Working Memory Training and Transfer: Theoretical and Practical Considerations

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Abstract The study of transfer and brain plasticity is currently one of the hot topics in cognitive science. Transfer refers to performance improvements in tasks that were not part of an intervention. In this chapter, we will provide evidence for the efficacy of several working memory (WM) interventions developed in our laboratories and review the emerging literature from other groups. We will discuss data that demonstrate transfer to non-trained tasks throughout the lifespan, that is, in young adults, in older adults, in typically developing children, as well as children with Attention-Deficit Hyperactivity Disorder (ADHD). We will also briefly discuss the neural correlates that underlie improvements as a function of WM training. In addition to describing successful instances of transfer, we will also point out that transfer effects can be elusive, and that some of the effects do not seem to be easily replicated. We argue that instead of taking inconsistencies as a proof for a lack of efficacy, researchers need to develop innovative approaches to move the cognitive training literature beyond the simple question of whether or not training is effective, and to address questions of underlying mechanisms, individual differences, and training features and parameters that might mediate and moderate the efficacy of training.

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1 Introduction

The study of transfer and brain plasticity is currently one of the hot topics in cognitive science but it has been an issue in educational research for many years. Transfer generally refers to the application of learning and skills in other contexts and new situations, and more specifically, in the context of cognitive interventions, transfer refers to performance improvements in tasks that were not part of the intervention. While some have argued that there is no evidence for transfer as a function of cognitive training, we and others have pointed out that certain kinds of interventions can be, indeed, effective, but that there are important boundary conditions that have to be taken into account when evaluating training success. In this chapter, we will provide evidence for the efficacy of several working memory (WM) interventions developed in our laboratories and review the emerging literature from other groups. We will discuss data that demonstrate transfer to non-trained tasks throughout the lifespan, that is, in young adults, in older adults, in typically developing children, as well as children with Attention-Deficit Hyperactivity Disorder (ADHD). We will also briefly discuss the neural correlates that underlie improvements observed as a function of WM training. In addition to describing successful instances of transfer, we will also point out that transfer effects can be elusive, and that some of the effects do not seem to be easily replicated. We argue that instead of taking inconsistencies as a proof for a lack of efficacy, researchers need to develop innovative approaches to move the cognitive training literature beyond the simple question of whether or not training is effective, and to address questions of underlying mechanisms, individual differences, and training features and parameters that might mediate and moderate the efficacy of training.

2 On Transfer

There are numerous commercial training interventions claiming to make us smarter. Some of the available interventions are increasingly used in the classroom environment with the hope of improving the users' cognitive ability and scholastic achievement. The common assumption and hope of those interventions are that the skills and knowledge acquired by playing such games and tasks will generalize and become applicable in new situations and domains, a process that is called 'transfer'. Transfer is an essential concept in the domain of education and learning because the main goal of education is to teach new generations of students to master professional and life demands, and not just to solve a specific math problem or know how to conjugate French verbs. But what do we mean by 'transfer'? Consider the following analogy—a driver might become proficient in backing up the car she is used to drive with in her narrow driveway. Now, if she borrows her neighbor's car, which is bigger, the driver may be able to apply her driving skills to the new situation. Although her parking may not be as fast or precise as it is in her own vehicle, she will probably still be successful. However, things would become very difficult if she would be asked to back up a trailer truck—although there are clearly similarities between a car and a trailer truck (steering wheel, break, gas, etc.), the trailer truck has other features which will make the transition difficult (e.g. the fact that there is a trailer that makes backing up decidedly harder for most people). Another example is if you would start to exercise on a regular basis by going running. As a consequence, you would not only improve in running, but as you are strengthening your cardiovascular system and leg muscles, you would also improve other functions that rely on a healthy cardiovascular system and stronger leg muscles, such as climbing stairs, biking, or swimming (e.g. [151]).

Although the existence of transfer in the physical domain is hardly surprising to anyone, demonstrating transfer in the cognitive domain has been difficult, and for over 100 years, arguments have been made about whether transfer exists or not [40, 113, 126, 128, 161]. Nonetheless, as Perkins and Salomon [117] have pointed out, any learning involves transfer in at least a trivial sense: there is no such thing as learning if there is no demonstration of the learning outcome in a different context, even if the context is very similar. The main question is thus how to distinguish between trivial transfer and transfer in which there is a meaningful generalization effect. Usually, researchers conceptually divide transfer into categories of "near" and "far" [128, 142, 170]. Near transfer refers to an effect of the trained task on a non-trained task that is closely related to it; far transfer refers to an effect of the trained task on a non-trained task that is quite different, perhaps sharing very few features (applying the concept to the car driving analogy, near transfer would refer to parking your car vs. your neighbor's car, and far transfer would refer to parking your car vs. parking a trailer truck). Unfortunately, there is neither a formal definition nor an operational method to measure the distance of transfer, although there are some attempts to do so [8]. Nevertheless, it may be most useful to understand near and far transfer effects as two points on a continuum and to use the distinction as a descriptive means to get at an intervention's impact [173].

