# Cognitive and Working Memory Training

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# Training Working Memory for 100 Days

## The COGITO Study

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This chapter is based on the theoretical framework for the study of adult cognitive plasticity by Lövdén, Bäckman, Lindenberger, Schaefer, and Schmiedek (2010) and on empirical findings from the COGITO Study (Schmiedek, Lövdén, & Lindenberger, 2010), conducted at the Max Planck Institute for Human Development. In the study, 101 younger and 103 older adults practiced a battery of working memory (WM), episodic memory, and perceptual speed tasks for 100 sessions. The design and analyses of the study include key features for producing and detecting transfer effects at the level of cognitive abilities. Among the features are: (a) an intensity and dosage of training that is likely to induce an enduring mismatch between functional supply and demand, which is conducive to plastic changes in cognitive abilities, and (b) a multivariate and heterogeneous battery of transfer tasks and sufficiently large samples to allow for the investigation of transfer of training at the level of latent factors. Younger adults showed short-term and long-term transfer effects for reasoning and episodic memory, whereas older adults showed only short-term transfer on a WM latent factor composed of tasks that resembled the practiced tasks, something that younger adults did as well. The chapter covers possible interpretations of the findings in terms of increases in WM capacity, improvements in the efficiency of material-independent or material-specific processes or strategies, and improvements in motivation and self-concept.

### Question 1: Theory of Working Memory Training

In a nutshell, WM is a system for keeping all sorts of content active in memory and organizing the processing of the content. Rather than assuming that this system has a fixed (traitlike) capacity (which training then would have to try to increase), we think that the WM system, in addition to capacitylike aspects, involves mechanisms that can work more or less efficiently and reliably, with the efficiency being subject to both traitlike and statelike variability and potentially also being amenable to improvements through practice.

Our view on WM is guided by concentric models of its architecture (Cowan, 1995; Oberauer, 2002) and by a focus on mechanisms of creating, maintaining, updating, and releasing bindings of different kinds of information (e.g., objects to spatial positions; Oberauer, 2005; Treisman & Gelade, 1980; Zimmer, Mecklinger, & Lindenberger, 2006). Furthermore, we consider models from computational neuroscience that aim to explain the conflicting modes of stability (of contents to be held in WM) and flexibility (of replacing contents and task sets in WM) as important (Cools & D'Esposito, 2011; Durstewitz & Seamans, 2008). Neuroscience models of selective updating (Frank, Loughry, & O'Reilly, 2001) are also relevant in this regard. Regarding our theoretical view on the plasticity of WM, we apply the general framework for the study of adult cognitive plasticity proposed by Lövdén et al. (2010).

Concentric models, such as those of Cowan (1995) and Oberauer (2002), conceive of WM as an activated part of long-term memory, with activated elements being directly accessible for cognitive processing (i.e., the region of direct access). The processing of elements requires that they be put in the focus of attention. Whether this focus can hold more than one element (or chunk of elements) at a time has been questioned (Oberauer & Bialkova, 2009) and so has the claim that training can enlarge the size of the focus (see Oberauer, 2006 and Verhaeghen, Cerella, & Basak, 2004, for opposing evidence).

A fixed-size focus of attention as well as a (possibly) immutable region of direct access do not preclude the possibility, however, that WM processes can gain efficiency with practice, thereby leading to improved performance (von Bastian & Oberauer, 2014). On the one hand, those processes might include basic cognitive processes like switching the focus of attention (Dorbath, Hasselhorn, & Titz, 2011) and component processes of updating information in WM (e.g., transformation, substitution, and retrieval; see Ecker, Lewandowsy, & Oberauer, 2014; Ecker, Lewandowsky, Oberauer, & Chee, 2010) that are relatively independent of the specific material being processed. On the other hand, efficiency might also improve in ways that are more specific to the particular material of the practiced task. This might be due to the use of strategies that work only for specific content (e.g., visualization of nouns) or due to material-specific automatization.

