M1 was utilized. However, only stimulation of the left DLPFC resulted in increased accuracy of memory updating.

Ohn et al. (2008) stimulated their subjects' left DLPFC with anodal tDCS for 30 min and investigated their performance on a three-back task during stimulation as well as after the stimulation had finished. Compared to a sham condition, accuracy of updating was increased after 20 min and even incremented after 30 min of stimulation. With this protocol, Ohn and colleagues could further show maintenance of performance enhancements up to 30 min after stimulation offset.

To investigate which neuropsychological mechanisms underlie enhancement by stimulation, Zaehle et al. (2011) stimulated their participants for 15 min (1 mA) by means of anodal tDCS over the left DLPFC. Improvement of a two-back task was stronger after application of anodal as compared to cathodal or no stimulation. Additionally, it was demonstrated that anodal stimulation increased the power of theta and alpha band activities, which are oscillations known to be associated with the processing of n-back tasks.

6.2.3. Enhancement of response inhibition by tDCS

Response inhibition is another EF already addressed in stimulation studies. Jacobson et al. (2011) have administered tDCS for 10 min (1 mA) before subjects had to perform a stop-signal task. Because the rIFC is a region crucially involved in response inhibition (e.g., Aron et al., 2004), this area was chosen as a target. Only by the application of anodal tDCS over the rIFC, the authors were able to show improved response inhibition as evidenced by reduced inhibition time (the so-called stop-signal response time, SSRT) when compared to a sham condition. Additionally, these effects were behaviorally specific, as RTs were not affected. To control for non-specific effects of tDCS, the right angular gyrus, a region not important for response inhibition, was also stimulated anodally, but without any behavioral effect. More recently, Jacobson et al. (2012) investigated the electrophysiological correlates of such a tDCS protocol over frontal brain regions and reported selective effects on frontal theta activity. These studies extend previous experiments that used TMS. Chambers et al. (2006) reported that temporary deactivation of the rIFC selectively impairs the ability to stop an initiated action. These neurostimulation findings confirm the notion that the rIFC is vital for mediating response inhibition.

Ditye et al. (2012) combined behavioral training in a stop-signal task for four days with stimulations of anodal tDCS over the rIFC. Just prior to task performance they were stimulated for 15 min (1.5 mA). In addition, it was tested for short term maintenance. The control group, which only participated in the behavioral training, did not show any beneficial effect concerning SSRT. In contrast, the stimulation group significantly improved during sessions three and four. However, 24 h after stimulation, beneficial effects vanished and thus were short-lived with this kind of protocol.

6.3. Application of neurofeedback training to enhance executive functions

To date, most neurofeedback studies focused on treating patients with intractable epilepsy or ADHD (Birbaumer et al., 2009). Concerning ADHD, a disorder strongly related to disrupted EFs (e.g., Barkley, 1997), neurofeedback has been shown to have a high level of efficacy (see the meta-analysis by Arns et al., 2009). The treatment

Table 1

Overview of behavioral studies. General abbreviations: TTV = training task variability, n.a. = not applied. r. = right, l. = left, fron. = frontal, gyr. = gyrus, sulc. = sulcus, middl. = middle, post. = posterior, pariet. = parietal, infer. = inferior, temp. = temporal, occip. = occipital, sup. = superior, medi. = medial, intrapar. = intraparietal, WMR = white matter region, anter. = anterior, corp. call. = corpus callosum, dors. = dorsal, vent. = ventral. Annotations for task switching: * = color-, number Stroop; ** = reading-, counting span; *** = figural reasoning task, letter series task, Raven's Standard Progressive Matrices; Δ = effects in food size task, not in number switching; ΔΔ = trend for 2-back task, not for keep track task; ΔΔΔ = no effects for flanker nor Stroop tasks. Annotations for memory updating: ○ = only training related increases and decreases are reported for the young adult group; ○○ = these activation changes reflect changes in a 2-back task with new stimuli compared to the 2-back training task. When not noted otherwise, changes are observed in both training groups; ○○○ = subtest of the Berlin Intelligence Structure Test; FA = fractional anisotropy.

Authors	Characteristics	Training duration	Control group	Participants	Training gain	Near transfer	Far transfer	Neuronal correlates
<i>Task switching</i>								
Kray and Lindenberger (2000)	TTV	4 sessions à ca. 45 min (total: 3 h)	/	n=120 (3 age groups)	Significant	n.a.	n.a.	n.a.
Minear and Shah (2008)	TTV	2 sessions, à 1 h (total: 2 h)	(2 training groups), active control group	n=93	Significant	Significant: untrained task-switching	n.a.	n.a.
Karbach and Kray (2009)	TTV	4 sessions à 30–40 min (total: 2.5 h)	(3 training groups), active control group	n=168 (3 age groups)	Significant	Significant: untrained task-switching	Significant: Stroop tasks*, verbal and spatial WM tasks**, and tests on fluid intelligence***	n.a.
Zinke et al. (2012)	Block wise feedback, combined physical and cognitive trainings	3 sessions à 20–25 min (total: 1–1.25 h)	(2 training groups) active-, passive control group	n=80 (adolescents)	Significant	Significant: reduced RT mixing cost in 1 of 2 tasks Δ	Significant: 1 of 2 updating tasks ΔΔ (trend) Not significant: conflict monitoring tasksΔΔΔ	n.a.
<i>Memory updating</i>								
Hempel et al. (2004)	3 fMRI measures	3 sessions 4 weeks	/	n=9	Significant	n.a.	n.a.	Inverse U-shaped activation function (sessions 0, 1, 2): r. intrapar. sulc. (BA 39/40), sup. pariet. lobe (BA 40)
Dahlin et al. (2008a)	TTV, TDA, retest after 18 months	15 sessions à 45 min 5 weeks (total: 11.25 h)	Passive control group	n=64 (2 age groups)	Significant	Significant: 3-back	Significant: computation span, digit span (WM), mental speed, APM	n.a.
Dahlin et al. (2008b)	TTV, TDA	15 sessions à 45 min 5 weeks (total: 11.25 h)	Passive control group	n=24 (2 age groups)	Significant	Significant: 3-back	Not significant: Stroop task	Increased activation (trained task): l. and r. striatum, r. temp. lobe, r. occip. lobe, decreased activation (trained task): r. fron. lobe, pariet. lobe, increased activation (transfer task): l. fron. lobe, l. pariet. lobe, l. temp. lobe, l. striatum, brain stem ○
Jaeggi et al. (2008)	TDA, dual n-back	8–19 sessions à 25 min	(4 training groups) passive control group	n=70	Significant	n.a.	Significant: BOMAT after 17 sessions	n.a.
Li et al. (2008)	Analysis of long term maintenance	45 sessions à 15 min	Passive control group	n=87 (2 age groups)	Significant, stable for 3 month	Significant: spatial 3-back, numerical 2, and 3-back tasks; stable for 3 month	Not significant: complex span task (WM)	n.a.
Jaeggi et al. (2010)	TDA	20 sessions à 25 min 4 weeks (8.3 h)	(2 training groups) passive control group	n=99	Significant	Significant: n-back with different stimuli	Significant: BOMAT and APM not significant: operation span task (WM)	n.a.
Takeuchi et al. (2010)	TTV, TDA	~39 sessions 2 months à 25 min	/	n=11	Significant	/	/	Increase in FA: in 2 WMR: close to the infer. pariet. sulc., adjacent to anter. part of corp. call., correlations: FA increase and training amount
Schneiders et al. (2011)	TDA	8–10 sessions à 50 min	(2 training groups) passive control group	n=48	Significant	Significant: visual n-back task with new stimuli	n.a.	Decreased activation (○○): r. mid. fron. gyr. (BA 9, BA)/46 (visual training), r. and l. intrapar. sulc. (BA 40), r. sup. medi. fron. gyr. (BA 6), r. mid. fron. gyr. (BA 9), r. mid. fron. gyr. (BA 9/46), l. middl. fron. gyr. (BA 6), l. medi. sup. fron. gyr. (BA 6)
Kühn et al. (2012)	3 fMRI measures, TDA	54 sessions	Active control group	n=46	Significant			Inverse U-shaped activation function (trained task, sessions 0, 1, 2);