Why should transfer occur in the first place? We and others have argued that transfer depends on the degree of process-overlap between the training task and the outcome measures—the more similar processes there are between the tasks, the higher the chances for transfer, which also relates to the argument of near and far transfer above [34, 71, 100]. Those overlaps can occur neurally in the form of shared brain areas or networks between training and outcome measures. Cognitively, such overlaps can occur in the form of common processing demands (e.g. attentional control), similar strategies that can be applied in the training and the transfer tasks (e.g. chunking), or an acquired "mindset" during training which facilitates transfer (e.g. increased self-confidence). Of course, those overlaps are not easily disentangled, and transfer can occur due through either one, or through a combination of different mechanisms [128].

3 Brain Training and Transfer: The Case of Working Memory

In this chapter, we will not focus on education in the broad sense as a means to investigate transfer, but rather, on a relatively narrow set of interventions that aim to improve certain specific cognitive skills over a relatively short timeframe. Such interventions are often referred to as 'brain training' tools, and there is a growing demand and market for such products (cf. [139]). Unfortunately, the scientific evidence demonstrating the efficacy of commercial interventions is rather sparse in that the effects (if they are assessed at all) rarely go beyond tasks that were specifically trained (cf. [63, 104] for recent meta-analyses). Nevertheless, there is accumulating evidence that certain cognitive interventions may indeed be effective. For example, there are a number of studies that demonstrated improvements in non-trained cognitive tasks after some form of WM, executive function, or attention training (see e.g. [20, 41, 70] for recent reviews). Not surprisingly, performance improvements are most often observed in tasks that are quite closely related to the trained task. For example, interventions designed to target WM skills typically result in improvements in non-trained measures of WM, i.e. they show near transfer effects ([98, 114], e.g. [66, 96, 127]). Nonetheless, there is also work demonstrating evidence for far transfer, for example, there is an accumulating number of studies reporting improvements in measures of fluid intelligence (Gf) after training on WM and related skills (see e.g. [77] for a recent overview). The concept of Gf has been introduced by Cattell [25] in that he described Gf as the ability to reason and to solve novel, abstract problems without relying on previously acquired skills or knowledge. Gf is contrasted with crystallized intelligence (Gc), i.e. the ability to use skills, knowledge, and experience. It has been argued that Gf facilitates learning in a general sense. Indeed, there is a lot of empirical evidence showing that Gf is the most reliable predictor for achievement, that is, individual differences in Gf predict successful performance in educational and professional settings (e.g. [38, 53]). As such, developing means to improve Gf is of particular relevance. Of course, improvements in Gf tasks can be easily obtained by practicing the Gf test themselves; however, such effects are highly specific and the tests lose their predictive value for other tasks [158], and furthermore, such improvements would not be considered as transfer but practice effects.

Researchers have used a wide variety of measures to assess improvements in Gf as a function of cognitive training, but most commonly, they have used visuospatial matrix reasoning measures such as Raven's progressive matrices [121]. The reason for this interest in matrices tests is because they are seen as being the most representative of Spearman's g [143], that is, a global measure of cognitive ability [55]. Nonetheless, other measures have been used in WM training studies as well, for example more verbal measures, such as analogies or inferences [76]. Furthermore, WM training research has begun to use multiple measures to assess Gf as a composite measure in order to reduce task-specific variance (e.g. [32, 76, 123, 131, 146]). Although the number of studies finding improvements in measures of Gf is still relatively small, a pattern seems to emerge revealing larger effect sizes in the visuospatial domain as compared to the verbal domain [22, 32, 77, 146]. This dissociation might have emerged as a function of the tests used (along with their psychometric properties), by the participants' familiarity with the material [77], or more generally by the fact that one domain might be more malleable to change than another (e.g. [86]). At the present stage of research, however, further work is needed to clarify this issue.

Apart from improvements in Gf, researchers have also observed transfer to basic attentional skills and visual processes [56, 57], language-related skills [29, 46, 99, 111], arithmetic and numeracy skills [94, 172], measures of academic achievement [63, 138], or even to self-regulatory behavior such as ADHD symptoms or drinking behavior in alcoholics and delay discounting in stimulant addicts [10, 14, 66, 93]. Thus, at the current stage of research, it seems like interventions that target skills related to WM and attentional control can be effective tools to improve higher cognitive skills—why might that be?