We supplement this view of WM with models from cognitive and computational neuroscience. Here we consider an attention function (of the lateral prefrontal cortex) that deals with active maintenance of content-unspecific (e.g., goal- and context-related) variables that serve to bind together distributed, capacity-limited, and content-specific internal representations that are held active in sensory cortices (Luck & Vogel, 2013; Sreenivasan, Curtis, & D'Esposito, 2014; Unsworth, Fukuda, Awh, & Vogel, 2014, 2015). This function, which serves the focus of attention, must, when faced with internal and external distraction, balance the demands of maintaining the focus of attention (i.e., stability) while also allowing rapid shifting (i.e., flexibility) of focus when needed (Cools & D'Esposito, 2011; Durstewitz & Seamans, 2008). Selective updating (not necessarily complete shifting) of parts of the focus of attention may occur through gating mechanisms (in striatal-prefrontal cortex interactions; Frank et al., 2001). We view WM training as potentially affecting the efficiency of these processes, without necessarily affecting any WM capacity per se. For example, achieving optimal tuning of the balance between stability and flexibility may be more beneficial for cognitive performance (Cools & D'Esposito, 2011). Rapid selective updating may be a partly content-unspecific neural process (Dahlin, Neely, Larsson, Bäckman, & Nyberg, 2008; D'Ardenne et al., 2012). Finally, the binding and biasing aspect of focusing attention may be critically dependent on reliable functional and structural large-scale brain connectivity, which is modifiable by cognitive training (Anguera et al., 2013; Lövdén, Bodammer, et al., 2010).

Regarding gains in material-specific efficiency, ample evidence exists that practice can improve the speed and accuracy of any basic cognitive decision or transformation process that is not yet fully overlearned (i.e., asymptotic performance levels have been reached). For example, most people will show practice-related improvements on an alpha span task simply because, before training, they are not at the asymptotes of their learning curves regarding the skill of quickly sorting words alphabetically. While such practice effects may lead to increases in the observable capacity specific to the alpha span (i.e., the set size of words that can reliably be processed), they should have no effect on WM tasks that do not involve this particular skill.

Generally, the basis for our concept of cognitive plasticity, and thus one of the backgrounds to our design of training studies, is a distinction of plastic changes from changes based on behavioral flexibility (Lövdén, Bäckman, et al., 2010). The human cognitive system generally exhibits an impressive amount of flexibility in adapting to changing environmental demands. When confronted with new WM tasks, for example, existing skills and available strategies can be explored and adapted to the task. This includes strategic choices of goal settings (e.g., trying to remember only a part of a presented memory list; Shing, Schmiedek, Lövdén, & Lindenberger, 2012), prioritization of subtasks (e.g., the primary task at the cost of the secondary task in complex span paradigms), speed–accuracy trade-off settings, the employment of verbalization and visualization strategies (Hertzog, Lövdén, Lindenberger, & Schmiedek, 2017), and more.

Such exploitation of behavioral flexibility can potentially lead to considerable improvements in performance. We distinguish such changes from plastic changes of the cognitive system by defining *plasticity* as the capacity for reactive change in the presence of an enduring mismatch between the demands confronting the cognitive system and the supply it is able to offer (Lövdén, Bäckman, et al., 2010). The defining characteristic of plastic changes is a widening of the range of behavioral flexibility itself. That is, we consider training-related changes in cognitive performance to be indicative of plasticity only if an increased functional supply allows for new or more difficult tasks to be dealt with. Of crucial importance is the proposition that only a considerable mismatch of demand and supply that endures for an extended time should be able to lead to such plastic changes.

Several characteristics that we think are essential for successful training programs follow from this. First, training should contain several tasks that differ in paradigm and content, to reduce the likelihood of successfully working on them using a limited number of strategies contained in the toolbox of behavioral flexibility. For the same reason, we even see advantages in changing or adding tasks during the course of training. Second, task difficulty should be dynamically adapted to each individual's performance level to keep up the mismatch of supply and demand. Third, training duration needs to be extensive. We consider it unlikely that a cumulated training time of a few hours (e.g., one week of daily practice for one hour each day) will lead to the kind of changes at the neuronal level that constitute plasticity.