Redick et al. (2012)	Pre, mid, posttest design, TDA, dual n-back training	20 sessions 3–4 weeks	Active control group	n = 75	Significant	<i>Significant:</i> untrained n-back, but for training and control group <i>Not significant:</i> multitasking	<i>Significant:</i> 2 subtests of the intelligence test, but for the training and control group <i>Not significant:</i> WM, fluid and crystallized intelligence, perceptual speed	r. striatum, specific r. and l. putamen; decreased activation session 1, 2: r. infer. fron. gyr. n.a.
Lilienthal et al. (2012)	TDA, dual n-back	8 sessions à 30 min	Active-, passive control group	n = 52	Significant	<i>Not significant:</i> cued recall task	<i>Significant:</i> running span task <i>not significant:</i> focus-switching, operation span, grid span task○○○	n.a.
<i>Response inhibition</i>								
Thorell et al. (2009)	TTV, children	25 session 5 weeks à 15 min (total: 6.25 h)	(2 training groups) active-, passive control group	n = 42 (2 age groups)	Significant (both go/no-go tasks, both flanker tasks, not significant (stop signal tasks))	<i>Not significant:</i> inhibition tasks	n.a.	n.a.
Thummala and Satpathy (2009)	Not yet published, TTV	20 sessions 4 weeks à 45 min (total: 15 h)	Active control group	n = 8	Significant	Not reported	Not reported	n.a.
<i>Dual task performance</i>								
Damos and Wickens (1980)		2 sessions	Active control group	n = 48	Significant	<i>Significant:</i> new dual task	n.a.	n.a.
McDowd (1986)	Hybrid training	6 sessions à 1 h 6 weeks (total: 6 h)	/	n = 12 (2 age groups)	Significant	n.a.	n.a.	n.a.
Kramer et al. (1995)	Hybrid training, feedback	5 session (total: 7 h)	(2 training groups),/	n = 59 (2 age groups)	Significant	<i>Significant:</i> new dual-task	n.a.	n.a.
Schumacher et al. (2001)	Hybrid training, fixed equal task priority, incentives	5 sessions	/	n = 8	Significant	n.a.	n.a.	n.a.
Hazeltine et al. (2002)	Hybrid training	2 weeks	/	n = 9	Significant	<i>Significant:</i> task with new stimulus response combinations	n.a.	n.a.
Bherer et al. (2005)	Individual feedback	5 sessions à 1 h, 3 weeks (total: 5 h)	(2 training groups) passive control group	n = 72 (2 age groups)	Significant	<i>Significant:</i> task with new stimuli, task with a stimuli of another modality	n.a.	n.a.
Erickson et al. (2007)	Individual adaptive feedback	5 sessions à 1 h (total 5 h)	Passive control group	n = 31	Significant	n.a.	n.a.	Increased activation (trained task): DLP; decreased activation (trained) (trained task): r. vent. inf. fron. gyr, r. sup. pariet. lobule, r. dors., infer. fron. gyr correlations: activation changes and RTs n.a.
Bherer et al. (2005)	Individual feedback	5 sessions à 1 h, 3 weeks (total: 5 h)	(2 training groups), passive control group	n = 88 (2 age groups)	Significant	<i>Significant:</i> task with new stimuli, task with new stimuli of another modality	n.a.	n.a.
Liepelt et al. (2011a)	Hybrid training	8–10 sessions	/	n = 8	Significant	n.a.	n.a.	n.a.
Liepelt et al. (2011b)	Hybrid training	6 sessions	(2 training groups),/	n = 16	Significant	<i>Significant:</i> task with new stimuli	n.a.	n.a.
Strobach et al. (2012)	Hybrid training	8 sessions	2 active control groups	n = 28	Significant	<i>Significant:</i> changed dual-task composition <i>Not significant:</i> task switching	n.a.	n.a.
Lussier et al. (2012)	Individual adaptive feedback	5 sessions	Passive control group	n = 66 (2 age groups)	Significant	<i>Significant:</i> tasks with new stimuli or response modality <i>not significant:</i> tasks with new stimulus and response modality	n.a.	n.a.

of ADHD with neurofeedback leads to specific and clinically relevant effects (Monasta et al., 2002).

Beyond behavioral effects, Levesque et al. (2006) nicely demonstrated neurofeedback effects on brain areas belonging to the fronto-striatal circuits in a pre/post-test training design. After neurofeedback training, only the experimental group, but not the control group, could successfully activate bilateral caudate, and left substantia nigra in an EF-task (counting Stroop). Regarding the MCC, relationships concerning psychopathological phenomena and neuroanatomical deviations have already been shown for several disorders including ADHD (Yücel et al., 2003). Furthermore, the MCC is a structure strongly related to EFs in general (Fan et al., 2003), or more specifically to conflict monitoring (Botvinick et al., 2001; Huster et al., in press). Interestingly, in contrast to the lack of long-term effects of medication, neurofeedback effects have been shown to last for at least two years (Gani et al., 2008). Most often, neurofeedback training addressing ADHD includes modulation of theta activity (4–8 Hz).

With healthy subjects, there are almost no neurofeedback studies focusing on EFs. However, Angelakis et al. (2007) have applied EEG neurofeedback in the alpha frequency range in a small sample of elderly subjects. The long-term training consisted of one to two sessions per week for a total of 31–36 sessions. By means of a pre/post-test training design, performance effects were investigated on three different EFs: memory updating (investigated by one-, two-, and three-back tasks), response inhibition (tested by a go/no-go task), as well as conflict monitoring (Stroop task) and compared to an active control group. Results showed a somewhat inconsistent picture concerning the performance of experimental and control groups, consisting of partial improvements in EFs (e.g., RT and accuracy in Stroop task) with the experimental group but poorer performance with the control group.

6.4. Summary of studies on neurostimulation and neurofeedback

Anodal tDCS over the DLPFC leads to enhanced performance in task switching (Leite et al., 2011) and memory updating (Fregni et al., 2005; Ohn et al., 2008; Zaehle et al., 2010). Neurostimulation has been shown to be able to increase the power of theta and alpha

oscillations (Zaehle et al., 2010). In addition, anodal tDCS over the rIFC has been shown to enhance response inhibition (Jacobson et al., 2011, 2012; Ditye et al., 2012). Stimulation protocols for the modulation of response inhibition also seem to affect frontal theta activity (Jacobson et al., 2012) (Table 2).