WM is the cognitive mechanism that supports active maintenance of task-relevant information during the performance of a cognitive task [6]. WM underlies the performance of virtually all complex cognitive activities [136]. Imagine yourself mentally calculating the 18 % tip for your dinner, participating in a conversation with your parents while simultaneously texting to your friend, or reading a complex paragraph in your History textbook. All of these tasks rely on deliberate WM processes in that they require multiple processing steps and temporary storage of intermediate results, going back and forth between different tasks, as well as resisting distracting information. People differ in how much information they can hold in WM, and how well they can maintain that information in the face of distraction [43, 84]. These individual differences predict how well individuals perform in school-relevant tasks such as mathematics and reading comprehension (e.g. [37, 49, 116]). WM capacity is also crucial for our ability to acquire new knowledge and skills [118]. Research has shown that WM is a better predictor of scholastic achievement than intelligence, especially in young children [2]. Deficits in WM are considered a primary source of cognitive impairment in numerous special-needs populations ranging from ADHD to mathematics disability [105]. WM also has significant effects on classroom behavior. For example, teachers are more likely to rate children with poor WM capacity as disruptive and inattentive [3, 48].

In sum, WM is a fundamental cognitive system that is highly relevant for success in and out of schools. Given the relevance of WM to daily life and educational settings, it is not surprising that many cognitive interventions target WM skills with the ultimate goal to obtain transfer in relevant areas such as scholastic achievement. Referring back to the analogy in the physical domain described earlier, we can characterize WM as taking the place of the cardiovascular system that underlies performance of many different activities. That is, we see WM as an underlying entity that determines the performance of a multitude of tasks, and thus, strengthening WM skills should lead to performance improvements in tasks that rely on the functioning of the WM system [85].

This idea of strengthening underlying processes to improve general performance is not new at all. Indeed, over 120 years ago, William James proposed that improving attention could have high practical importance by stating that[1]

> "An education which would improve attention would be the education par excellence" (James, 1890, The Principles of Psychology, Vol. 1, p. 424).

James explained the importance of strengthening attentional skills by referring to the crucial role of attentional control for human performance:

> "(. . .) the faculty of voluntarily bringing back a wandering attention, over and over again, is the very root of judgment, character, and will. (. . .)" (p. 424).

He also pointed out some of the major practical difficulties that accompany the design of interventions, and he suggested that the most promising approach would be to somehow capture a person's interest and motivation, one of the critical features of programs that aim to keep participants training for longer than just one or two sessions [74].

Klingberg and colleagues were among the first to use a WM training based on the premises outlined above [92, 93; but see 1 for a very early and pioneering example]. They developed an intervention that consisted of a battery of computerized tasks targeting mainly WM processes. Those tasks were embedded into an interesting videogame environment to make the intervention engaging and motivating. Another critical feature was that their tasks were adaptive. That is, the tasks became incrementally harder as the participants improved, and rewards were provided based on performance. The authors targeted children with ADHD as training population because WM deficits are often among the core symptoms in ADHD [169]. The authors' rationale was that training WM should reduce ADHD symptoms, and in addition, yield transfer to other tasks that rely on WM. Indeed, both studies demonstrated that a 5-week intervention resulted in reduced ADHD symptoms, as well as in transfer effects to non-trained variants of the trained tasks, in a measure of executive control (the Stroop task), and, finally, to Ravens' matrix reasoning, a common proxy for Gf. Since then, this intervention has been further developed and used by other researchers, and it is currently marketed under the name 'Cogmed' (most recently distributed by Pearson). Unfortunately, although near transfer effects on non-trained measures of WM are consistently observed using this particular intervention, the far transfer effects do not seem to be easily replicated, neither by the Klingberg group [13, 160], nor by other groups using the same program [18, 64, 65]. Nonetheless, there is a recent study by an independent group that replicated the improvement on parent-rated ADHD symptoms [10], the improvements on Gf [124], and another recent study even reported improvements in scholastic achievement measures in an applied school setting [63]. Taken together,

[1]Note that by referring to James' quote it is not our intention to equate WM with attention without a proper and detailed discussion of the matter. Instead we want to emphasize the idea entailed in the quote that training underlying processes is likely to affect not only the trained process but all other cognitive functions that rely at least in part on those functions.

it seems that the training regimen developed by Klingberg and colleagues does have important benefits, even though those benefits are most consistently expressed as near transfer effects (see also [104]). From an applied point of view, however, near transfer effects can be very useful given the importance of WM for scholastic achievement.