In sum, we think that extended practice on diverse and challenging WM tasks can lead to improvements in the efficiency of creating, maintaining, updating, and releasing bindings and the corresponding interplay of stability and flexibility of cognitive representations in WM. To exclude the possibility that observed improvements in performance can be interpreted as manifestations of behavioral flexibility, it is of great importance to demonstrate the emergence of plastic changes. This can be achieved by showing improvements on transfer tasks that minimize the likelihood of improvements based on the application of strategies and skills specific to the practiced tasks, or general improvements in motivation and/or self-concept.

## Question 2: Major Claims of Working Memory Training

Earlier cognitive intervention work at the Max Planck Institute for Human Development has shown that instruction and practice of certain strategies (e.g., mnemonic techniques like the method of loci) can lead to considerable improvements of performance in episodic memory tasks in both younger and older adults (Baltes & Kliegl, 1992). Also, improvements in performance on fluid intelligence tasks due to practice were shown (Ball et al., 2002; Baltes, Dittmann-Kohli, & Kliegl, 1986). Common to these training studies, however, was the finding that the effects were highly task-specific, that is, the effects did not show transfer beyond the paradigms that were part of the training (for a review of this work, see Baltes & Lindenberger, 1988). Therefore, the improvements have to be considered to be largely manifestations of behavioral flexibility.

In a first attempt to evaluate to effectiveness of WM training (Li et al., 2008), 19 younger adults (age 20–30 years) and 21 older adults (age 70–80 years) practiced two versions of a spatial 2-back task in 45 practice sessions, which led to transfer to spatial 3-back and numerical 2-back tasks. The results indicated that specific updating mechanisms could be improved independently from the content of the tasks. Whether the improvements also led to improvements at the level of more general factors of WM or fluid intelligence, however, could not be investigated with the small samples in the study.

The COGITO Study, which was designed with a focus on investigating day-to-day fluctuations in cognitive performance (Schmiedek, Lövdén, & Lindenberger, 2013), implemented several of the features discussed above as being relevant for plastic changes of WM. Compared to the training in the study by Li et al. (2008), the training was more diverse, more extensive, and better tailored to individual performance levels. Diversity was ensured by including three WM tasks that differed in paradigm as well as in content (figural-spatial, 3-back; verbal, alpha span; and numerical, memory updating) together with three episodic memory tasks and a total of six perceptual speed tasks (three comparison and three two-choice reaction tasks). The inclusion of non-WM tasks potentially served two beneficial purposes in the service of improving the effectiveness of the WM training. First, diversity of abilities required by the tasks can make a training program more varied and motivating. Second, episodic memory tasks especially might also train binding mechanisms that are recruited by WM.

Training was extensive, with a total duration of 100 training sessions, each lasting for 45 minutes to one hour. Task difficulty was individualized by setting presentation times of the WM and episodic memory tasks and masking times of the three choice-reaction time tasks of perceptual speed to appropriate levels based on individual pretest performance (see Schmiedek et al., 2010). The levels were chosen in a way to keep participants' performance from both floor and ceiling across the 100 training sessions. This worked quite well for most of the participants. In fact, average learning curves for the WM tasks (as well as the episodic memory tasks) indicated that training gains did not reach an asymptote within 100 training sessions but continued to show small but steady improvements until the very end of the observation period.

Transfer effects were assessed at the latent factor level. To this end, comprehensive transfer batteries were included in extensive pretest and posttest sessions. The sessions contained three WM tasks based on the same paradigms as the trained ones but with different task content. This included numerical 3-back, spatial memory updating, and animal span (i.e., sorting animals according to size), three complex span WM tasks, nine tasks each of reasoning, episodic memory, perceptual speed from the Berlin Intelligence Structure Test (Jäger, Süß, & Beauducel, 1997), a paired associates test, and Raven's matrices.

This allowed us to create measurement models for factors of WM updating, WM complex span, and the broad abilities of reasoning, episodic memory, and perceptual speed. In addition, the sample sizes for both younger adults (101 in the training group and 44 in the no-training control group) and older adults (103 in the training group and 39 in the no-training control group) were large enough to allow for structural equation modeling and the investigation of transfer effects at the latent factor level using latent change score models (McArdle, 2009).