7. Discussion

Cognitive training is a comparably young research field. Nevertheless, a synopsis of the actual literature is strongly needed to guide future research. Studies on the training of task switching, memory updating, response inhibition, and dual-task processing have shown to differently apply training criteria and training principles. Results are ambiguous with respect to trainability and transferability of EFs. Neural correlates have mainly been investigated via fMRI with respect to memory updating. Activation changes have been observed in fronto-parietal regions, as well as the striatum. Stimulation studies show positive results concerning EF improvements by applying short one-session tDCS over the DLPFC for improving task-switching and memory updating, or over the rIFC for the enhancement of response inhibition. However, these training protocols only lead to short-dated effects. Neurofeedback constitutes a promising approach concerning long-term maintenance as has been shown in studies addressing disrupted EFs; studies on healthy participants, however, have only rarely been conducted. Thus, crucial questions that need consideration are: 1) Is it possible to compare different behavioral training types concerning their effectiveness? 2) What are the prerequisites for transfer? 3) Do neurostimulation and neurofeedback techniques constitute suitable neurocognitive interventions for the enhancement of executive functions? 4) What do training-related neural correlates of enhanced executive functions tell us about training mechanisms?

7.1. Is it possible to compare different training types concerning their effectiveness?

Concerning behavioral training, currently available task switching, memory updating, response inhibition, and dual task training procedures

Table 2

Overview of stimulation studies. Abbreviations: M1 = primary motor cortex, SSRT = stop signal reaction time.

Authors	Characteristics	Participants	Control condition	Stimulation gain	Neuronal correlates
<i>Task switching</i>					
Leite et al. (2011)	Anodal tDCS over the DLPFC; 1 mA for 15 min	n = 30	Control group: without stimulation; experimental group: anodal and cathodal stimulation of DLPFC; control site: anodal stimulation of M1	Task-switching	n.a.
<i>Memory updating</i>					
Fregni et al. (2005)	Anodal tDCS over the left DLPFC; 1 mA for 10 min	n = 15	Control group: without stimulation; Experimental group: anodal and cathodal stimulations, control site: anodal stimulation of M1	3-Back task	n.a.
Ohn et al. (2008)	Anodal tDCS over the left DLPFC; 1 mA for 30 min; assessment during stimulation and after 30 min	n = 15	Control group: without stimulation	3-Back task; maintained for 30 min	n.a.
Zaehle et al. (2011)	Anodal tDCS over the left DLPFC; 1 mA for 15 min	n = 16	Control group: without stimulation; experimental group: anodal and cathodal stimulations	2-Back task	Increased theta and alpha powers
<i>Response inhibition</i>					
Jacobson et al. (2011)	Anodal tDCS over the rIFC; 1 mA for 10 min	n = 22	Control group: without stimulation; experimental group: anodal and cathodal stimulations; control site: anodal stimulation of right angular gyrus	Stop-signal task (reduced SSRT)	n.a.
Jacobson et al. (2012)	Anodal tDCS over rIFC and IPFC; 1 mA for 15 min	n = 11	Control group: without stimulation	Stop-signal task (reduced ssrt)	Diminution of theta power during rest
Ditye et al. (2012)	Anodal tDCS over the rIFC; 1.5 mA for 15 min before behavioral training (8 min), 4 sessions, 4 days	n = 22	Active control group: pure behavioral training; experimental group: anodal and cathodal stimulations	Stop-signal task (reduced SSRT); effects vanished after 24 h	n.a.

only partially meet common evaluation criteria (e.g., controlling differently for repetition and/or non-specific effects) and diverge with respect to the implementation of training principles (e.g., concerning the implementation of training task variability and/or adaptation of task difficulty). The first aspect concerns the type of control group (including an active or passive control group) that will automatically tap the size of training benefits and thus also affects effect sizes. Training gains will be higher using a passive group compared to an active control group. For instance, Kühn et al. (2012) used a rather conservative control procedure for their memory updating training as the active control group was trained on the same tasks as the experimental group but using lower difficulty and shorter training sessions. Effects in this study will differ compared to studies with similar training characteristics, but using a passive control group. The second aspect concerns the efficacy of training. Up to now it is hard to determine which training regime is especially effective, because effect sizes are not always reported for training gains and transfer effects. Thus, sufficient information should be provided in future publications to calculate effect sizes. This way, it will also be possible to discern which subject groups will benefit most from EF training.

7.2. What are the prerequisites for transfer?

In the context of behavioral training, transfer has the purpose to test if the function of interest has indeed been improved and not only single task specific factors. Hence, improvements are not only expected with respect to other modalities, but also near transfer to non-trained tasks related to the function of interest should be exhibited. Although neuromodulatory approaches do not face such a problem at first sight, they still are expected to specifically and exclusively affect frequency bands that are associated with the function of interest instead of modulating other general factors promoting behavioral effects. In line with this, Zoefel et al. (2010) proposed the criterion of interpretability regarding the chosen frequency in neurofeedback studies that can be applied to tACS studies as well.

However, which theoretical considerations exist concerning far transfer effects? With regard to far transfer to other EFs, it has already been known for some time that single EFs are correlated yet separable; an issue often discussed under the term “unity and diversity” of EFs (e.g., Miyake et al., 2000). Some studies already reported far transfer effects to other EFs, but overall the picture is rather mixed. Concerning task switching training, diverging results are reported for transfer to conflict monitoring. For instance, based on Karbach and Krays' (2009) training regime, a performance gain was shown for the Stroop task, whereas Zinke et al. (2012) reported the absence of such effects with a flanker- and a Stroop task. Regarding the training duration and usage of training task variability, however, these studies may not be comparable. The study by Zinke et al. was slightly shorter with three sessions and a total duration of 1–1.25 h; Karbach and Kray had subjects train for four sessions and a total of 2.5 h incorporating training task variability. Such differences may account for variations in the reported training benefits, which could also affect far transfer with respect to mixing- and/or switching costs (see Table 1). The training of memory updating has been shown to have no effect on conflict monitoring (as measured with the Stroop task) in the studies of Dahlin et al. (2008a,b) who actually discussed a neuroscientific prerequisite for transfer, i.e. the recruitment of common brain areas by tasks for different functions.

To test for far transfer, not only other EFs but also WM- and fluid intelligence measures have been investigated (e.g., Karbach and Kray, 2009; Dahlin et al., 2008a; Jaeggi et al., 2008, 2010). Far transfer effects of EF training to WM and fluid intelligence may reflect the commonality of all three cognitive functions in “fluid cognition”. This concept was introduced by Blair (2006) to point to overlapping processes within these concepts.