In terms of ameliorating ADHD symptoms, one of the major goals of the intervention program, a recent review classified Cogmed as a 'Possibly Efficacious Treatment for youth with ADHD' using established evidence-based treatment criteria as proposed by the Society for Clinical Child and Adolescent Psychology [28]. Nonetheless, despite the promising effects, the intervention remains controversial as documented in a recent special issue on the topic that appeared in the Journal of Applied Research in Memory and Cognition (Volume 1; see e.g. [140]). Although we agree that the evidence for Cogmed's efficacy to date is mixed, we have argued that it is probably too early for a final verdict, especially since there are over 60 ongoing studies using the program [76]. Furthermore, the few studies that have been published have populations that are rather diverse and hardly comparable across studies (e.g. ranging from typically developing children to stroke patients), and often, the outcome measures were not comparable either. Thus, we have emphasized that it is likely that those factors along with individual differences could account for the mixed effects observed to date [137]. On another level, the intervention has also been criticized as 'kitchen sink approach' as it contains many different tasks, which might or might not contribute to transfer, and as such, it is not possible to get at the underlying mechanisms of transfer. Such a criticism also applies to other interventions that rely on a diverse battery of tasks ([131], e.g. [90]). This critique is certainly appropriate from an experimental standpoint, however, such an approach has merits from a practical point of view since it is certainly more interesting for participants to train on a diverse battery of task rather than repeating the same task over and over again [69, 76]. Thus, if researchers are interested in generalized improvements and do not necessarily care *why* the improvements occur, it might be better to rely on the combination of multiple components, hoping that one or more of them will be successful.

On the other hand, other research groups have taken a different approach by relying on a more narrow set of tasks, for example on so-called WM capacity tasks such as reading span tasks [16, 22, 29, 99, 164]. Those interventions are usually adaptive as well in that they adjust to the participants' performance. All of those interventions consistently observed transfer within the trained WM domain. In addition, some report far transfer effects, e.g. to reading-related processes [29, 99], or to measures of intelligence [16, 166]. However, improvements in fluid intelligence are not consistently observed [29, 99], and it has been argued that such span-type interventions might be restricted in their generalizing ability.

Although we have used span-type interventions in some of our studies as well [22, 99], more often we have been taking yet another approach by relying on an n-back task as the intervention vehicle. In this task, participants are required to process a continuous stream of stimuli (e.g. letters, shapes, or locations; presented in 3 s intervals) and decide for each stimulus whether or not it matches the one that was presented *n* items previously. For example, if participants are asked to do a 2-back task, the following letter stream contains two targets: L-K-P-**K**-F-R-K-**R**-R (i.e., the second K and the second R; highlighted in bold for illustration purposes). This task has been widely used in the neuroimaging literature to investigate the underlying mechanisms of WM load (cf. [112] for a meta-analysis). For our interventions, we have made the task adaptive in that its difficulty (i.e. load) varies from one block of trials to another by changing the level of *n* [83]. That is, adjustments are made continuously based on the trainee's performance: As performance improves, the level of *n* will be increased in the next block (for example, from a 2-back to a 3-back); as it worsens, the level of *n* will be decreased in the next block (for example, from a 2-back to a 1-back). As such, the task always remains demanding and tailored to individual performance (cf. [71] for a first description of the intervention). We have argued that some of the task's features are highly relevant for the concept of training, that is, this task involves *multiple* WM processes, such as storage, but also interference resolution, attentional control, as well as sustained attention [83, 152]. We found the n-back task to be promising as a training vehicle because n-back performance reliably predicts Gf and measures of executive control [55, 72, 73, 87], and furthermore, it is highly predictive for academic achievement and teacher-reported behavioral problems such as impulsivity and hyperactivity (e.g. [5]).

To date, we have used our adaptive n-back intervention in multiple studies with young adults, and we observed improvements in various matrix reasoning tasks that are strongly related to Gf [71, 73, 77]. We have also shown that the longer participants train on the task, the more improvements they show in Gf, that is, we have demonstrated a dose–response effect of training. Recently, we have replicated this finding in a sample of healthy older adults [146]. In addition, several other research groups have successfully replicated transfer to measures of Gf using the n-back task as training vehicle [32, 78, 120, 125, 134, 147, 155], and others have observed performance improvements in other domains as well, such as executive control and WM capacity [4, 96, 98, 127].

More recently, we adapted an adult version of the n-back task for children and created a video game-like context by incorporating features garnered from the video-game literature such as points, high scores, and appealing graphics and themes [50, 101, 119, 144]. We found that this video-game-like intervention led to improvements in non-trained measures of WM, but also in measures of sustained attention and inhibition in typically developing children and children with ADHD [75]. In addition, we also found transfer to matrix reasoning tasks, but critically, only in children who showed considerable gains in the training task [74]. Similar patterns have also been observed by Zhao and colleagues who trained typically developing children on a WM updating task related to n-back, that is, they demonstrated improvements in Gf, which correlated with the improvement in the training task [175]. Finally, another group has demonstrated a relationship between training performance and outcome in the domain of language skills in young adults [111], in sum, training *quality* seems to be an important feature to determine training success.