Results at the observed task level were mixed, with several tasks (or task parcels) of WM, reasoning, and episodic memory showing significant interactions of occasion and group in the younger and older groups (see Figure 3.1; Schmiedek et al., 2010). More importantly, results from latent change score models demonstrated significant transfer at the latent ability factor level for the near WM factor (i.e., of tasks based on the same paradigms as the trained ones) for both younger and older adults and also for reasoning and episodic memory

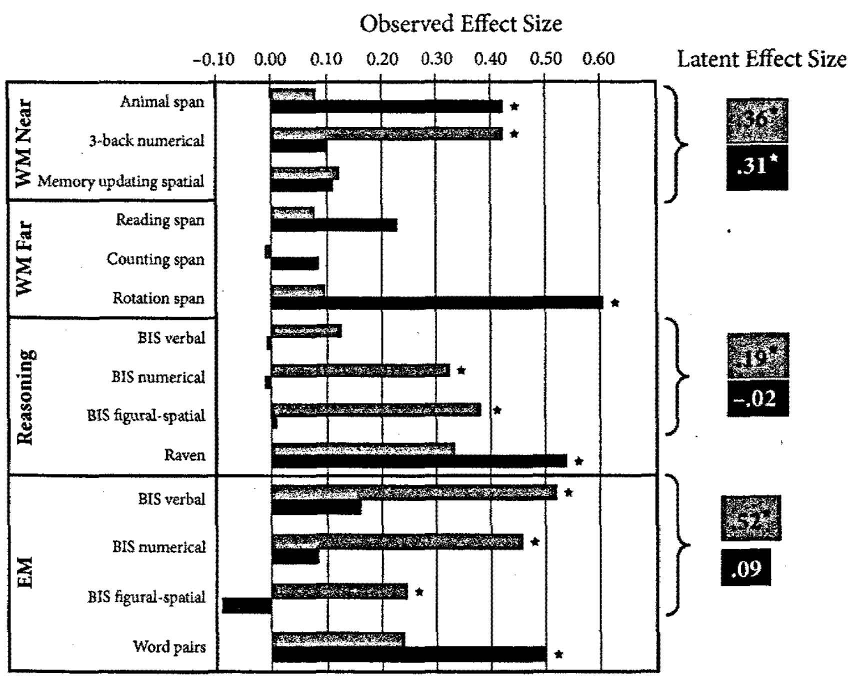


**Figure 3.1.** Observed and latent net effect sizes of performance gains from pretest for WM, reasoning, and episodic memory (EM). Bars show net effect sizes (standardized changes in the experimental group minus standardized changes in the control group), separately for younger adults (gray bars) and older adults (black bars). Statistically significant net effect sizes correspond to reliable interactions (*: $p < .05$) between group (experimental vs. control) and occasion (pretest vs. posttest). Reproduced from Schmiedek et al. (2010).

for the younger adults (Schmiedek et al., 2010). Furthermore, analyses of individual differences in training and transfer effects showed ability-specific relations of corresponding factors of practiced and transfer tasks for WM and episodic memory. This renders general motivational effects less likely and strengthens an interpretation of the effects being located at the level of broad abilities. This is important, especially considering that the control group was not active.

Using data from a two-year follow-up study, which repeated the posttest assessment, we could further investigate whether the effects for the latent ability factors of reasoning and episodic memory were maintained over an extended period of time for the group of younger adults. Latent change score models for the participants who returned for follow-up sessions (80 in the training group and 32 in the control group) indicated that there were reliable long-term effects for both broad abilities (see Figure 3.2; Schmiedek, Lövdén, & Lindenberger, 2014a). Comparisons of self-reported motivation to work on the tasks from both groups on the different occasions did not provide any evidence for motivational factors' being responsible for these effects.

In sum, the latent change score analyses of the COGITO Study data have provided evidence that extensive training with a challenging task battery that includes several WM tasks based on different paradigms can produce transfer effects that, while not necessarily being strong in terms of conventional evaluation of effect sizes, have the breadth as well as the duration that renders them potentially beneficial for everyday cognitive functioning. We attribute the fact that we found effects at the latent ability level not to the superiority of our particular choice of tasks (many other WM updating tasks could serve as well), but to the amount of time the cognitive systems of our participants were put in a condition of mismatch between supply and demand. Still, the training program implemented in COGITO likely could be improved if larger effectiveness and efficiency were the goal. First, some of the perceptual speed tasks could be substituted with additional WM tasks of still different paradigms. Second, task difficulty could be adapted dynamically for each participant.