However, it still is not entirely clear to what extent these constructs overlap. Studies focusing on the relationship between EFs and WM suggested memory updating as a common cognitive process (e.g., Bledowski et al., 2009). Furthermore, Baddeley's influential multi-component model (1986, 2003) additionally conceptualized the “central executive”, which seems to be directly related to EFs. In 2010, McCabe and colleagues performed a factor analytic approach and demonstrated strong correlations between different measures of WM and EFs. They further indicated the existence of a common executive attention component (McCabe et al., 2010). Studies focusing on the relationship between EFs, fluid intelligence, and WM were also performed. Fluid intelligence is defined as a latent trait extracted from various reasoning tests reflecting higher mental abilities (Carroll, 1993). The influence of WM on such reasoning tests is obvious. Engle (2002), for instance, proposed executive attention as a common process of WM and fluid intelligence. Studies utilizing neuropsychological test batteries demonstrated correlations between fluid intelligence, switching, response inhibition, and memory updating (Salthouse et al., 1998, 2003). Similar assessments by Friedman et al. (2008) revealed strong correlations of memory updating, but not of response inhibition or task switching, with both fluid and crystallized intelligence. In order to investigate the association of fluid intelligence and WM-capacity, Kane et al. (2005) performed a factor analysis based on data from different studies and showed strong correlations ($r=.72$). Last, but not least WM-capacity and fluid intelligence were shown to share common genetic variance (Luciano et al., 2001).

Hence, transfer effects are to be expected because of overlapping neural and cognitive processes. Here, the work of Niendam et al. (2012) on one common super-ordinate, and other functionally more specialized networks, provides an appropriate framework for the advancement of far transfer of EF training procedures.

7.3. Do neurostimulation and neurofeedback techniques constitute suitable neurocognitive interventions for the enhancement of executive functions?

Specifically for neurostimulation, studies have shown beneficial effects on executive functioning mainly utilizing tDCS (Fregni et al., 2005; Jacobson et al., 2011, 2012; Leite et al., 2011; Ohn et al., 2008; Zaehle et al., 2010). Current data suggest that repetitive TMS and tDCS can lead to effects outlasting the actual stimulation for up to several hours (e.g., Paulus, 2011). However, most studies investigate tDCS only within one measurement session, leaving long-term retention effects unexplored. Thus, repetitive daily stimulations are suggested as a more efficient stimulation protocol (e.g., Paulus, 2011). The combination of cognitive training and neurostimulation may also have great potential. Apart from Ditye et al.'s (2012) experiment on response inhibition, Reis et al. (2009) performed a motor skill training paradigm consisting of five training sessions while their participants received anodal tDCS. Due to this stimulation, skill acquisition was optimized and remained augmented when compared to a sham condition for at least three months. Similarly, Cohen Kadosh et al. (2010) applied a similar methodological combination investigating numerical learning, and showed effects at six months after training offset.

In general, active engagement, enhanced self-efficacy, as well as long term effects (e.g., Gani et al., 2008; Monastra et al., 2002) suggest that neurofeedback should constitute a promising neurocognitive training approach. However, besides the aforementioned studies almost no neurofeedback training has been published directly focusing on the enhancement of EFs. For the development of neurocognitive training, the identification of particular oscillations associated with EFs seems to be of crucial importance. Concerning EFs, frontal-midline theta is suggested as a correlate (e.g., Cavanagh et al., 2011; Nigbur et al., 2011; Trujillo and Allen, 2007; Moore, 2005) and might serve as an ideal parameter for tACS and neurofeedback (see Enriquez-Geppert et al., submitted for publication). All in all, training protocols have to be

extended, adapted, and possibly combined with behavioral training to enable improved and long lasting maintenance of EFs.

7.4. What do training-related neural correlates of enhanced executive functions tell us?

Considering the effects of behavioral training, first studies are focused on training-related changes in the actually trained task (Hempel et al., 2004; Dahlin et al., 2008b; Kühn et al., 2012; Erickson et al., 2007; Takeuchi et al., 2010). Transfer to tasks using other modalities (Schneiders et al., 2011) or even far transfer has not been regularly studied so far. Memory updating training, however, has shown that the parietal lobe exhibits changes in activations. Beyond its involvement in visuo-spatial processing, this region has also been found to be correlated with WM performance (Wager and Smith, 2003). In a lesion study by Koenigs et al. (2009) the intra-parietal cortex was of utter importance for the manipulation, but not for the retention or retrieval of information. Similarly, changes in activation in the striatum due to training have been observed as well. In a meta-analysis, the striatum was shown to be functionally connected to other cortical areas involved in EFs including the DLPFC and the anterior MCC (Postuma and Dagher, 2006). In accordance with these results are structural changes observed by Takeuchi et al. (2010) in the vicinity of the intra-parietal sulcus and tracts connecting both DLPFCs.

However, as EFs are supposed to be mediated by both a shared super-ordinate network as well as functionally more specific networks for individual EFs, one crucial question is whether or not behavioral training, neurostimulation, and neurofeedback specifically affect any of these networks. Similarly, the discussed intervention types may differently modulate relevant brain networks (qualitatively or quantitatively) when enhancing functional proficiency. To this end, Voss et al. (2012) could nicely demonstrate training type specific interactions of large scale networks with skill training, especially concerning the fronto-parietal and the cingulo-opercular networks.

7.5. Conclusion

Given the general relevance of EFs, a crucial goal is the optimization of EFs' efficiency. Although the reviewed findings are not perfectly consistent, trainability and transferability of different training regimes suggest optimism. The actual synopsis suggests benefits of training procedures with respect to both the basic understanding of EFs as well as their possible enhancement.

Conflict of interest

The authors declare no conflict of interest.