As for the interventions discussed further above, this work is not without controversy either (see e.g. [141]). For example, there are a few studies from other research groups that fail to show transfer to Gf after n-back training. Notably, there are two studies that fail to find improvements in Gf, however, they observe transfer in other non-trained measures, and the failure to find group differences in Gf could be attributed to either the selection of the control task, or the fact that the intervention time was too short ([96, 127]; cf. [77] for further discussion). But there are also studies that did not observe transfer in *any* of their outcome measures [30, 123, 159]. Those studies are difficult to interpret since there are of course many reasons that could give rise to null-effects, such as sample size, population differences, the selection of outcome measures, measurement issues (e.g. lack of reliability in the outcome measures), lack of training quality (i.e. lack of training improvement), individual differences, motivational or other issues (cf. [77] for further discussion). Nonetheless, such null-effects can be informative to further investigate important boundary conditions and to get at the underlying mechanisms of training and transfer; issues that we will address in the next sections.

4 Why is There Transfer? In Search of Underlying Mechanisms

Despite the accumulating evidence that there are generalizing effects after WM training, we only have a very vague idea *why* transfer effects occur. Thus, to date we can only speculate about the possible underlying mechanisms of training and transfer. As Chein and Morrison pointed out [29], there are many reasons why participants could perform better after training, such as changes in strategies, improved executive control, speed of processing, pre-existing individual differences and motivational factors, or simply familiarity with the stimuli and improved test-taking skills. What makes it even more difficult for research is the fact that transfer could also occur by a combination of those factors. Nonetheless, the question is whether we can derive some general principles from the existing literature that might shed some light on the underlying mechanisms. In the following, we will separately describe potential cognitive and neural mechanisms, although we acknowledge that the two domains are certainly intertwined.

5 Cognitive Mechanisms

We and others have argued that in order for transfer to occur, one important mechanism might be that training and transfer tasks need to share a common processing basis [71, 82]. What could be the common cognitive mechanism that could drive transfer effects from n-back training to such diverse tasks such as executive control and reasoning? One prominent feature of the n-back task is that participants have to resolve interference in that they frequently encounter so-called "lure" trials. For example, a stimulus that appeared three or one items back during a 2-back task is considered a lure. Going back to our earlier example of a 2-back task, L-K-P-**K**-F-R-*K*-**R**-*R*, the third K as well as the third R are lure trials (indicated in italics for illustration purposes). That is, those are items that were presented three and/or one positions back in the sequence rather than the required two back, and thus, they promote a sense of familiarity that participants have to suppress.

Due to the restricted set of unique stimuli that we have been using in our task versions (6 or 8), lure trials are a frequent occurrence, and thus, the participants are required to resolve interference and resist distraction while doing the task. It is conceivable that the participants' ability to resolve interference is strengthened by our form of training, which in turn, might be responsible for the transfer to other domains that require interference resolution, such as matrix reasoning. Indeed, in matrix reasoning tasks, such as Ravens, participants have to discriminate between target patterns and patterns that are quite similar but are missing one or two important components of the correct solution. In addition to pattern discrimination, the Ravens task also requires participants to discriminate between current rules and rules that are no longer relevant. Thus, as in the n-back task, performing well in Ravens requires resisting distraction and interference resolution [36, 168]. This hypothesis is further strengthened by previous findings showing that individual differences in Gf are predicted by lure interference in n-back tasks [54, 87]. More direct evidence for such a model comes from recent intervention work showing that training on an n-back task with a controlled (and high) number of lure trials predicted performance on a reading task which explicitly required interference resolution (i.e. decoding garden path sentences), a result which was not present in a group that trained on an n-back task without lures [111]. Another issue that might drive the generalization effect is the ability for sustained attention and response inhibition, both of which are presumably involved in successful n-back performance. Consistent with this notion, we have repeatedly found robust training-related improvements in n-back lure trials, in addition to sustained attention and response inhibition tasks such as the continuous performance test (CPT) in both typically developing children as well as children with ADHD [75].

Of course, there might be other underlying cognitive mechanisms that drive transfer from n-back to higher cognitive functions. The two potential mechanisms might not be the only mechanisms driving transfer, but they are the ones that we are currently exploring in our ongoing research. Additional research from other groups will hopefully contribute to shed more light on the underlying cognitive mechanisms of transfer and ultimately provide models that can be used to further refine the existing interventions.

6 Neural Mechanisms

Another path to investigate underlying mechanisms of WM training is provided by the field of neuroscience using various methods. It is currently assumed that chances for transfer increase if the training task activates identical or at least comparable brain areas as the transfer task, which is a similar assumption as the one discussed in the previous section concerning cognitive mechanisms. And indeed, it has been demonstrated that transfer occurs if the training and the transfer task engage overlapping brain regions, but not if the training and transfer task engage different brain regions [34].