We do not see our main contribution to the field of cognitive training research as the development of a task battery of particular advantage over other training that focuses on WM updating. Instead, we hope to have provided convincing arguments for the importance of implementing training programs with sufficient dosage and of evaluating training effectiveness with appropriate methods.

## Question 3: Methodological Issues

We are not contesting the benefits of randomization in evaluation research; rather, we think that the question of which control conditions are used might be

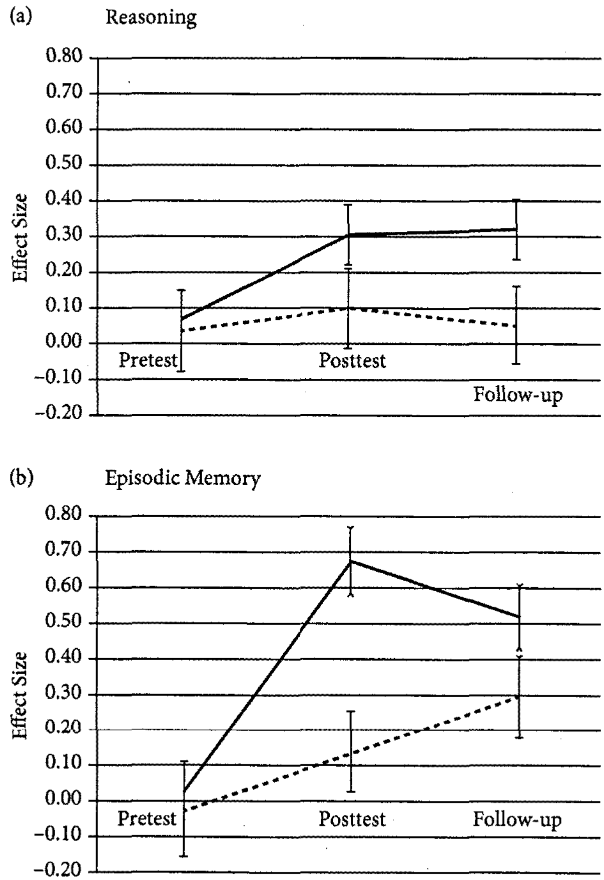


**Figure 3.2.** Latent means and associated standard errors for the training and control groups at pretest, posttest, and follow-up. Training group shown with solid lines, control with dashed lines. (a) latent factor of reasoning; (b) latent factor of episodic memory. As the indicator tasks of the latent factors were standardized by SDs at pretest, latent means are in effect size metric. Reproduced from Schmiedek et al. (2014).

more important than how participants get into the different conditions. When important aspects like motivation and subjective evaluation of the potential benefit of the training are equated across experimental conditions, the danger of participants' selecting themselves into treatment conditions in ways that confound treatment effects with pretraining ability may be minimized even in the absence of randomized assignment to groups. Conversely, perfect randomization of participants into groups may not allow answering the question about whether plastic changes have occurred if the control condition is less motivating or less able to foster a self-concept regarding cognitive ability than the condition of the target training.

Regarding the question of the mechanisms of training and transfer effects, it can be as important to show the limits of transfer effects as it can be to show their breadth. To exclude the possibility that, for example, increased motivation or self-concept is responsible for presumed improvements in cognitive resources, it might be helpful to define ability factors that should not show transfer effects. Ideally, theoretical models of the mechanisms of transfer allow for prediction of patterns of present and absent transfer to support the convergent and discriminant validity of the training effects. Such an approach has been used in an exemplary way by von Bastian and Oberauer (2013), who tested predictions of a cognitive process model by comparing transfer at the latent factor level for different target constructs across training conditions that focused on storage and processing, relational integration, and supervision as a theoretically defined functional category of WM.