References

- Angelakis, E., Stathopoulou, S., Fryniare, J.L., Green, D.L., Lubar, J.F., Kounios, J., 2007. EEG neurofeedback: a brief overview and an example of peak alpha frequency training for cognitive enhancement in the elderly. *The Clinical Neuropsychologist* 21, 110–129.
- Arns, M., de Ridder, S., Strehl, U., Breteler, M., Coenen, A., 2009. Efficacy of neurofeedback treatment in ADHD: the effects on inattention, impulsivity and hyperactivity: a meta-analysis. *Clinical EEG and Neuroscience* 40, 180–189.
- Aron, A.R., Robbins, T.W., Poldrack, R.A., 2004. Inhibition and the right inferior frontal cortex. *Trends in Cognitive Sciences* 8, 170–177.
- Bäckman, L., Dixon, R.A., 1992. Psychological compensation: a theoretical framework. *Psychological Bulletin* 112, 259–283.
- Baddeley, A.D., 1986. Working Memory. Oxford Univ. Press, Oxford.
- Baddeley, A.D., 2003. Working memory: looking back and looking forward. *Nature Reviews. Neuroscience* 4, 829–839.
- Bandura, A., 1997. Self-efficacy: The Exercise of Control. W.H. Freeman, New York, p. 604.
- Barkley, R.A., 1997. ADHD and the Nature of Self-control. Guilford Press, New York.
- Basar, E., Güntekin, B., 2008. A review of brain oscillations in cognitive disorders and the role of neurotransmitters. *Brain Research* 1235, 172–193.
- Basar, E., Basar-Eroglu, C., Karakas, S., Schürmann, M., 2000. Brain oscillations in perception and memory. *International Journal of Psychophysiology: Official Journal of the International Organization of Psychophysiology* 35, 95–124.
- Bernstein, L.J., Beig, S., Siegenthaler, A.L., Grady, C.L., 2002. The effect of encoding strategy on the neural correlates of memory for faces. *Neuropsychologia* 40, 86–98.
- Berryhill, M.E., Hughes, H.C., 2009. On the minimization of task switch costs following long-term training. *Attention, Perception, & Psychophysics* 71, 503–514.
- Bherer, L., Kramer, A.F., Peterson, M.S., Colcombe, S., Erickson, K., Becht, E., 2005. Training effects on dual-task performance: are there age-related differences in plasticity of attentional control? *Psychology and Aging* 20, 695–709.
- Biederman, J., Monuteaux, M.C., Doyle, A.E., Seidman, L.J., Wilens, T.E., Ferrero, F., Morgan, C., Faraone, S.V., 2004. Impact of executive function deficits and attention-deficit/hyperactivity disorder, ADHD on academic outcomes in children. *Journal of Consulting and Clinical Psychology* 72, 757–766.
- Birbaumer, N., Ramos Murguialday, A., Weber, C., Montoya, P., 2009. Neurofeedback and brain-computer interface clinical applications. *International Review of Neurobiology* 86, 107–117.
- Blair, C., 2006. How similar are fluid cognition and general intelligence? A developmental neuroscience perspective on fluid cognition as an aspect of human cognitive ability. *The Behavioral and Brain Sciences* 29, 109–160.
- Blair, C., Razza, R.P., 2007. Relating effortful control, executive function, and false belief understanding to emerging math and literacy ability in kindergarten. *Child Development* 78, 647–663.
- Bledowski, C., Rahm, B., Rowe, J.B., 2009. What 'works' in working memory? Separate systems for the selection and updating of critical information. *Journal of Neuroscience* 29, 13735–13741.
- Botvinick, M.M., Braver, T.S., Barch, D.M., Carter, C.S., Cohen, J.C., 2001. Conflict monitoring and cognitive control. *Psychological Review* 108, 624–652.
- Broadbent, D.E., 1971. Decision and Stress. *Nature*, 459. Academic Press, London, pp. 663–667.
- Campbell, D.T., Stanley, J.C., 1963. Experimental and quasi-experimental designs for research. Rand McNally, Chicago, p. 84.
- Carlson-Catalano, J., Ferreira, C., 2001. Linking self-efficacy theory to neurofeedback: a conceptual framework for 'practice and research'. *Applied Psychophysiology and Biofeedback* 26, 242.
- Carroll, J.B., 1993. Human Cognitive Abilities: A Survey of Factor-Analytic Studies. Cambridge University Press, New York.
- Cavanagh, J.F., Zambrano-Vasquez, L., Allen, J.J.B., 2011. Theta lingua franca: a common mid-frontal substrate for action monitoring processes. *Psychophysiology* 49, 220–238.
- Cepeda, N., Kramer, A.F., Gonzalez de Sather, J.C.M., 2001. Changes in executive control across the life span: examination of task-switching performance. *Developmental Psychology* 37, 715–730.
- Chambers, C.D., Bellgrove, M.A., Stokes, M.G., Henderson, T.R., Garavan, H., Robertson, I.H., Morris, A.P., Mattingley, J.B., 2006. Executive "brake failure" following deactivation of human frontal lobe. *Journal of Cognitive Neuroscience* 18, 444–455.
- Dahlin, E., Nyber, L., Bäckman, L., Neely, A.S., 2008a. Plasticity of executive functioning in young and older adults: immediate training gains, transfer, and long-term maintenance. *Psychology and Aging* 23, 720–730.
- Dahlin, E., Neely, A.S., Larsson, A., Bäckman, L., Nyberg, L., 2008b. Transfer of learning after updating training mediated by the striatum. *Science* 320, 1510–1512.
- Damos, D.L., Wickens, C.D., 1980. The identification and transfer of timesharing skills. *Acta Psychologica* 46, 15–39.
- Demos, J.N., 2004. Getting Started with Neurofeedback. Norton, New York.
- Diamond, A., Barnett, W.S., Thomas, J., Munro, S., 2007. Preschool program improves cognitive control. *Science* 318, 1387–1388.
- Ditye, R., Jacobson, L., Walsh, V., Lavidor, M., 2012. Modulating behavioral inhibition by tDCS combined with cognitive training. *Experimental Brain Research* 291, 363–368.
- Dosenbach, N.U.F., Fair, D.A., Cohen, F.L., Schlaggar, B.L., Petersen, S.E., 2008. A dual-networks architecture of top-down control. *Trends in Cognitive Sciences* 12, 99–105.
- Dowsett, S.M., Livesey, D.J., 2000. The development of inhibitory control in preschool children: effects of "executive skills" training. *Developmental Psychobiology* 26, 161–174.
- Duncan, J., 1986. Disorganisation of behaviour after frontal lobe damage. *Cognitive Neuropsychology* 3, 271–290.
- Egner, T., Strawson, E., Gruzelier, J.H., 2002. EEG signature and phenomenology of alpha/theta neurofeedback training versus mock feedback. *Applied Psychophysiology and Biofeedback* 27, 261–270.
- Engle, R.W., 2002. Working memory capacity as executive attention. *Current Directions in Psychological Science* 11, 19–23.
- Enriquez-Geppert, S., Konrad, C., Patnev, C., Huster, R.J., 2010. Conflict and inhibition differentially affect the N200/P300 complex in a combined go/no and stop-signal task. *NeuroImage* 51, 877–887.
- Enriquez-Geppert, S., Huster, R.J., Scharfenort, R., Mokom, Z.N., Zimmermann, J., Herrmann, C.S., (in press). Modulation of frontal-midline theta by neurofeedback. *Biological Psychology*.
- Erickson, K.I., Colcombe, S.J., Wadhwa, R., Bherer, L., Peterson, M.S., Scalf, P.E., Kim, J.S., Alvarado, M., Kramer, A.F., 2007. Training-induced functional activation changes in dual-task processing. An fMRI study. *Cerebral Cortex* 17, 192–204.
- Fan, J., Flombaum, J.I., McCandliss, B.D., Thomas, K.M., Posner, M.I., 2003. Cognitive and brain consequences of conflict. *NeuroImage* 18, 42–57.
- Fikke, L.T., Melinder, A., Landro, N.I., 2011. Executive functions are impaired in adolescents engaging in non-suicidal self-injury. *Psychological Medicine* 41, 601–610.