In terms of quantitative brain activation changes as a result of WM training, there are currently different hypotheses concerning the direction of the effects (cf. [21]). For example, it is conceivable that the same brain areas are active before and after training, but as a result of the intervention, there is *less* activation in these areas after training which suggests an increase in neural efficiency. Another possible outcome is that the same brain areas are active as well, but now there is *more* activation after training, suggesting that the brain cells are now working harder. A third possibility is a combination of these two potential effects, i.e., a simultaneous increase and decrease of activations, which could vary by brain region. Such an outcome could reflect practice-related changes in cortical representations in task-related areas resulting in an activation increase in those areas, whereas activation decreases in other brain areas that serve more general processes such as attentional control could reflect more automatic and more efficient processing. Another and last potential outcome is that as a result of training, old and new brain areas are active, suggesting that the training induced new ways to deal with a task, for example by developing new task-related strategies. An excellent discussion of these hypothesized effects can be found in Kelly et al. [88].

To date, there are only a handful of published studies that examined activation changes as a result of n-back training [23, 60, 132, 133, 135]. These studies seem to provide converging evidence in two ways. First, n-back training leads to activation changes mainly in prefrontal and also parietal brain regions (especially right Brodmann areas 40, 6 and 9); regions that are assumed as being part of the WM network as well as in reasoning and attentional control. Second, activations seem to increase in the beginning of the training, i.e., when the training task is still fairly new to participants (for example, in the first 1–2 weeks of training), but they decrease with prolonged training (for example in the final 3–4 weeks of training). This pattern suggests that at the beginning of training, the brain has to work harder to cope with the task demands, but with increased time on task, the neural processing becomes more efficient [23].

Besides investigating activation changes with fMRI methods, researchers have also been investigating other neural correlates of cognitive training, such as changes in functional connectivity (e.g. [96]), volume changes in gray matter (e.g. [154]), changes in fiber tracts via diffusion tensor imaging (DTI) (e.g. [153]), changes in dopaminergic functions (e.g. [103]), or even the effects of certain genotypes or polymorphisms on training outcome (e.g. [12, 19]).

Despite the emerging literature, there are still relatively few studies available that use neuroscience methods to get at the underlying mechanisms of WM training. Additionally, the training and transfer tasks used in these studies vary considerably, and therefore, the current result patterns are still rather inconclusive (cf. [21, 68, 80] for recent reviews). Further research is clearly needed to elucidate the neural correlates of training, but we see neuroimaging as an invaluable approach to deepen our understanding of the underlying mechanisms of WM training and transfer.

7 How Can We Make Training Effective? Issues for Future Research

What are the critical conditions that have to be met in order for training to be successful? Apart from further investigating the underlying mechanisms of training and transfer, there are other factors that will deserve the attention of future research. We have already discussed the importance of targeting WM and related processes as underlying mechanism for complex cognition, and further, we have outlined the beneficial effects of targeting multiple processes during training as it will increase the chances for process and neural network overlap, and as such, the chances for transfer. But there are also other factors that might be important for transfer to occur, and we will outline a few of those factors in the following.

7.1 Minimizing Strategy Use and Maximizing Variability

As outlined above, our intervention approach can be described as 'process-specific', that is, rather than improving a strategy or practicing a specific task to perfection, it has been our aim to improve the underlying processing system, and in particular, WM skills [100]. That is, we have argued that in order to obtain transfer, the intervention should minimize the development of explicit strategies and skills that are specific to the task in question. Indeed, it has been shown that strategy training usually only leads to very narrow transfer ([44, 108, 109], but see [24, 145]).

A related principle is that there should be variability during training so that individuals may develop more flexible ways to approach the task in contrast to developing strategies that are only applicable to one training task [52, 130]. For example, participants could be exposed to different tasks in different contexts in order to maximize transfer. This principle may account for some of the success of intervention studies that rely on batteries of tasks as training interventions (such as [13, 93, 102, 131, 160]), however, as discussed above, this kitchen-sink approach is not ideal from an experimental point of view.

Another approach to induce task variability within the same task is to incorporate various difficulty levels [71, 73, 77], as well as varying material and contexts within the same training task [74]. This can be achieved by implementing an adaptive training method that adjusts the training difficulty to the performance of each subject (see [156] for a pioneering study). This principle adds to the motivational features of the task by keeping it constantly challenging across the entire intervention period. The balance of task engagement and challenge of this principle may be important for training success. That is, the goal of our adaptive procedure has been to make sure that the task is not too easy for participants in order to avoid repeated practice and automaticity, which would trigger the development of specific strategies, and further, it has been our aim to prevent participants from becoming bored with the task. But on the other hand, we make sure that the task is not becoming too difficult either, in order to prevent that participants are overwhelmed and become discouraged and lose motivation to train. Indeed, studies that have not used adaptive training programs failed to show transfer (cf. [92, 93]—control groups, [33, 97]).