Testing the predictions empirically can most convincingly be done based on latent factors for the constructs that define the convergent and discriminant relations (Noack, Lövdén, & Schmiedek, 2014). The proof of cognitive training's effectiveness is transfer to cognitive abilities relevant to competence in everyday life, including educational or job achievement. Regarding scientific approaches to demonstrate transfer, we hold critical views on two commonly applied practices, namely the use of single transfer tasks per ability and the attempt to classify those into ordinal categories of transfer distance (e.g., near versus far). First, we think that it does not suffice to demonstrate improvements attributable to training (e.g., by means of a control group design) in single tasks that are thought to measure the targeted ability. Abilities can never be directly measured by single tasks, because the latter always contain variance due to measurement error and task-specific processes and skills. Showing training-related improvements on a single task will always leave open the question of whether the improvements can really be attributed to improvements in the latent (i.e., not directly observable) ability or if they are due to improvements of task-specific skills, the acquisition of task-specific strategies, and the like.

Second, we think that the common practice of attempting to classify transfer tasks as indicating near or far transfer is not fruitful for research on cognitive interventions because it seems close to impossible to agree on definitions of those classifications. What one group of researchers considers far transfer might be near transfer from the theoretical perspective of another group. In our view, the problems associated with investigating transfer based on target abilities classified as near or far and operationalized by single tasks can and should be overcome by approaches that take theory and empirical knowledge regarding the structural relations among the trained and transfer tasks into account. Preferably, we should aim to demonstrate transfer at the level of latent factors, with the definition of factors and the choice of tasks determined by established hierarchical models of cognitive abilities (Lövdén, Bäckman, et al., 2010; Noack, Lövdén, Schmiedek, & Lindenberger, 2009).

With the aim of interpreting such structural relations among tasks within a theoretical frame, models like the three-stratum model of Carroll (1993) can serve to replace arbitrary classifications as near versus far with classifications of transfer "at the level of" narrow, broad, or general abilities, thereby providing a common ground for the communication and evaluation of transfer effects. Demonstrating transfer at the level of the broad ability of fluid intelligence, for example, would then require showing improvements at the level of a latent factor that is operationalized with several heterogeneous tasks (i.e., differing in paradigm and/or content).

The tasks should psychometrically be good indicators of fluid intelligence and be sampled from the construct space of this broad cognitive ability in a way that the space is broadly covered (Little, Lindenberger, & Nesselroade, 1999). If, for instance, only tasks of figural-spatial induction were used (e.g., figural analogies, figural series, and figural matrices), then possible improvements of the factor that represents their common variance cannot unambiguously be interpreted as improvements of fluid intelligence, because effects might be constrained to a narrower factor of figural inductive reasoning, which is nested in the fluid intelligence factor.

The correlational associations between training and transfer tasks also permit the formulation of expectations about the size of transfer effects (McArdle & Prindle, 2008). Specifically, based on the observed correlation between the trained task (or trained ability construct) and the transfer task (or transfer ability construct) at pretest and the effect size of gains on the trained task (or trained ability construct), one can compute the expected effect size of gains on the transfer task (or transfer ability construct) under the assumption that training gains reflect unbiased improvements in the ability targeted by the transfer task (or transfer ability construct; cf. Lawley, 1943; Pearson, 1903). If the observed transfer effect falls below this expectation, as Rode, Robson, Purviance, Geary, and Mayr (2014) found when training WM in school-age children, then this means that improvements on the trained tasks were biased toward factors that are unrelated to the cognitive ability targeted by the transfer task (or transfer ability construct). It would be desirable for researchers to routinely compare the magnitude of observed transfer effects against this expectation.

Some commercial cognitive training programs seem to promise improvements at the level of general cognitive ability, which comprises broad cognitive abilities like reasoning, episodic memory, and perceptual speed. Such effects, in our view, would have to be demonstrated by showing training-related changes of a latent factor at the top of a hierarchy of a considerable number of factors that are each based on a comprehensive assessment battery of tasks. Such general effects are not necessary for a training to be evaluated as effective, however, because improvements even in narrow abilities might be of sufficient practical relevance. It is important, though, that the true scope of WM training's effectiveness be determined by locating transfer in hierarchical models. Knowing about the validity of established cognitive ability factors regarding real-life outcomes, then, can help in the evaluation of potential training benefits. Certainly, one can also attempt to measure real-life outcomes directly. If this is done with objective tasks that cover a predefined domain of everyday functioning, again, latent factor approaches could be used to test whether the desired general improvements really have been achieved. If the scientific focus is instead on general resource constructs from cognitive psychology, like WM, rather than on psychometric abilities, latent factor approaches and hierarchical structure models can also be readily applied (Miyake et al., 2000; Miyake & Friedman, 2012; Schmiedek, Lövdén, & Lindenberger, 2014b).