- Fisk, J.E., Sharp, C.A., 2004. Age-related impairment in executive functioning: updating, inhibition, shifting, and access. *Journal of Clinical and Experimental Neuropsychology* 26, 874–890.
- Fox, N.A., Calkin, S.D., 2003. The development of self-control of emotion: intrinsic and extrinsic influences. *Motivation and Emotion* 27, 7–26.
- Fregni, F., Boggio, P.S., Nitsche, M., Bermpohl, F., Antal, A., Feredoes, E., Marcolin, M.A., Rigonatti, S.P., Silva, M.T.A., Paulus, W., Pascual-Leone, A., 2005. Anodal transcranial direct current stimulation of prefrontal cortex enhances working memory. *Experimental Brain Research* 166, 23–30.
- Fields, R.D., 2008. White matter in learning, cognition and psychiatric disorders. *Trends in Neuroscience* 31, 361–370.
- Friedman, N.P., Miyake, A., Young, S.E., DeFries, J.C., Corley, R.P., Hewitt, J.K., 2008. Individual differences in executive functions are almost entirely genetic in origin. *Journal of Experimental Psychology. General* 137, 201–225.
- Fuster, J.M., 1990. Behavioral electrophysiology of the prefrontal cortex of the primate. *Progress in Brain Research* 85, 313–323.
- Gani, C., Birbaumer, N., Strehl, U., 2008. Long term effects after feedback of slow cortical potentials and of theta-beta-amplitudes in children with attention-deficit/hyperactivity disorder, ADHD. *International Journal of Bioelectromagnetism* 4, 209–232.
- Goldberg, E., Seidmann, L.K., 1991. Higher cortical functions in normals and in schizophrenia: a selective review. In: Steinhauser, S.R., Gruzelier, Zubin J. (Eds.), *Handbook of schizophrenia*. Elsevier, Amsterdam, pp. 397–433.
- Hanslmayr, S., Sauseng, P., Doppelmayr, M., Schabus, M., Klimesch, W., 2005. Increasing individual upper alpha power by neurofeedback improves cognitive performance in human subjects. *Applied Psychophysiology and Biofeedback* 30, 1–10.
- Hazeltine, E., Teague, D., Ivry, R.B., 2002. Simulations dual-task performance reveals parallel response selection after practice. *Journal of Experimental Psychology. Human Perception and Performance* 28, 527–545.
- Hempel, A., Giesel, F.L., García Caraballo, N.M., Amann, M., Meyer, H., Wüstenberg, T., Essig, M., Schröder, J., 2004. Plasticity of cortical activation related to working memory during training. *The American Journal of Psychiatry* 161, 745–747.
- Herrmann, C.S., Knight, R.T., 2001. Mechanism of human attention: event-related potentials and oscillations. *Neuroscience and Biobehavioral Reviews* 25, 465–476.
- Herrmann, C.S., Munk, M.H., Engel, A.K., 2004. Cognitive functions of gamma-band activity: memory match and utilization. *Trends in Cognitive Sciences* 8, 347–355.
- Hossiep, R., Turck, D., Hasella, M., 1999. Bochumer Matrizentest: BOMAT-Advanced-Short Version. Hogrefe, Göttingen.
- Huster, R.J., Enriquez-Geppert, S., Pantev, C., Bruchmann, M., 2013. Variations in midcingulate morphology are related to ERP indices of cognitive control. *Brain Structure & Function* 22. <http://dx.doi.org/10.1016/j.jippsycho.2012.08.001> (in press) (epub ahead of print).
- Jacobson, L., Lavitt, D.C., Lavidor, M., 2011. Activation of inhibition: diminishing impulsive behavior by direct current stimulation over the inferior frontal gyrus. *Journal of Cognitive Neuroscience* 23, 3380–3387.
- Jacobson, L., Ezra, A., Berger, U., Lavidor, M., 2012. Modulating oscillatory brain activity correlates of behavioral inhibition using transcranial direct current stimulation. *Clinical Neurophysiology* 123, 979–984.
- Jaeggi, S.M., Buschkuhl, M., Jonides, J., Perrig, W.J., 2008. Improving fluid intelligence with training on working memory. *Proceedings of the National Academy of Sciences of the United States of America* 105, 6829–6833.
- Jaeggi, S.M., Stieder-Luethi, B., Buschkuhl, M., Su, Y.F., Jonides, J., Perrig, W.J., 2010. The relationship between n-back performance and matrix reasoning – implications for training and transfer. *Intelligence* 38, 625–635.
- Jäger, A.O., Süß, H.M., Beauducel, A., 1997. Berliner Intelligenzstruktur-Test, BIS-Test. Form 4. Handanweisung. Hofgrefe, Göttingen, Germany.
- Johnston, S.J., Boehm, S.G., Healy, D., Goebel, R., Linden, D.E.J., 2009. Neurofeedback: a promising tool for the self-regulation of emotion networks. *NeuroImage* 49, 1066–1072.
- Jones, L.B., Rothbart, M.K., Posner, M.I., 2003. Development of executive attention in preschool children. *Developmental Science* 6, 498–504.
- Kane, M.J., Hambrick, D.Z., Conway, A.R.A., 2005. Working memory capacity and fluid intelligence are strongly related constructs: comment on Ackerman, Beier, and Boyle, 2005. *Psychological Bulletin* 131, 66–71.
- Karbach, J., Kray, J., 2009. How useful is executive control training? Age differences in near and far transfer of task-switching training. *Developmental Science* 12, 978–990.
- Karni, A., Meyer, G., Jeszczard, P., Adams, M.M., Turner, R., Ungerleider, L.G., 1995. Functional MRI evidence for adult motor cortex plasticity during motor skill learning. *Nature* 377, 155–158.
- Kelly, A.M.C., Garavan, H., 2005. Human functional neuroimaging of brain changes associated with practice. *Cerebral Cortex* 15, 1089–1102.
- Kerns, J.G., 2006. Anterior cingulate and prefrontal cortex activity in an fMRI study of trial-to-trial adjustments on the Simon task. *NeuroImage* 15, 399–405.
- Klingberg, T., 2010. Training and plasticity of working memory. *Trends in Cognitive Sciences* 14, 317–324.
- Koenigs, M., Barbey, A.K., Postle, B.R., Grafman, J., 2009. Superior parietal cortex is critical for the manipulation of information in working memory. *Journal of Neuroscience* 29, 14920–14986.
- Kolb, B., Whishaw, I.Q., 1998. Brain plasticity and behavior. *Annual Review of Psychology* 49, 43–64.
- Kramer, A.F., Larish, J.F., Strayer, D.L., 1995. Training for attentional control in dual task settings: a comparison of young and old adults. *Journal of Experimental Psychology. Applied* 20, 75–76.