7.2 Distribution of Training

Another open question concerns the optimal scheduling and duration of training. We and others have shown that there is a dose–response effect of training in which larger transfer effects occur with longer training time [9, 35, 71, 146]. Interventions that last about a month are most frequently used, although there are shorter WM interventions that have proved to be beneficial as well (e.g. [16, 99, 176]). Overall, the optimal duration and spacing of a successful intervention is still largely unknown, and to our knowledge, there are no studies to date that have investigated the role of spacing and frequency of WM training, although the role of spacing has been extensively investigated in the domain of skill acquisition and learning (see e.g. [27, 27], for reviews).

7.3 Motivation

It makes intuitive sense that motivation should play an important role in any kind of training. For example, let us consider we wanted to get in better cardiovascular shape. In order to substantially improve our fitness level, it is not enough to just walk, we actually have to run. We believe that the same principle applies to cognitive training as well. Thus, if you do not want to engage and get better, you will likely not improve as much as someone who puts a lot of effort into training. As we discussed before, both training quantity and quality are important. Only children who improve in the training task demonstrate transfer [74], and transfer increases with increasing training time [9, 35, 71, 146]. Therefore, intrinsic motivation and persistence is necessary in order to achieve a high quality of training over a long period of time. One of the challenges for intervention developers is to design the tasks so that the participants remain interested and motivated to stay engaged for more than one session. However, the development of motivational features is not an easy endeavor, as we want to avoid participants to be motivated only by extrinsic factors, which ultimately, is detrimental for performance [39, 77].

In a similar vein, self-efficacy beliefs and beliefs in the malleability of intelligence seem important for training success [77]. Previous research found that individuals who believe that intelligence is fixed are more likely to disengage and withdraw from tasks that are perceived as being too challenging. In contrast, individuals with a malleable mindset about intelligence are more likely to pull through challenging tasks (e.g. [15], see also [42]).

7.4 The Role of Age and Individual Differences

Transfer effects following WM training have been observed over a wide population range, from typically developing preschoolers (e.g. [13, 160]), school-aged children (e.g. [74, 99, 175]), to young adults (e.g. [29, 71, 73, 77, 147]), and older adults (e.g. [16, 22, 34, 97, 131, 146, 176]). Further, there is evidence that WM training is also effective in special-needs populations with pre-existing WM deficits, such as ADHD (e.g. [65, 93]), learning disabilities (e.g. [64, 124, 164]), Cochlear Implant users [95], and Schizophrenia [102]. The question is whether there is a particular population for whom the training might work best (cf. [20, 74]). For example, it seems harder to demonstrate transfer in older than young adults, and furthermore, there are even differences within old age in that the effect sizes decrease as a function of age [17, 34, 97, 131, 176]. Age-related limitations in plasticity might be a restricting factor for training and transfer. Consequently, it might be that transfer is more likely in younger adults and children [47], and also for those participants who are still highly functioning (cf. [165]). However, the successful training studies with special needs populations and children with WM deficits have thus far suggested otherwise, and further, our own and other groups' research has shown that it is usually those individuals who start off with the lowest scores who profit the most, presumably because they have more room to improve [71, 74, 146, 163, 176]. Those findings are of particular interest when it comes to the application of this line of work in older adults. What we have to consider is that even though there is reduced plasticity in old age, it does not mean that the brain and cognition are not malleable after a certain age. As has been shown in various studies now, there is ample evidence that it is still possible to improve cognition in old age, and that those improvements are maintained over several years, and a lot of this evidence comes from the ACTIVE study ([171], e.g. [81]). Nonetheless, the differential training and transfer effects that are observed across age groups can serve as a model to study developmental trajectories and further inform the design of targeted interventions that can be modified to reach specific age groups [68].

In addition to age and pre-existing ability, there might be other factors that drive training success, such as personality, need for cognition, and beliefs in the malleability of intelligence (e.g. [77, 150]). To conclude, the issue of individual differences and training has been largely overlooked until very recently [137].

8 How Broad Is the Transfer?

Unfortunately, to date, there is minimal evidence that WM training extends beyond laboratory tasks to direct measures of scholastic achievement or real-world outcomes. Nonetheless, there are notable exceptions in important clinical domains related to executive control, such as symptom reductions in ADHD, alcohol abuse, or psychosocial functioning in schizophrenia (e.g. [10, 66, 92, 93, 102, 124]).

Furthermore, there is evidence for improved reading skills in typically developing children and adults [29, 46, 99, 111], and there are studies that have demonstrated improvements in scholastic achievement after training on WM or attentional skills involving executive control [63, 89, 138, 172], or, finally, there are reports demonstrating improvements in daily living activities in older adults [122, 171]. Nonetheless, such reports are still rare, and future research will have to further determine the real-life applications of brain training. Translating WM training from the laboratory into the real world, for example by bringing it into the classroom and by assessing its efficacy with measures of scholastic achievement will be a challenging undertaking: The application in classroom settings will come with unique problems and will certainly have an impact on training quality and fidelity, which are among the key issues for transfer to occur [77]. But as others have shown, this endeavor is not impossible [63].