Statistically, change at the level of latent ability factors can be investigated with latent change score models (McArdle, 2009; McArdle & Prindle, 2008). This requires measurement models with factor loadings, intercepts, and preferably also residual variance parameters being invariant across occasions (e.g., pretest, posttest, and follow-up in intervention studies). Not being able to show such measurement invariance can be indicative of the presence of task-specific effects (Noack et al., 2014). Careful investigation of this issue should, therefore, not be seen as a nuisance but as an enterprise that is informative about the levels at which transfer effects might take place. It should be noted, however, that the use of confirmatory measurement models in a structural equation modeling framework creates a need for larger samples than provided by many cognitive intervention studies. Because different experimental (e.g., training and control) groups can be analyzed simultaneously, using multigroup structural equation modeling with measurement model parameters constrained to be equal across groups, sample sizes do not necessarily have to be unrealistically large. A review of the training literature indicated that examples of empirical studies that meet the standards of latent change modeling (multiple indicators and a relatively large sample) exist but are the exception rather than the rule (Noack et al., 2014).

## Question 4: Contributions to the Field

Conclusions regarding the understanding of WM based on our studies should be modest. Our studies have contributed a pattern of findings of transfer at the observed and latent factor level that fit well into theoretical perspectives that propose a central role for binding and updating mechanisms in WM and its relation to reasoning (Wilhelm, Hildebrandt, & Oberauer, 2013). The observed pattern is that transfer effects are present at the latent factor level for reasoning and for WM updating tasks of different content than the trained ones, but not for complex span tasks. One can ask whether and how this pattern of findings can be explained in terms of the possible effects of training: (a) increases in WM capacity, (b) improvements in the efficiency of material-independent basic WM processes, (c) improvements of material-specific processes, (d) improvements in more or less material-specific strategies, and (e) improvements in motivation and self-concept.

While we cannot exclude improvements in motivation and self-concept as contributing factors to the transfer effects based on our study design, which included a no-contact control group, the findings on self-reported motivation to work on the training tasks do not give any indication that (changes in) motivation differed between the experimental groups. Furthermore, the explanation of the pattern of transfer effects in terms of motivational factors would necessitate the assumption that motivational effects are less pronounced for complex span tasks.

Improvements in more or less material-specific strategies are likely to contribute to the transfer effects on WM updating tasks with different content. While the applicability of certain cognitive strategies (like visualization) is often tied to specific material and their efficient use requires task-specific adaptations, one can also think of less material-dependent strategies that might help to optimize the aspects of performance that were fed back to our participants and used as dependent measures in our analyses. Such strategies could include the adaptive setting of goals or speed–accuracy trade-offs, which might be applicable to the trained as well as the untrained WM updating tasks (cf. von Bastian & Oberauer, 2014). For example, participants who used a strategy of selectively trying to memorize only a subset of items in the numerical updating task (see Shing et al., 2012, for evidence indicating the presence of such a strategy) might transfer this strategy to the spatial updating task that was included in the transfer battery. It is very unlikely, however, that such strategies could help to improve performance on the reasoning transfer tasks. The potential creativity of people means they may come up with new strategies, and it is impossible to definitely exclude this possibility, but accounts based on strategies that were applied to—and themselves practiced with—the trained WM tasks do not seem to work well as an explanation for the overall pattern of findings.

If we wanted to explain the observed transfer effects on WM updating tasks and on reasoning in terms of an increased capacity of the WM system, we would have to provide an explanation for the lack of transfer to complex span tasks, which serve as well-established measures of this capacity. While ceiling effects of our versions of the complex span tasks for a number of our younger participants might serve as such an explanation, we think that it might also be that WM capacity did not improve in such a way that the WM system could hold more pieces of any kind of information ready for processing after training.