- Kramer, A.F., Larish, J.L., Weber, T.A., Bardell, L., 1999. Training for executive control: task coordination strategies and aging. In: Gopher, D., Koriat, A. (Eds.), *Attention and Performance XVII: Cognitive Regulation of Performance: Interaction of Theory and Application*. MIT Press, Cambridge, MA, pp. 617–652.
- Kray, J., Lindenberger, U., 2000. Adult age differences in task switching. *Psychology and Aging* 15, 126–147.
- Kühn, S., Schmiedek, F., Noack, H., Wenger, E., Bodammer, N.C., Lindenberger, U., Lövdén, M., 2012. The dynamics of change in striatal activity following updating training. *Human Brain Mapping*. <http://dx.doi.org/10.1002/hbm.22007> (Epub ahead of print).
- Leite, J., Carvalho, S., Fregni, F., Goncalves, O.F., 2011. Task-specific effects of tDCS-induced cortical excitability changes on cognitive and motor sequence set shifting performance. *PLOS One* 6, e24140.
- Levesque, J., Beauregard, M., Mensour, B., 2006. Effect of neurofeedback training on the neural substrates of selective attention in children with attention-deficit/hyperactivity disorder: a functional magnetic resonance imaging study. *Neuroscience Letters* 394, 216–221.
- Levin, H.S., Culhane, K.A., Hartmann, J., Evankovich, K., Mattson, A.J., Harward, H., Ringholz, G., Ewingcobb, L., Fletcher, J.M., 1991. Developmental-changes in performance on tests of purported frontal-lobe functioning. *Developmental Neuropsychology* 7, 377–395.
- Li, S.C., Schmiedek, F., Huxhold, O., Röcke, C., Smith, J., Lindenberger, U., 2008. Working memory plasticity in old age: practice gain, transfer, and maintenance. *Psychology and Aging* 23, 731–742.
- Liepelt, R., Fischer, R., Frensch, P.A., Schubert, T., 2011a. Practice-related reduction of dual-task costs under conditions of a manual-pedal response combination. *Journal of Cognitive Psychology* 23, 29–44.
- Liepelt, R., Strobach, T., Frensch, P., Schubert, T., 2011b. Improved intertask coordination after extensive dual-task practice. *The Quarterly Journal of Experimental Psychology* 26, 1–22.
- Lilenthal, L., Tamez, E., Shelton, J.T., Myerson, J., Hale, S., 2012. Dual n-back training increases the capacity of the focus of attention. *Psychonomic Bulletin & Review* (Epab ahead of print).
- Linden, D.E.J., Habe, I., Johnston, S.J., Linden, S., Tatineni, R., Subramanian, L., Sorger, B., Dealy, D., Goebel, R., 2012. Real-time self-regulation of emotion networks in patients with depression. *PloS One* 7, e38115.
- Lövdén, M., Bäckman, L., Lindenberger, U., Schaefer, S., Schmiedek, F., 2010. A theoretical framework for the study of adult cognitive plasticity. *Psychological Bulletin* 136, 659–676.
- Luciano, M., Wright, M., Smith, G.A., Geffen, G.M., Geffen, L.B., Martin, N.G., 2001. Genetic covariance among measures of information processing speed, working memory, and IQ. *Behavior Genetics* 31, 581–592.
- Luria, A.R., 2002. Frontal lobe syndromes. In: Pinken, P.J., Bruyn, G.W. (Eds.), *Handbook of Clinica Neurology*, vol 2. North Holland, Amsterdam, pp. 725–757.
- Lussier, M., Gagnon, C., Bherer, L., 2012. An investigation of response and stimulus modality transfer effects after dual-task training in younger and older. *Frontiers in Human Neuroscience* 6, 1–11.
- McCabe, D.P., Roedinger, H.L., McDaniel, M.A., Balota, D.A., Hambrick, D.Z., 2010. The relationship between working memory capacity and executive functioning: evidence for a common executive attention construct. *Neuropsychology* 24, 222–243.
- McDowd, J.M., 1986. The effects of age and extended practice on divided attention performance. *Journal of Gerontology* 41, 764–769.
- Meiran, N., 1996. Reconfiguration of processing mode prior to task performance. *Journal of Experimental Psychology. Learning, Memory, and Cognition* 22, 1423–1422.
- Meyer, D.E., Kieras, D.E., 1997. A computational theory of executive cognitive processes and multiple-task performance: part 1. Basic mechanisms. *Psychological Review* 104, 3–65.
- Miller, E.K., Desimone, R., 1994. Parallel neuronal mechanisms for short-term memory. *Science* 263, 520–522.
- Miller, M., Hinshaw, S.P., 2010. Does childhood executive function predict adolescent functional outcomes in girls with ADHD? *Journal of Abnormal Child Psychology* 38, 315–326.
- Minear, M., Shah, P., 2008. Training and transfer effects in task switching. *Memory & Cognition* 36, 1470–1483.
- Miyake, A., Friedman, N.P., 2012. The nature and organization of individual differences in executive functions: four general conclusions. *Current Directions in Psychological Science* 21, 8–14.
- Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A.M., Wagner, T., 2000. The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: a latent variable analysis. *Cognitive Psychology* 41, 49–100.
- Monastrá, V.J., Monastrá, D.M., George, S., 2002. The effects of stimulant therapy, EEG biofeedback, and parenting style on the primary symptoms of attention-deficit/hyperactivity disorder. *Applied Psychophysiology and Biofeedback* 27, 231–249.
- Moore, N.C., 2005. The neurotherapy of anxiety disorders. *Journal of Adult Development* 12, 147–154.
- Morrison, A.B., Chein, J.M., 2011. Does working memory training work? The promise and challenges of enhancing cognition by training working memory. *Psychonomic Bulletin & Review* 18, 46–60.
- Narli, S., 2011. Is constructivist learning environment really effective on learning and long-term knowledge retention in mathematics? Example of the infinity concept. *Educational Research and Reviews* 6, 36–49.
- Neuling, T., Wagner, S., Wolter, C.H., Zaehler, R., Herrmann, C.S., 2012. Finite-element model predicts current density distribution for clinical applications of tDCS and tACS. *Frontiers in Psychiatry* 3, 1–10.
- Niendam, T.A., Lair, A.R., Kimberly, L.R., Dean, Y.M., Carter, C.S., 2012. Meta-analytic evidence for a superordinate cognitive control network subserving diverse executive functions. *Cognitive, Affective, & Behavioral Neuroscience* 12, 241–268.
- Nigbur, R., Ivanova, G., Stürmer, B., 2011. Theta power as a marker for cognitive interference. *Clinical Neurophysiology* 49, 220–238.