9 How Long Do the Effects Last?

Unfortunately, we still do not know whether transfer effects last beyond the training period, and if so, for how long. Only a handful of studies have tested the long-term effects of training by re-testing the experimental and control groups several months or even years after training completion [16, 22, 74, 93, 122, 164, 171, 176]. The few studies that have looked into this issue provide encouraging evidence that some of the effects are long lasting. More difficult to interpret are a set of studies that found transfer effects only at follow-up several months after training completion while there were no effects at post-test right at the end of the intervention [64, 164]. The mechanisms of such effects have been described as "sleeper effects", although it is not clear how they arise and further research in needed to elucidate this issue. It has been argued that transfer might be maintained or even increased by cascading effects, for example by improved self-efficacy beliefs, which are then applicable in various situations [59, 91]. On the other hand, if we assume that WM training processes are comparable to processes that occur with cardiovascular training, the longevity of the effects will probably be limited: If you stop running on a regular basis, your fitness levels will dissipate quicker than one might hope. Therefore, a potential approach to maximize long-term retention is to include booster sessions after training completion (e.g. [7, 11, 26, 58, 167]). However, future research will have to determine the frequency and duration of such booster session in order to maximize retention effects.

10 Could There Be Negative Effects of Training?

Given the many positive effects that might accompany WM training, there is a legitimate question of whether there are any downsides of training WM skills as well. One could argue that WM training might take away precious time from other important activities, such as physical exercise, socializing with your friends, or practicing your musical instrument. And of course, it will be certainly more efficient to just sit down and study your multiplication table or study for the LSAT instead of training WM, and we are by no means suggesting that n-back training should *replace* any of those approaches. But on the other hand, if WM training is used *in addition* to those activities, it might be indeed a valuable endeavor to facilitate learning, and in our various approaches, our daily training time has been limited to as little as 10 min a day [74]; hardly a significant time investment even if it would turn out not to be working for an individual, which is of course always a possibility. Another downside might be the cost of some of the marketed products, that is, training WM might come with a significant financial investment. Nonetheless, there are many free or very affordable alternatives available either online or as applications.[2]

Other potential downsides have been suggested as well, for example, whether improving cognitive control could potentially reduce performance of other functions that require *less* cognitive control, such as creativity or early language development [68]. As discussed above, there are developmental periods that might have to be taken into consideration as which might influence training efficacy, however, at the current stage of research, very little is known about those issues, and so far, we are not aware of any detrimental effects of WM training on cognition.

11 Conclusion

In sum, current research indicates that there is good reason to conclude that training WM skills can be beneficial, not only to improve WM skills themselves, but also to improve skills that rely on the integrity of WM functions, such as attentional control, language-related abilities, Gf, or scholastic achievement. Nonetheless, there are many open questions when it comes to the underlying mechanisms of transfer, as well as the extent of transfer and the longevity of the effects. Furthermore, there have been some concerns regarding the effect sizes and replicability of far transfer effects. Thus, one of the foremost goals of future research should be to shed light on those issues by systematically exploring the underlying mechanisms and determining the variables that make an intervention most effective, as well as disentangling the mediators (*why* participants benefit) and moderators (*who* might benefit) of training and transfer. Furthermore, it is still an open question to what extent WM training affects measures of academic achievement and daily life.

It is important to note that we are not suggesting that there is anything "magical" about WM training, that is, it requires hard work and engagement from both, participants and researchers in order to be effective. To reiterate our analogy

[2]Note that we are neither supporting nor endorsing any of the marketed products. The software that we developed in our laboratory and that is described in published articles is freely available for research purposes.

from physical training, it is certainly not enough to leisurely stroll to improve cardiovascular fitness, but rather, you have to run and challenge yourself. We think that the same is true in the domain of WM and general cognitive function.

Finally, we would like to emphasize that we do not want to imply that WM training is the only approach to improve cognition. WM training has been serving as our model to explore near and far transfer effects, as well as to determine the relationship between WM and higher cognitive function. That said, there are certainly other approaches that are just as valuable. While education seems to be by far the most effective approach to improve cognitive ability (cf. [69]), there are other interventions that might serve as supplement to boost and/or maintain cognitive function, either separately, or in combination with other approaches (cf. also [41]). Examples for such approaches are cognitive enrichment and stimulation [45, 61, 106, 110, 115, 148, 162], musical training [107, 129], physical exercise [31], mediation [79, 157], social interaction [174], but also nutrition [51], or pharmacological interventions [149]. To conclude, WM training is one of many approaches that could be used to improve cognitive function. There is certainly no one-size-fits-it-all approach in the domain of cognitive improvement, and future research will hopefully shed more light on what interventions work best for which individual, and under which particular circumstances.

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