It is more likely that improvements in the efficiency of relatively material-independent basic WM processes underlie the transfer effects to WM updating as well as to reasoning. The processes include the creation, maintenance, updating, and dissolving of bindings that give rise to mental representations needed to do WM updating tasks and that can be argued to be required for successfully solving reasoning tasks of many kinds (Wilhelm et al., 2013). Evidence has been provided that updating processes can be improved by training, possibly due to increased striatal dopamine release (for a review, see Bäckman & Nyberg, 2013). In line with this notion, we have reported findings from the COGITO Study showing that carriers of the Val allele of the COMT polymorphism, who have less dopamine expressed in the prefrontal cortex, performed worse on the WM updating tasks at baseline but showed larger practice gains in these tasks from training than carriers of the Met allele (Bellander et al., 2015).

We relate this result to available evidence indicating that Met carriers perform better than Val carriers in WM tasks mainly taxing maintenance, whereas Val carriers perform better at updating (Bilder, Volavka, Lachman, & Grace, 2004; Colzato, Waszak, Nieuwnhuis, Posthuma, & Hommel, 2010). Val carriers may show larger training gains, because updating operations carry greater potential for plasticity than maintenance operations or because the task demands reward improvements in updating more than improvements in maintenance. Finally, we have reported alterations of the white-matter tracts that connect the left and right hemispheres of the frontal lobes from the COGITO intervention (Lövdén, Bodammer, et al., 2010). Training affected several metrics of white-matter microstructure, as probed with diffusion-tensor imaging, and increased the area of the anterior part of the corpus callosum (i.e., the genu). The alterations were of similar magnitude in younger and older adults. These findings are in line with animal evidence on the activity-dependent regulation of adult myelination (Fields, 2008; Zatorre, Fields, & Johansen-Berg, 2012). In line with evidence on functional connectivity from other groups (Anguera et al., 2013; Chapman et al., 2015), our findings on training-induced change in structural connectivity suggest that the binding and biasing aspect of focusing attention, which critically depends on reliable large-scale connectivity (Wang, 2010), may be malleable through experience.

If such improvements are at the heart of transfer effects to WM and reasoning, why does improved efficiency of updating bindings not benefit individual performance on complex span tasks? This might seem particularly surprising given that latent factors of updating and complex span tasks have been found to be highly, or even perfectly, correlated in untrained samples (Schmiedek, Hildebrandt, Lövdén, Wilhelm, & Lindenberger, 2009; Schmiedek et al., 2014b; Wilhelm et al., 2013). Besides the already mentioned possibility that improvements on complex span tasks might have been constrained to some degree by ceiling effects, we would like to offer another interpretation. Generally, the fact that individual differences in performance on two kinds of paradigms correlate highly in a sample of untrained participants does not imply that improvements on one of the paradigms need to be matched by improvements in the other. It might be that the common variance in complex span and updating tasks before training was largely dominated by individual differences in the capacity of the WM system to reliably hold a limited number of elements active in WM. The extensive practice on WM updating tasks might have increased the efficiency of the WM system in quickly and reliably changing these elements and their associations. The resulting capacity to quickly establish and manipulate complex mental representations might aid successful processing of complex reasoning tasks. It might not be beneficial for performance on complex span tasks, though, with their smaller demand on permanently and flexibly updating mental representations. Improvements on complex span tasks might depend more on the efficient employment of retrieval strategies from secondary (long-term) memory for items that exceed the capacity of primary (short-term) memory (Unsworth & Engle, 2007). Recent evidence suggests that the ability to establish and retrieve associations in secondary memory might contribute to reasoning performance independently of the role of primary memory (Shipstead, Lindsey, Marshall, & Engle, 2014; Unsworth et al., 2014), so an interesting question for future research would be whether training modules that focus on this ability might produce transfer to complex span tasks and further increase the transfer effects to reasoning that can be produced by updating training alone.

In sum, a number of explanatory mechanisms might be involved in the total pattern of effects, involving increased use of more or less material-dependent strategies and adaptations to task demands. The core of the latent transfer effects to reasoning may be improvements in the general efficiency and reliability in building and updating bindings as a basis for complex mental representations and manipulations. To achieve such improvements, extensive and intensive training of several updating tasks with different contents, adaptive difficulty, and a motivating implementation seems to be the most promising approach.

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