- Nissen, M., Bullemer, P., 1987. Attentional requirements of learning: evidence from performance measures. *Cognitive Psychology* 19, 1–32.
- Nitsche, M.A., Paulus, W., 2000. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *The Journal of Physiology* 527, 633–639.
- Ohn, S.H., Park, C.I.I., Yoo, W.K., Ko, M.H., Choi, K.P., Kim, G.-M., Lee, Y.T., Kim, Y.H., 2008. Time-dependent effect of transcranial direct current stimulation on the enhancement of working memory. *Neuroreport* 19, 43–47.
- Oken, B.S., Flegal, K., Zajdel, D., Kishiyama, S., Haas, M., Peters, D., 2008. Expectancy effect: impact of pill administration on cognitive performance in healthy seniors. *Journal of Clinical and Experimental Neuropsychology* 30, 7–17.
- Pashler, H., 1994. Dual-task interference in simple tasks: data and theory. *Psychological Bulletin* 116, 220–224.
- Paulus, W., 2011. Transcranial electrical stimulation (tES –tDCS: tRNS, tACS) methods. *Neuropsychological Rehabilitation* 21, 602–617.
- Petersen, S.E., van Mier, H., Fiez, J.A., Raichle, M.E., 1998. The effects of practice on the functional anatomy of task performance. *Proceedings of the National Academy of Sciences of the United States of America* 95, 853–860.
- Poldrack, R.A., 2000. Imaging brain plasticity: conceptual and methodological issues – a theoretical review. *NeuroImage* 12, 1–13.
- Postuma, R.B., Dagher, A., 2006. Basal ganglia functional connectivity based on a meta-analysis of positron emission tomography and functional magnetic resonance imaging publications. *Cerebral Cortex* 16, 1508–1521.
- Rabin, L.A., Fogel, J., Nutter-Upham, K.E., 2011. Academic procrastination in college students: the role of self-reported executive function. *Journal of Clinical and Experimental Neuropsychology* 33, 344–357.
- Raven, J.C., 1990. Advanced Progressive Matrices: Sets, I, II. Oxford University Press, Oxford.
- Redick, T.S., Shipstead, Z., Harrison, T.L., Hicks, K.L., Freid, D.E., Hambrick, D.Z., Kane, M.J., Engle, R.W., 2012. No evidence of intelligence improvement after working memory training: a randomized, placebo-controlled study. *Journal of Experimental Psychology. General* 18. <http://dx.doi.org/10.1037/a0029082> (Epub ahead of print).
- Reis, J., Schambra, H.M., Cohen, L.G., Buch, E.R., Fritsch, B., Zarahn, E., Celnik, P.A., Krakauer, J.W., 2009. Noninvasive cortical stimulation enhances motor skill acquisition over multiple days through an effect on consolidation. *Proceedings of the National Academy of Sciences of the United States of America* 106, 1590–1595.
- Ros, T., Munneke, M.A., Ruge, D., Gruzelier, J.H., Rothwell, J.C., 2010. Endogenous control of waking brain rhythms induces neuroplasticity in humans. *The European Journal of Neuroscience* 31, 770–778.
- Salminen, T., Strobach, R., Schubert, T., 2012. On the impacts of working memory training on executive functioning. *Frontiers in Human Neuroscience* 6, 1–11.
- Salthouse, T.A., Fristoe, N., McGuthry, K.E., Hambrick, D.Z., 1998. Relation of task switching to speed, age, and fluid intelligence. *Psychology and Aging* 13, 445–461.
- Salthouse, T.A., Atkinson, T.M., Berish, D.E., 2003. Executive functioning as a potential mediator of age-related cognitive decline in normal adults. *Journal of Experimental Psychology. General* 132, 566–594.
- Schmiedeck, F., Lövdén, M., Lindenberger, U., 2010. Hundred days of cognitive training enhance broad cognitive abilities in adulthood: findings from the COGITO study. *Frontiers in Aging Neuroscience* 2, 1–10.
- Schneider, W., Detweiler, M., 1988. The role of practice in dual-task performance: toward workload modelling in a connectionist/control architecture. *Human Factors* 30, 593–566.
- Schneiders, J.A., Opitz, B., Krick, C.M., Mecklinger, A., 2011. Separating intra-modal and across-modal training effects in visual working memory: an fMRI investigation. *Cerebral Cortex* 21, 2555–2564.
- Schumacher, E.H., Seymour, T.L., Glass, J.M., Fencsik, D.E., Lauber, E.J., Kieras, D.E., Meyer, D.E., 2001. Virtually perfect time sharing in dual-task performance: uncorking the central cognitive bottleneck. *Psychological Science* 12, 101–108.
- Seiferth, N.Y., Thienel, R., Kirchner, T., 2007. *Exekutive Funktionen*. In: Schneider, F., Fink, G.R. (Eds.), *Funktionelle MRT in Psychiatrie und Neurologie*. Springer Berlin Heidelberg, pp. 265–277.
- Shipstead, Z., Redick, T.S., Engle, R.W., 2010. Does working memory training generalize? *Psychologica Belgica* 50, 245–276.
- St. Clair-Thompson, H., Stevens, R., Hung, A., Bolder, E., 2010. Improving children's working memory and classroom performance. *Educational Psychology* 30, 203–219.
- Strobach, T., Liepelt, R., Schubert, T., Kiesel, A., 2011. Task switching: effects of practice on switch and mixing costs. *Psychological Research* 76, 74–83.
- Strobach, T., Liepelt, R., Schubert, T., Kiesel, A., 2012. Task switching: effects of practice on switch and mixing costs. *Psychological Research* 76, 74–83.
- Takeuchi, H., Sekiguchi, A., Taki, Y., Yokoyama, S., Yomogida, Y., Komuro, N., Yamamoto, T., Suzuki, S., Kawashima, R., 2010. Training of working memory impacts structural connectivity. *Journal of Neuroscience* 30, 3297–3303.
- Taylor, P.C., Thut, G., 2012. Brain activity underlying visual perception and attention as inferred from TMS-EEG: a review. *Brain Stimulation* 5, 124–129.
- Thorell, L.B., Lindqvist, S., Bergman Nutley, S., Bohlin, G., Klingberg, T., 2009. Training and transfer effects of executive functions in preschool children. *Developmental Science* 12, 106–113.
- Thummala, K., Satpathy, A., 2009. Improvements in executive functions through inhibition training for undergraduates with ADHD. <http://www.ncur20.ws/presentations/1/179/paper.pdf>.
- Trujillo, L.T., Allen, J.J.B., 2007. Theta EEG dynamics of the error-related negativity. *Clinical Neurophysiology* 118, 645–886.
- Tulving, E., Schacter, D.L., 1990. Priming and human memory systems. *Science* 247, 301–306.
- Voss, M.W., Prakash, R.S., Erickson, K.I., Boot, W.R., Basak, C., ..., Kramer, A.F., 2012. Effects of training strategies implemented in a complex videogame on functional connectivity of attentional networks. *NeuroImage* 59, 138–148.
- Wager, T.D., Smith, E.E., 2003. Neuroimaging studies of working memory: a meta-analysis. *Cognitive, Affective, & Behavioral Neuroscience* 3, 255–274.
- Weiskopf, N., Scharnowski, F., Veit, R., Goebel, R., Birbaumer, N., Mathiak, K., 2005. Self-regulation of local brain activity using real-time functional magnetic imaging fMRI. *The Journal of Physiology* 98, 357–373.
- Welford, A.T., 1980. Choice reaction time: basic concepts. In: Welford, A.T. (Ed.), *Reaction Times*. Academic Press, New York, pp. 73–128.
- Williams, P.G., Thayer, J.F., 2009. Executive functioning and health: introduction to the special series. *Annals of Behavioral Medicine* 37, 101–105.
- Yücel, M., Wood, S.J., Fornito, A., Rifffkin, J., Velakoulis, D., Pantelis, C., 2003. Anterior cingulate dysfunction: implications for psychiatric disorders? *Journal of Psychiatry & Neuroscience* 28, 350–354.
- Zaehle, T., Rach, S., Herrmann, C.S., 2010. Transcranial alternating current stimulation enhances individual alpha activity in human EEG. *PLoS One* 5, e13766.
- Zaehle, T., Sandmann, P., Thorne, J.D., Jäncke, L., Herrmann, C.S., 2011. Transcranial direct current stimulation of the prefrontal cortex modulates working memory performance: combined behavioural and electrophysiological evidence. *BMC Neuroscience* 12, 1–11.
- Zinke, K., Einert, M., Pfennig, L., Kriegel, M., 2012. Plasticity of executive control through task switching training in adolescents. *Frontiers in Human Neuroscience* 6, 1–15.
- Zoefel, B., Huster, R.J., Herrmann, C.S., 2010. Neurofeedback training of the upper alpha frequency band in EEG improves cognitive performance. *NeuroImage* 54, 1427–1431.